Higher radial and orbital excitations in the charmed meson family

Qin-Tao Song,[1,2,4,*] Dian-Yong Chen,[1,2,†] Xiang Liu,[2,3,‡] and Takayuki Matsuki[5,6,§]
[1]Nuclear Theory Group, Institute of Modern Physics of CAS, Lanzhou 730000, China
[2]Research Center for Hadron and CSR Physics, Lanzhou University & Institute of Modern Physics of CAS, Lanzhou 730000, China
[3]School of Physical Science and Technology, Lanzhou University, Lanzhou 730000, China
[4]University of Chinese Academy of Sciences, Beijing 100049, China
[5]Tokyo Kasei University, 1-18-1 Kaga, Itabashi, Tokyo 173-8602, Japan
[6]Theoretical Research Division, Nishina Center, RIKEN, Saitama 351-0198, Japan
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Using abundant experimental information about charmed mesons together with recent research, we systematically study higher radial and orbital excitations in the charmed meson family by analyzing the mass spectrum and by calculating their Okubo-Zweig-Iizuka-allowed two-body decay behaviors. This phenomenological analysis reveals underlying properties of the newly observed charmed states $D(2550)$, $D^*(2600)$, $D^*(2760)$, $D(2750)$, $D_J(2580)$, $D_J^*(2650)$, $D_J^*(2760)$, $D_J(2740)$, $D_J(3000)$, and $D_J^*(3000)$ to provide valuable information about the charmed mesons still missing in experiments.

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I. INTRODUCTION

In the past years, experimentalists have made great advances in observing charmed mesons and accordingly the list of charmed mesons collected by the Particle Data Group (PDG) has become increasingly lengthy [1]. Candidates for the higher radial and orbital excitations in the charmed meson family are the newly observed mesons $D(2550)$, $D^*(2600)$, $D^*(2760)$, and $D(2750)$ from *BABAR* [2] and $D_J(2580)$, $D_J^*(2650)$, $D_J^*(2760)$, $D_J(2740)$, $D_J(3000)$, and $D_J^*(3000)$ from LHCb [3], whose experimental information, together with other observed charmed mesons, is given in Table I.

These new observations and the present research status motivate us with great interest to carry out a systematic and phenomenological study of higher radial and orbital excitations in the charmed meson family, which will reveal the underlying properties of the observed charmed mesons and provide much more information for their further experimental search.

Although a couple of works have studied the heavy-light systems, including charmed mesons with their decay modes [10–17], in this work we focus mainly on application of our modified Godfrey-Isgur model developed in Ref. [18] to calculate the mass spectrum and decay behaviors of charmed mesons. The main difference between our model and the Godfrey-Isgur (GI) model proposed in Ref. [19] is that the confining potential br in the GI model is replaced by the screened one $V^{\rm scr} = b(1 - e^{-\mu r})/\mu$ to reflect the unquenched effect (see Ref. [18] for more details). This model includes such a screening effect that a linear confinement term br be screened or softened at large distances by virtual quark pairs and dynamical fermions [20,21], which is important especially for higher radial and orbital excitations. Even though the GI model does not consider the screening effect, it has been successful in describing the low-lying states [19]. With the modified GI model, we will show quite a successful mass spectrum of the high-lying charmed meson family. Having abundant experimental data, we are able to compare our theoretical values with the corresponding experimental results, which can not only test the reliability of our modified GI model, but also give some useful structure information about the observed charmed mesons. In addition, we will predict masses of some missing charmed mesons, which give an important hint to experimentally explore these missing states.

One more valuable lesson we learned from the former work Ref. [18] is that an experimental value of a mixing angle which is close to the one in the heavy quark limit determines relative decay widths, broad or narrow, with the same J^P states in two spin multiplets. These results are found to be model independent. The same scenario can be applied to the charmed meson family too and details will be described later.

After analyzing the mass spectrum of charmed mesons, in this work we further study two-body Okubo-Zweig-Iizuka-allowed (OZI) decays of charmed mesons, where the quark pair creation (QPC) model [22–28] is applied to calculating strong decays. With the modified GI model, we obtain the numerical wave functions of charmed mesons, which can be applied to calculating strong decays of

*songqint@impcas.ac.cn
†Corresponding author.
chendy@impcas.ac.cn
‡Corresponding author.
xiangliu@lzu.edu.cn
§matsuki@tokyo-kasei.ac.jp

TABLE I. Experimental information of the observed charmed mesons.

State	Mass (MeV) [1]	Width (MeV) [1]	First observation	Observed decay modes
D	1864.84 ± 0.07			
D^*	2010.26 ± 0.07	0.083		
$D_1(2420)$	2421.4 ± 0.6	70 ± 21	ARGUS [4]	$D^*\pi$
$D_2^*(2460)$	2464.3 ± 1.6	$20 \pm 10 \pm 5$	TPS [5]	$D^+\pi^-$
$D_1(2430)$	$2427 \pm 26 \pm 25$	$384^{+107}_{-75} \pm 75$	Belle [6]	$D^*\pi$
	2477 ± 28	266 ± 97	*BABAR* [7]	$D^*\pi$
$D_0^*(2400)$	$2308 \pm 17 \pm 32$	$276 \pm 21 \pm 63$	Belle [6]	$D\pi$
	$2407 \pm 21 \pm 35$	$240 \pm 55 \pm 59$	FOCUS [8]	$D\pi$
	$2297 \pm 8 \pm 20$	$273 \pm 12 \pm 48$	*BABAR* [9]	$D\pi$
$D(2550)$	$2539.4 \pm 4.5 \pm 6.8$	$130 \pm 12 \pm 13$	*BABAR* [2]	$D^*\pi$
$D^*(2600)$	$2608.7 \pm 2.4 \pm 2.5$	$93 \pm 6 \pm 13$	*BABAR* [2]	$D^{(*)}\pi$
$D(2750)$	$2752.4 \pm 1.7 \pm 2.7$	$71 \pm 6 \pm 11$	*BABAR* [2]	$D^*\pi$
$D^*(2760)$	$2763.3 \pm 2.3 \pm 2.3$	$60.9 \pm 5.1 \pm 3.6$	*BABAR* [2]	$D\pi$
$D(2580)$	$2579.5 \pm 3.4 \pm 5.5$	$177.5 \pm 17.8 \pm 46.0$	LHCb [3]	$D^*\pi$
$D_J^*(2650)$	$2649.2 \pm 3.5 \pm 3.5$	$140.2 \pm 17.1 \pm 18.6$	LHCb [3]	$D^*\pi$
$D_J(2740)$	$2737.0 \pm 3.5 \pm 11.2$	$73.2 \pm 13.4 \pm 25.0$	LHCb [3]	$D^*\pi$
$D_J^*(2760)$	$2761.1 \pm 5.1 \pm 6.5$	$74.4 \pm 3.4 \pm 37.0$	LHCb [3]	$D^{(*)}\pi$
$D_J(3000)$	2971.8 ± 8.7	188.1 ± 44.8	LHCb [3]	$D^*\pi$
$D_J^*(3000)$	3008.1 ± 4.0	110.5 ± 11.5	LHCb [3]	$D\pi$

charmed mesons, where we give partial and total widths of charmed mesons under discussion and some typical ratios relevant to these decays.

Combining the analysis of the mass spectrum with the calculation of the decay widths, we can learn the properties of higher radial and orbital excitations in the charmed meson family. Furthermore, we can also shed light on the underlying structures of the observed charmed states under discussion, which is the main task of this work.

This paper is organized as follows. In Sec. II we give a concise review on the observed charmed mesons. Then, the mass spectrum will be analyzed in Sec. III, where the modified GI model is briefly introduced. In Sec. IV we will give a brief review of the QPC model and calculate the two-body OZI-allowed decay of the charmed mesons under discussion by the QPC model. This paper will end with a short summary in Sec. V.

II. STATUS OF THE OBSERVED CHARMED MESONS

Before investigating the observed charmed mesons, we need to briefly review the present research status on candidates of higher radial and orbital excitations of the charmed meson family.

A. $D_0^*(2400)$, $D_1(2430)$, $D_1(2420)$, and $D_2^*(2460)$

As the first observed P-wave charmed meson, $D_1(2420)$ was reported in the $D^*\pi$ invariant mass distribution by the ARGUS Collaboration, where its measured mass and width are $M = 2420 \pm 6$ MeV and $\Gamma = 70 \pm 21$ MeV, respectively [4]. In 1989, the TPS Collaboration confirmed $D_1(2420)$ in the $D^{*+}\pi^-$ decay channel [5]. According to this decay mode, its spin-parity is either $J^P = 1^+$ or 2^+. The angular momentum analysis by the ARGUS Collaboration further shows that the observed $D_1(2420)$ has $J^P = 1^+$ [29]. The $D_1(2420)$ has been confirmed by other experiments [2,6,30–40] too.

The Belle Collaboration observed a broad state $D_1(2430)$ with mass $M = 2427 \pm 26 \pm 20 \pm 15$ MeV and width $\Gamma = 384^{+107}_{-75} \pm 24 \pm 70$ MeV by analyzing the $B \to D^*\pi\pi$ process, where its spin-parity is determined as $J^P = 1^+$ by the helicity distributions [6]. In 2006, the *BABAR* Collaboration studied the $D^*\pi$ invariant mass spectrum, where the broad $D_1(2430)$ was confirmed [7].

Besides $D_1(2430)$, Belle announced the observation of another broad state $D_0^*(2400)$, which has mass $M = 2308 \pm 17 \pm 15 \pm 28$ MeV with $J^P = 0^+$ [6]. The $D_0^*(2400)$ was also confirmed by the FOCUS and *BABAR* Collaborations with $M = 2403 \pm 14 \pm 35$ MeV [8] and $M = 2297 \pm 8 \pm 5 \pm 19$ MeV [9], respectively. Since different experiments gave quite different mass values for $D_0^*(2400)$, we will discuss mass dependence of the $D_0^*(2400)$ decay by varying mass in the range $(2290 \sim 2350)$ MeV. The $D_0^*(2400)$ as a P-wave state with $J^P = 0^+$ is supported by the theoretical works [10,11,14,41].

The TPS Collaboration observed the charmed meson with $M = 2459 \pm 3$ MeV and $\Gamma = 20 \pm 10 \pm 5$ in the invariant mass spectrum of $D^+\pi^-$ [5], which shows that this meson has either $J^P = 0^+$ or 2^+. This observation was confirmed by the ARGUS Collaboration in the $D^+\pi^-$ channel, and their angular momentum analysis suggests the $J^P = 2^+$ assignment to this state [30]. Thus, this resonance is named $D_2^*(2460)$. Later, the

CLEO Collaboration again confirmed the existence of $D_2^*(2460)$, where it has mass $M = 2461 \pm 3 \pm 1$ MeV and width $\Gamma = 20^{+9+9}_{-10+12}$ MeV. In addition, the ratio

$$\frac{\mathcal{B}(D_2^*(2460) \to D^+\pi^-)}{\mathcal{B}(D_2^*(2460) \to D^{*+}\pi^-)} = 2.3 \pm 0.8 \tag{1}$$

was measured as well in Ref. [31], which is consistent with the theoretical calculations in Refs. [10,11,16,41–44]. In recent years, many other experiments have reported $D_2^*(2460)$ [2,8,9,29,32–40,45].

The above experimental information indicates that there are two charmed mesons with $J^P = 1^+$. In the heavy quark limit $m_Q \to \infty$, $\vec{j}_\ell = \vec{S}_q + \vec{L}$ is a good quantum number, where $\vec{S}_q$ is the spin of a light quark and $\vec{L}$ is its angular momentum. Thus, heavy-light mesons can be classified by j_ℓ^P. Two 1S-wave charmed mesons form one doublet $(0^-, 1^-)$ with $j_l^P = \frac{1}{2}^-$. Four 1P-wave charmed mesons can be grouped into two doublets, $(0^+, 1^+)$ and $(1^+, 2^+)$, with $j_l^P = \frac{1}{2}^+$ and $j_l^P = \frac{3}{2}^+$, respectively. Since states with $J^P = 1^+$ in $(0^+, 1^+)$ and $(1^+, 2^+)$ doublets decay into $D^*\pi$ via S-wave and D-wave [10,11,14,41,46–48] in the heavy quark limit, respectively, the charmed mesons with $J^P = 1^+$ in $(0^+, 1^+)$ and $(1^+, 2^+)$ doublets have broad and narrow widths, respectively, which makes us easily distinguish between the two 1^+ charmed mesons experimentally observed; i.e., $D_1(2430)$ and $D_1(2420)$ belong to the doublets $(0^+, 1^+)$ and $(1^+, 2^+)$ [10,11,14,41,42,44], respectively.

B. $D(2550)$, $D_J(2580)$, $D^*(2600)$, and $D_J^*(2650)$

The $D(2550)$ was observed by the *BABAR* Collaboration, which has the mass $M = 2539.4 \pm 4.5 \pm 6.8$ MeV and width $\Gamma = 130 \pm 12 \pm 13$ MeV [2]. The $D(2550)$ is suggested to be a candidate for $D(2^1S_0)$ by the helicity distribution analysis [2]. In 2013, an unnatural state $D_J(2580)$ was found in the $D^*\pi$ invariant mass spectrum by the LHCb Collaboration through the process $pp \to D\pi X$ [3]. The resonance parameters of $D_J(2580)$ are similar to those of $D(2550)$, so $D(2550)$ and $D_J(2580)$ are regarded as the same state.

The mass of $D(2550)$ or $D_J(2580)$ is consistent with the theoretical prediction of $D(2^1S_0)$ in Ref. [19]. In addition, the decay width of $D(2^1S_0)$ was calculated by the QPC model [46], which is close to the lower limit of experimental width of $D(2550)/D_J(2580)$. In addition, the theoretical studies presented in Refs. [49,50] also show that $D(2550)$ can be $D(2^1S_0)$, the first radial excitation of D mesons. However, the authors in Refs. [11,51–53] indicated that the theoretical total width of $D(2^1S_0)$ is far below the experimental value of $D(2550)$.

The *BABAR* Collaboration reported a resonance $D^*(2600)$ with mass $M = 2608.7 \pm 2.4 \pm 2.5$ MeV and width $\Gamma = 93 \pm 6 \pm 13$ MeV, which is regarded as a radial excitation of D^* by the helicity distribution analysis [2], and they also measured the ratio [2]

$$\frac{\mathcal{B}(D^{*0}(2600) \to D^+\pi^-)}{\mathcal{B}(D^{*0}(2600) \to D^{*+}\pi^-)} = 0.32 \pm 0.02 \pm 0.09. \tag{2}$$

A natural state $D_J^*(2650)$ was found in the $D^*\pi$ invariant mass spectrum by the LHCb Collaboration through the process $pp \to D^*\pi X$ [3], where $D_J^*(2650)$ is tentatively identified as a $J^P = 1^-$ state, a radial excitation of D^*. Therefore, $D_J^*(2650)$ [3] and $D^*(2600)$ [2] are the same state.

In Ref. [54], they predicted that the mass of $D(2^3S_1)$ is 2620 MeV via the constituent quark model, which is in good agreement with the experimental value of $D^*(2600)$. Moreover, the ratio $\Gamma(D(2^3S_1)^0 \to D^+\pi^-)/\Gamma(D(2^3S_1)^0 \to D^{*+}\pi^-) = 0.47$ was predicted via the relativistic chiral quark model [10], which is close to the upper bound of Eq. (2). In Ref. [11], the authors calculated a mass spectrum and wave functions of charmed mesons via a relativistic quark model and then adopted the obtained masses and wave functions as an input to estimate hadronic decay widths. Here, the predicted mass of $D(2^3S_1)$ is 2692 MeV, which is heavier than $D^*(2600)$, while the predicted total width of $D(2^3S_1)$ is consistent with the experimental data of $D^*(2600)$. Furthermore, the assignment 2^3S_1 to $D^*(2600)$ is also supported by the studies in Refs. [49–53,55,56].

C. $D^*(2760)$, $D_J^*(2760)$, $D(2750)$, and $D_J(2740)$

The $D^*(2760)$ observed by the *BABAR* Collaboration in the $D\pi$ invariant mass spectrum [2] can be assigned to a D-wave charmed meson since its mass is consistent with the theoretical prediction in Ref. [19]. Later, LHCb announced the observation of a natural state $D_J^*(2760)$ with mass $M = 2761.1 \pm 5.1 \pm 6.5$ MeV and width $\Gamma = 74.4 \pm 3.4 \pm 37.0$ MeV. Both $D^*(2760)$ and $D_J^*(2760)$ can be regarded as the same state since these two states have similar widths and masses [57].

Comparison between the prediction in Ref. [11] and the experimental data of $D^*(2760)$ shows that $D^*(2760)$ can be either $D(1^3D_1)$ or $D(1^3D_3)$. However, the assignment of $D^*(2760)$ to $D(1^3D_1)$ or $D(1^3D_3)$ cannot be supported by the result shown in Ref. [46] since the calculated total widths of these two assignments are far larger than the experimental value. Later, in Ref. [51], it was suggested that $D^*(2760)$ is a mixture of the 2^3S_1 and 1^3D_1 states, which is also supported by the study presented in Ref. [49]. However, calculation by the constituent quark model shows that the $D(1^3D_3)$ assignment of $D^*(2760)$ cannot be excluded [52], which is also supported by the works in Refs. [51,53,55,58].

Besides $D^*(2760)$, another state $D(2750)$ was also observed by the *BABAR* Collaboration in the $D^*\pi$ mass spectrum, where its mass and width are $M = 2752.4 \pm 1.7 \pm 2.7$ MeV and $\Gamma = 71 \pm 6 \pm 11$ MeV, respectively [2]. Although $D(2750)$ can be a good candidate of a D-wave charmed meson according to the mass spectrum analysis in Ref. [19], the helicity distribution analysis of $D(2750)$ does not support the $D(1^3D_1)$ and $D(1^3D_3)$ assignments [2]. *BABAR* also gave the ratio [2]

$$\frac{\mathcal{B}(D^*(2760)^0 \to D^+\pi^-)}{\mathcal{B}(D(2750)^0 \to D^{*+}\pi^-)} = 0.42 \pm 0.05 \pm 0.11. \quad (3)$$

As an unnatural state, $D_J(2740)$ was found by the LHCb Collaboration, which has mass $M = 2737.0 \pm 3.5 \pm 11.2$ MeV and $J^P = 2^-$ [3]. Due to the similarity between $D(2750)$ and $D_J(2740)$, it is possible that $D(2750)$ and $D_J(2740)$ are the same state. Before the observation of $D(2750)/D_J(2740)$, the masses of two 2^- charmed mesons were predicted in Ref. [11], where the masses of the 2^- charmed mesons belonging to the $(1^-, 2^-)$ and $(2^-, 3^-)$ doublets are 2883 MeV and 2775 MeV, respectively, which shows that $D(2750)/D_J(2740)$ as a 2^- state with $j_\ell^P = 5/2^-$; i.e., $(2^-, 3^-)$ is more favorable. However, we also notice that the corresponding theoretical width of this 2^- state is not consistent with the experimental value. After observing $D(2750)/D_J(2740)$, the authors of Ref. [58] calculated the ratio $\Gamma(D^*(2760)^0 \to D^+\pi^-)/\Gamma(D(2750)^0 \to D^{*+}\pi^-)$ by adopting an effective Lagrangian approach, which is consistent with the experimental data, where $D^*(2760)$ and $D(2750)$ are identified as the 1^3D_3 and 2^- states in the $(2^-, 3^-)$ doublet, respectively. The studies in Refs. [49,52,53,55] also suggested that $D(2750)$ is a 2^- state in the $(2^-, 3^-)$ doublet.

D. $D_J(3000)$ and $D_J^*(3000)$

The LHCb Collaboration observed the unnatural state $D_J(3000)$ in the $D^*\pi$ invariant mass spectrum [3], where its resonance parameters are

$$M = 2971.8 \pm 8.7 \text{ MeV}, \qquad \Gamma = 188.1 \pm 44.8 \text{ MeV}.$$

Then, different theoretical groups carried out the study of $D_J(3000)$. In Ref. [59], $D_J(3000)$ is regarded as the first radial excitation of $D_1(2430)$, which was also confirmed by Refs. [56,60]. However, other possible assignments to $D_J(3000)$ were proposed, i.e., the $D(3^1S_0)$ [50] and $D(3^+)$ [56] assignments.

A natural state $D_J^*(3000)$ was also reported by LHCb in the $D\pi$ invariant mass spectrum [3], which has

$$M = 3008.1 \pm 4.0 \text{ MeV}, \qquad \Gamma = 110.5 \pm 11.5 \text{ MeV}.$$

The $D_J^*(3000)$ is variously explained as $D(2^3P_0)$ [59], $D(1^3F_2)$ [56], and $D(1^3F_4)$ [50,56,60].

III. MASS SPECTRUM

For the heavy-light meson system, we need to adopt a relativistic quark model to study their mass spectrum since a relativistic effect for a heavy-light meson system is significant. The Godfrey-Isgur (GI) model can well describe the meson spectrum [19], which is a typical quenched quark model. After the discovery of $D_{s0}(2317)$ [61–64], $D_{s1}(2460)$ [62–65], and $X(3872)$ [66], theorists realized that it is necessary to take into account coupled channel effects, especially for higher radial and orbital excitations of hadrons [67–70], where the coupled channel effects may change the meson spectrum. This motivates us to modify the GI model by considering the coupled channel effects.

In general, spontaneous creation of light quark-antiquark pairs inside a meson can soften a linear confinement potential br by screening a color charge at distances larger than about one fermi [21], which is known as the screening effect. The screening effect has been seen by the unquenched lattice QCD and holographic models [71–73]. The mass suppression can be caused by both the screening and coupled channel effects. Although the screening effect can have an almost equivalent description as the coupled channel effect, we need to emphasize that the screening effect cannot depict the near-threshold effect as the coupled channel effect does [74], which is obtained by studying the charmonium spectrum. The authors of this paper made a comparison of the results by adopting the screening and coupled channel effects. Applying the idea in Ref. [74] to our case, we can similarly study a charmed meson spectrum. However, it is a complicated task and can be assessed in a future theoretical work.[1]

In Refs. [18,75,76], the screening effect was taken into account when studying the mass spectra of light mesons, charmonia, and charmed-strange mesons. Mezzoir *et al.* provided a description of a highly excited light-quark meson spectrum by flattening the confining potential br at distances larger than r_s [75]. The screened potential model [77,78] was adopted to compute the charmonium spectrum [76]. In our recent work [18], the screening effect was introduced to modify the GI model, where the mass spectrum of the charmed-strange meson family with this treatment is greatly improved compared with the results of the GI model. As a sister work of Ref. [18], the present work focuses on the charmed mesons applying the modified GI model [18] to obtain their mass spectrum.

In the GI model, the confining potential br is smeared out to include relativistic effects, i.e.,

$$\tilde{V}(r) = \int d^3\boldsymbol{r}'\rho_{12}(\boldsymbol{r} - \boldsymbol{r}')br'. \quad (4)$$

[1]We would like to thank the referee for his/her useful suggestion on this point.

Here, the GI model is a quenched quark model in the sense that the effect of quark-antiquark pairs is not introduced [19]. In order to take account of the screening effect in the GI model, the confining potential br is replaced with [77,78]

$$br \to V^{\mathrm{scr}}(r) = \frac{b(1-e^{-\mu r})}{\mu}, \quad (5)$$

where $V^{\mathrm{scr}}(r)$ behaves like br at short distances and constant b/μ at large distances. Furthermore, the smearing function is introduced to take into account the nonlocality property of potentials [19], i.e.,

$$\tilde{V}^{\mathrm{scr}}(r) = \int d^3\boldsymbol{r}'\rho_{12}(\boldsymbol{r}-\boldsymbol{r}')\frac{b(1-e^{-\mu r'})}{\mu}. \quad (6)$$

A detailed explanation of how to introduce the screening effect into the GI model can be found in Ref. [18].

The mass spectrum of charmed mesons is calculated in the GI model and the modified GI model, which is shown in Table II. Here, all the parameters of the modified GI model are the same as those of the GI model [19] except for the additional parameter μ in $\tilde{V}^{\mathrm{scr}}(r)$. In this table, we present the theoretical predictions of the mass spectrum with several values of μ, 0.01,0.02,0.03, and 0.04 GeV. In order to choose a suitable value for μ, we calculate the χ^2 of the predicted masses for each μ. In Table III we list the theoretical results with the least value of $\mu = 0.03$ GeV together with experimental data. Here the concrete expression for χ^2 is

$$\chi^2 = \sum_i \left(\frac{\mathcal{A}_{\mathrm{Th}}(i) - \mathcal{A}_{\mathrm{Exp}}(i)}{\mathrm{Error}(i)}\right)^2, \quad (7)$$

where $\mathcal{A}_{\mathrm{Th}}(i)$ and $\mathcal{A}_{\mathrm{Exp}}(i)$ are theoretical and experimental values, respectively. $\mathrm{Error}(i)$ denotes the experimental error of the mass of a charmed meson. A minimum of χ^2 is obtained by our model with $\mu = 0.03$ GeV. Eventually, the modified GI model with this value of μ improves the whole description of the charmed meson mass spectrum compared with the GI model (see Table III for more details).

In Table III, we further make a comparison between experimental data and theoretical values obtained via the modified GI model. Besides the 2^1S_0 and 2^3S_1 states, a difference between theoretical and experimental values of other charmed mesons is less than 20 MeV. We can conclude from the mass spectrum analysis, i.e.,

(1) Two $1S$ states and four $1P$ states in the charmed meson family can be well reproduced by the modified GI model.

(2) Both $D(2550)$ reported by the *BABAR* Collaboration [2] and $D_J(2580)$ from the LHCb Collaboration [3] are usually considered as a candidate of $D(2^1S_0)$. Here, the mass of $D(2550)$ is quite close to the theoretical mass of $D(2^1S_0)$, while the mass of $D_J(2580)$ is larger than the theoretical mass of $D(2^1S_0)$ by about 40 MeV.

(3) There exist two experimental results $D^*(2600)$ and $D_J^*(2650)$ from *BABAR* [2] and LHCb [3], both of which can be a candidate of $D(2^3S_1)$. Our result shows that $D^*(2600)$ is closer to the theoretical mass of $D(2^3S_1)$.

(4) $D(2750)/D_J(2740)$ is a good candidate of $D(1D_2)$, while $D^*(2760)/D_J^*(2760)$ corresponds to $D(1^3D_1)$ or $D(1^3D_3)$.

(5) $D_J(3000)$ and $D_J^*(3000)$ can be candidates of $D(3^1S_0)$ and $D(3^3S_1)$, respectively. In addition,

TABLE II. The calculated masses of charmed mesons by the modified GI model and comparison with those obtained by the GI model. Here, we take several μ values, $\mu = 0.01, 0.02, 0.03$, and 0.04 GeV, to show μ dependence of the modified GI model. Values in brackets for the GI model and $\mu = 0.03$ are those of $R = 1/\beta$, which can be determined by solving $\int \Psi_{nLM}^{\mathrm{SHO}}(\mathbf{p})^2 p^2 d^3\mathbf{p} = \int \Phi(\mathbf{p})^2 p^2 d^3\mathbf{p}$, where $\Psi_{nLM}^{\mathrm{SHO}}(\mathbf{p})$ is a SHO wave function and $\Phi(\mathbf{p})$ is the wave function of a charmed meson which we obtain by solving an eigenvalue equation. We need to emphasize that we do not consider mixing among states with the same quantum number when presenting the results. μ is in units of GeV, while R is in units of GeV^{-1}.

		Modified GI model			
	GI model	$\mu = 0.01$	$\mu = 0.02$	$\mu = 0.03$	$\mu = 0.04$
1^1S_0	1874(1.52)	1869	1865	1861(1.54)	1855
2^1S_0	2583(2.08)	2566	2550	2534(2.22)	2518
3^1S_0	3068(2.33)	3037	3005	2976(2.50)	2945
1^3S_1	2038(1.85)	2032	2027	2020(1.89)	2015
2^3S_1	2645(2.17)	2628	2610	2593(2.33)	2576
3^3S_1	3111(2.38)	3079	3047	3015(2.56)	2983
1^1P_1	2457(2.00)	2447	2436	2426(2.08)	2415
2^1P_1	2933(2.27)	2909	2885	2861(2.44)	2837
1^3P_0	2398(1.85)	2387	2376	2365(1.92)	2354
2^3P_0	2932(2.22)	2907	2881	2856(2.38)	2831
1^3P_1	2465(2.00)	2453	2441	2431(2.08)	2419
2^3P_1	2952(2.27)	2927	2902	2877(2.44)	2852
1^3P_2	2501(2.22)	2490	2479	2468(2.33)	2456
2^3P_2	2957(2.38)	2933	2908	2884(2.56)	2859
1^1D_2	2827(2.27)	2807	2791	2773(2.38)	2755
2^1D_2	3225(2.44)	3193	3160	3128(2.63)	3095
1^3D_1	2816(2.13)	2798	2780	2762(2.27)	2744
2^3D_1	3231(2.33)	3198	3164	3131(2.56)	3097
1^3D_2	2834(2.27)	2816	2797	2779(2.38)	2761
2^3D_2	3235(2.44)	3202	3169	3136(2.63)	3102
1^3D_3	2833(2.38)	2815	2797	2779(2.56)	2761
2^3D_3	3226(2.50)	3194	3162	3129(2.70)	3097
1^1F_3	3123(2.44)	3097	3072	3046(2.63)	3019
1^3F_2	3132(2.33)	3106	3080	3053(2.50)	3027
1^3F_3	3129(2.44)	3104	3078	3051(2.63)	3025
1^3F_4	3113(2.50)	3088	3063	3037(2.70)	3011

TABLE III. Comparison of experimental data and theoretical results. Here, we also list the χ^2 values for different models. The notation L_L is introduced to express mixing states of ${}^1L_L$ and ${}^3L_L$. Here, the results listed in the last column are calculated by the modified GI model with $\mu = 0.03$ GeV which gives the least χ^2 value among several μ's.

	$n^{2S+1}L_J$	Experimental values [1]	GI model [19]	Modified GI model
D	1^1S_0	1864.84 ± 0.07	1874	1861
D^*	1^3S_1	2010.26 ± 0.07	2038	2020
$D_0^*(2400)$	1^3P_0	2318 ± 29	2398	2365
$D_1(2420)$	$1P_1$	2421.4 ± 0.6	2467	2434
$D_1(2430)$	$1P_1$	$2427 \pm 26 \pm 25$	2455	2424
$D_2^*(2460)$	1^3P_2	2464.3 ± 1.6	2501	2468
$D(2550)$	2^1S_0	$2539.4 \pm 4.5 \pm 6.8$ [2]	2583	2534
$D^*(2600)$	2^3S_1	$2608.7 \pm 2.4 \pm 2.5$ [2]	2645	2593
$D(2750)$	$1D_2$	$2752.4 \pm 1.7 \pm 2.7$ [2]	2845	2789
$D^*(2760)$	1^3D_3	$2763.3 \pm 2.3 \pm 2.3$ [2]	2833	2779
χ^2	···	···	45 677	5748

the mass spectrum study cannot exclude a possibility of $D_J(3000)$ and $D_J^*(3000)$ as the $1F$ states in the charmed meson family. We also notice that the theoretical masses of the $2P$ states are about 100 MeV smaller than the corresponding experimental data of $D_J(3000)$ and $D_J^*(3000)$.

We also notice a study of the heavy-light meson spectroscopy within the framework of the QCD-motivated relativistic quark model based on the quasipotential approach [79]. The conclusion of the mass spectrum obtained above in the present work is consistent with those of Ref. [79].

In order to clearly identify the properties of the observed charmed mesons, we need to perform a systematic study of their decay behaviors, which is the main task in the next section.

IV. STRONG DECAY BEHAVIORS

Study of the two-body OZI-allowed strong decay behaviors of the observed and the predicted charmed mesons can provide much more information on the features of the charmed mesons under discussion, which includes total and partial decay widths. What is more important is that the inner structure of the observed charmed mesons given by the mass spectrum analysis in Sec. III can be further tested here.

As an effective approach to study the OZI-allowed strong decays of hadrons, the QPC model is applied to compute the OZI-allowed strong decays of charmed mesons, which was first proposed by Micu [22] and further developed by the Orsay group [23–28]. Here, a meson decay occurs through a flavor and color singlet quark-antiquark pair created from the vacuum. To depict a $q\bar{q}$ pair creation from the vacuum, the transition operator $\mathcal{T}$ is introduced as

$$\mathcal{T} = -3\gamma\sum_m \langle 1m; 1-m|00\rangle \int d\mathbf{p}_3 d\mathbf{p}_4 \delta^3(\mathbf{p}_3+\mathbf{p}_4) \times \mathcal{Y}_{1m}\left(\frac{\mathbf{p}_3-\mathbf{p}_4}{2}\right)\chi^{34}_{1,-m}\phi^{34}_0(\omega^{34}_0)_{ij} b^\dagger_{3i}(\mathbf{p}_3) d^\dagger_{4j}(\mathbf{p}_4), \tag{8}$$

where γ is a dimensionless constant which reflects the strength of creating a quark-antiquark pair from the vacuum. In Ref. [80], $\gamma = 8.7$ is obtained for the $u\bar{u}/d\bar{d}$ pair creation by fitting with the experimental data, where the $SU(3)$ flavor singlet wave function was adopted, while for reflecting the $SU(3)$ breaking effect we take $\gamma = 8.7/\sqrt{3}$ for the $s\bar{s}$ pair creation as suggested in Ref. [23]. We need to explain why there exists an extra $1/\sqrt{3}$ factor for the $s\bar{s}$ pair creation. In Ref. [23], the authors realized the $SU(3)$ and $SU(4)$ breaking by defining the flavor function ϕ_0 of a $q\bar{q}$ pair created from the vacuum; i.e., ϕ_0 reads $\phi_0 = u\bar{u} + d\bar{d} + \sigma_s(s\bar{s}) + \sigma_c(c\bar{c})$ where $\sigma_s = m_u/m_s$, $\sigma_c = m_u/m_c$, and σ_s expresses the $SU(3)$ breaking. In order to check whether the estimate of σ_s is in agreement with hadron spectroscopy, the authors of Ref. [23] calculated ratios $r_{a_2(1320)} = \Gamma(a_2(1320)\to\pi\eta)/\Gamma(a_2(1320)\to K\bar{K})$ and $r_{f_2(1270)} = \Gamma(f_2(1270)\to\pi\pi)/\Gamma(f_2(1270)\to K\bar{K})$ by the QPC model to obtain $r_{a_2} = 0.8/(\sigma_s)^2$ and $r_f = 9.6/(\sigma_s)^2$. Comparing the above ratios with the experimental data $r_{a_2} = 3.2$ and $r_f = 30$, they found that $\sigma_s \approx 1/\sqrt{3}$ is a reasonable estimate. In our work we adopt $\phi_0^{34} = (u\bar{u} + d\bar{d} + s\bar{s})/\sqrt{3}$ as the flavor $SU(3)$ singlet wave function. To show the $SU(3)$ breaking, the creation strength for $u\bar{u}$ and $d\bar{d}$ is defined as γ, while for the strength of $s\bar{s}$ creation we have $\gamma/\sqrt{3}$, which is equivalent to the description in Ref. [23]. In Eq. (8), symbols $\mathbf{p}_3$ and $\mathbf{p}_4$ stand for momenta of the quark and antiquark, respectively. $\mathcal{Y}_{\ell m}(\mathbf{p}) = |\mathbf{p}|^\ell Y_{\ell m}(\mathbf{p})$ is the solid harmonic polynomial and $\chi^{34}_{1,-m}$ is the spin triplet state. The quantum number of a quark-antiquark pair is $J^{PC} = 0^{++}$, determined by coupling the orbital angular momentum with the spin angular momenta, which indicates the conservation of angular momentum J, P parity, and C parity in the course of strong interaction. $\phi_0^{34} = (u\bar{u} + d\bar{d} + s\bar{s})/\sqrt{3}$ and $(\omega_0^{34})_{ij} = \delta_{ij}/\sqrt{3}$ are the $SU(3)$ flavor and color functions, respectively, with i and j being the color indices.

The transition matrix of a process $A \to BC$ can be expressed as

$$\langle BC|T|A\rangle = \delta^3(\mathbf{p}_B + \mathbf{p}_C)\mathcal{M}^{M_{JA}M_{JB}M_{JC}}, \tag{9}$$

where $\mathbf{p}_B$ and $\mathbf{p}_C$ are the momenta of mesons B and C, respectively. $|A\rangle$, $|B\rangle$, and $|C\rangle$ denote mock states [81]. The mock state of a meson A can be defined as

$$|A(n^{2S+1}L_{JM_J})(\mathbf{p}_A)\rangle = \sqrt{2E}\sum_{M_S,M_L}\langle LM_L;SM_S|JM_J\rangle\chi^A_{S,M_S} \times\phi^A\omega^A\int d\mathbf{p}_1 d\mathbf{p}_2\delta^3(\mathbf{p}_A-\mathbf{p}_1-\mathbf{p}_2) \times\Psi^A_{nLM_L}(\mathbf{p}_1,\mathbf{p}_2)|q_1(\mathbf{p}_1)\bar{q}_2(\mathbf{p}_2)\rangle, \quad (10)$$

where χ^A_{S,M_S}, ϕ^A, and ω^A are spin, flavor, and color wave functions of a meson A, respectively. $\Psi^A_{nLM_L}(\mathbf{p}_1,\mathbf{p}_2)$ is a spatial wave function of meson A, which can be obtained in the modified GI model. Furthermore, the amplitude $\mathcal{M}^{M_{JA}M_{JB}M_{JC}}$ can be related to the partial wave amplitude $\mathcal{M}^{JL}$ via the Jacob-Wick formula [82], i.e.,

$$\mathcal{M}^{JL}(A\to BC) = \frac{\sqrt{2L+1}}{2J_A+1}\sum_{M_{JB},M_{JC}}\langle L0;JM_{JA}|J_AM_{JA}\rangle \times\langle J_BM_{JB};J_CM_{JC}|JM_{JA}\rangle\mathcal{M}^{M_{JA}M_{JB}M_{JC}}.$$

Therefore, the total decay width can be expressed as

$$\Gamma = \pi^2\frac{|\mathbf{p}_B|}{m_A^2}\sum_{J,L}|\mathcal{M}^{JL}|^2. \quad (11)$$

After this brief introduction of the QPC model, we perform a phenomenological analysis of charmed mesons in the following. When calculating a decay width, we adopt the numerical wave function for a charmed meson obtained in this work and the one for a charmed-strange meson from Ref. [18]. Additionally, we still employ the simple harmonic oscillator wave function for light mesons such as π and K, where the corresponding β values are taken from Ref. [41]. We need to emphasize that the mass is taken from PDG [1] for the observed meson. For the charmed mesons which are still missing, we use the theoretical predictions calculated in the modified GI model, the results listed in Table. II, and/or Fig. 1 as an input.

A. 1*P* states

As the 1^3P_0 state, $D_0^*(2400)$ has been observed by three different experiments. However, the experimental masses are quite different from one another as shown in Table I. Therefore, in this work we take the mass range ($2.29\sim2.35$ GeV) of $D_0^*(2400)$ to discuss mass dependence of the calculated decay width. Here, $D_0^*(2400)$ only decays into $D\pi$. In Fig. 2, we present the mass dependence of the decay width of $D_0^*(2400)$. We find that our results are consistent with experimental data $\Gamma = 276\pm21\pm63$ [6], $\Gamma = 240\pm55\pm59$ [8], and $\Gamma = 273\pm12\pm48$ [9].

In the following, we study $D_1(2420)$ and $D_1(2430)$, which are mixtures of the 1^1P_1 and 1^3P_1 states. $D_1(2420)$ and $D_1(2430)$ satisfy the relation

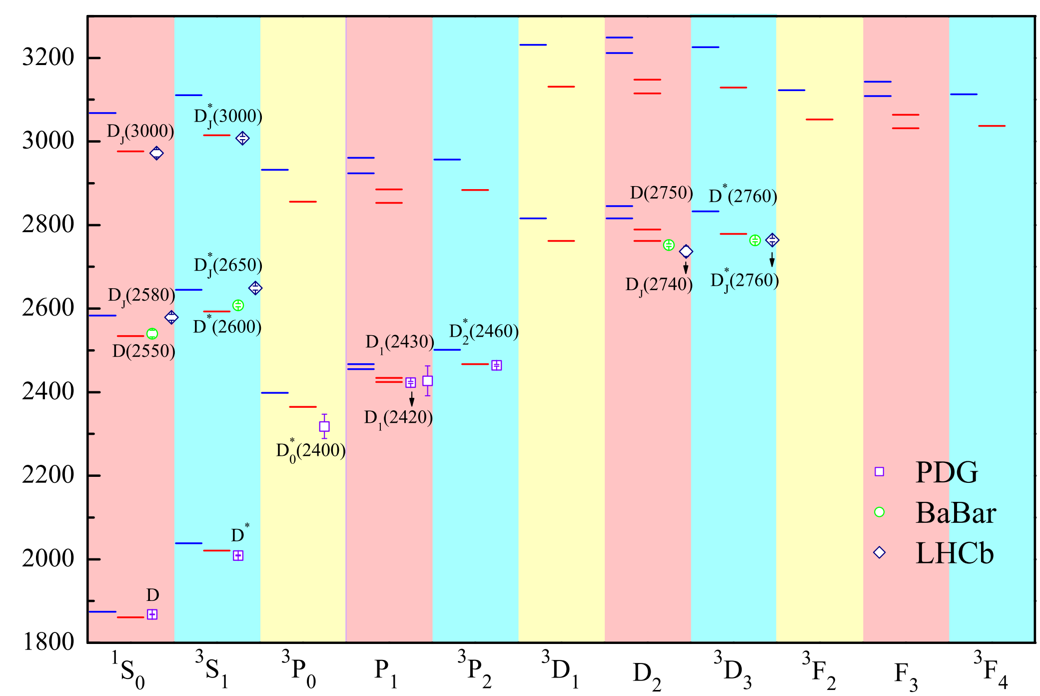

FIG. 1 (color online). Mass spectrum of charmed mesons (in units of MeV). Here, the blue lines stand for the results of the GI model [19], while the red lines are those of the modified GI model with $\mu = 0.03$ GeV. The purple squares denote the experimental data taken from PDG [1], while the green circles and blue lozenges are experimental masses of Refs. [2] and [3], respectively. The corresponding $^{2S+1}L_J$ quantum numbers are listed on the abscissa. In addition, when there exists a mixture of n^1L_L and n^3L_L states, we use a notation L_L.

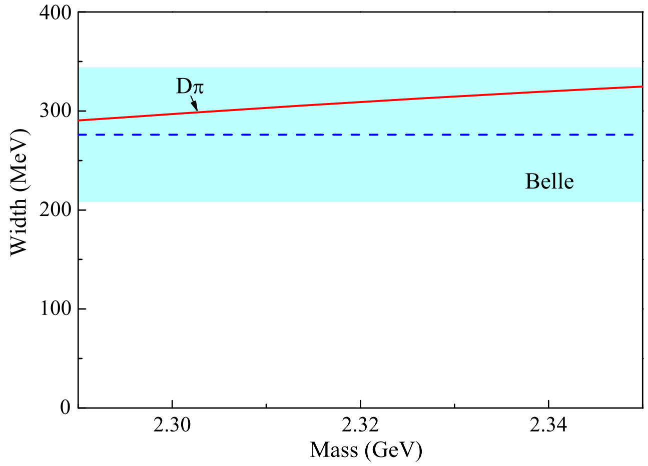

FIG. 2 (color online). Mass dependence of the width of $D_0^*(2400)$ and comparison with the Belle data [6]. The mass range of $D_0^*(2400)$ is 2920 ∼ 2350 MeV.

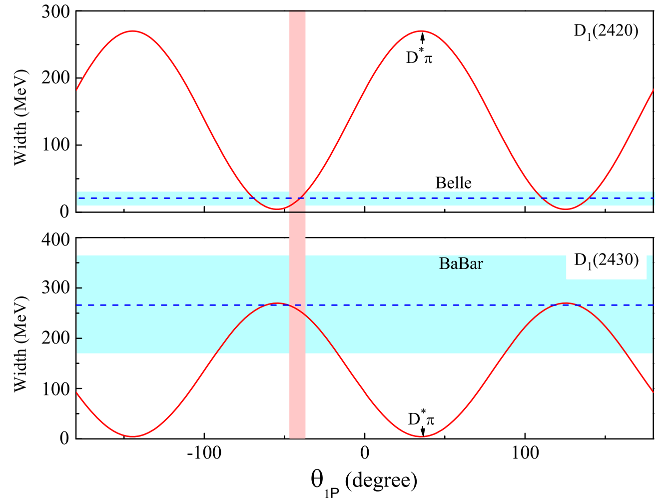

FIG. 3 (color online). The θ_{1P} dependence of the decay widths of $D_1(2420)$ and $D_1(2430)$.

$$\begin{pmatrix} |D_1(2430)\rangle \\ |D_1(2420)\rangle \end{pmatrix} = \begin{pmatrix} \cos\theta_{1P} & \sin\theta_{1P} \\ -\sin\theta_{1P} & \cos\theta_{1P} \end{pmatrix} \begin{pmatrix} |1^1P_1\rangle \\ |1^3P_1\rangle \end{pmatrix}, \quad (12)$$

where the mixing angle is $\theta_{1P} = -54.7°$, which is determined by the heavy quark limit [41,83,84].

The width of $D_1(2420)$ ($\Gamma = 70 \pm 21$) was first measured by the ARGUS Collaboration [4]. However, different experiments provided different widths as $\Gamma = 13 \pm 6^{+10}_{-5}$ MeV [29], $\Gamma = 23^{+8+10}_{-6-3}$ MeV [31], and $\Gamma = 21 \pm 5 \pm 8$ MeV [36]. Here, we take the median as the width, i.e., the measurement $\Gamma = 21 \pm 5 \pm 8$ MeV from the Belle Collaboration [36]. $D_1(2430)$ is a broad state, which has the width $\Gamma = 384^{+107}_{-75} \pm 75$ MeV given by Belle [6] and $\Gamma = 266 \pm 96$ MeV by *BABAR* [7]. Both $D_1(2430)$ and $D_1(2420)$ only decay into $D\pi$. In Fig. 3, we show the decay widths of $D_1(2420)$ and $D_1(2430)$ depending on the mixing angle θ_{1P}, where our results are consistent with the experimental data when taking $-45.6° < \theta_{1P} < -37.2°$, which is close to $\theta_{1P} = -54.7° = -\arcsin(\sqrt{2/3})$ in the heavy quark limit [41,83,84].

The $D_2^*(2460)$ is considered as the 1^3P_2 state. Its decay channels are $D\pi$, $D^*\pi$, $D\eta$, and D_sK, whose theoretical values of decay widths are shown in Table IV. The total width is 14.86 MeV and the branching ratio $\mathcal{B}(D_2^*(2460)^0 \to D^+\pi^-)/\mathcal{B}(D_2^*(2460)^0 \to D^{*+}\pi^-)$ is 1.96. There are several different experimental widths for $D_2^*(2460)$, i.e., $\Gamma = 20 \pm 10 \pm 5$ MeV from the TPS Collaboration [5], $\Gamma = 20^{+9+9}_{-10-12}$ MeV from the CLEO Collaboration [31], and $45.6 \pm 4.4 \pm 6.7$ MeV from the Belle Collaboration [6]. Our theoretical width is consistent with the TPS data [5] and the CLEO data [31]. Furthermore, our ratio is in good agreement with experimental values $\mathcal{B}(D^+\pi^-)/\mathcal{B}(D^{*+}\pi^-) = 2.3 \pm 0.8$ [31] and $\mathcal{B}(D^+\pi^-)/\mathcal{B}(D^{*+}\pi^-) = 1.9 \pm 0.5$ [6] measured by CLEO and Belle, respectively.

In this subsection, $D_0^*(2400)$, $D_1(2420)$, $D_1(2430)$, and $D_2^*(2460)$, which are well established as $1P$ charmed mesons, have been analyzed, which makes us safely adopt the QPC model and the related model parameters to further study the following charmed mesons under discussion.

B. 2*S* and 1*D* states

The $D(2550)/D_J(2580)$ [2,3] is usually considered as a candidate of the 2^1S_0 state. The main decay channels of $D(2550)$ are $D^*\pi$ and $D_0^*(2400)\pi$ as shown in Table IV, which can explain why *BABAR* and LHCb first observed

TABLE IV. The partial and total widths of charmed mesons $D_2^*(2460)$, $D(2550)/D_J(2580)$, and $D(2600)/D_J^*(2650)$. We mark the OZI-forbidden channels by with the "⋯" symbol. If the channels depend on other parameters, we label them with "□" and show the widths in Fig. 4. All values are in units of MeV.

Channels	$D_2^*(2460)$	$D(2550)/D_J(2580)$	$D(2600)/D_J^*(2650)$
$D\pi$	9.17	⋯	□
$D\eta$	0.02	⋯	□
D_sK	1.0×10^{-4}	⋯	□
$D^*\pi$	4.67	67.56	□
$D^*\eta$	⋯	⋯	□
D_s^*K	⋯	⋯	□
$D_0^*(2400)\pi$	⋯	4.09	⋯
$D_2^*(2460)\pi$	⋯	⋯	□
$D_1(2420)\pi$	⋯	⋯	□
$D_1(2430)\pi$	⋯	⋯	□
Total width	14.86	71.65	⋯

$D(2550)/D_J(2580)$ in the $D^*\pi$ channel. The total width is obtained as 71.65 MeV which is comparable with the lower bound of the *BABAR* data [2] and is smaller than the LHCb value [3]. Considering this situation, we also suggest more precise measurement of the resonance parameters of $D(2550)/D_J(2580)$, which will be helpful for further testing the 2^1S_0 assignment to $D(2550)/D_J(2580)$.

In the following, we study $D^*(2600)/D_J^*(2650)$ [2,3] with $J^P = 1^-$, which is a mixture of the 2^3S_1 and 1^3D_1 states. Here, $D^*(2600)$ and its orthogonal partner satisfy

$$\begin{pmatrix} |D^*(2600)\rangle \\ |D^{*\prime}(1^-)\rangle \end{pmatrix} = \begin{pmatrix} \cos\theta_{SD} & \sin\theta_{SD} \\ -\sin\theta_{SD} & \cos\theta_{SD} \end{pmatrix} \begin{pmatrix} |2^3S_1\rangle \\ |1^3D_1\rangle \end{pmatrix}, \tag{13}$$

where the mixing angle θ_{SD} is introduced to describe mixing between $D(2^3S_1)$ and $D(1^3D_1)$.

The θ_{SD} dependence of the total width, partial decay widths, and ratio $\mathcal{B}(D^*(2600) \to D^+\pi^-)/\mathcal{B}(D^*(2600) \to D^{*+}\pi^-)$ of $D^*(2600)$ are shown in Fig. 4, where two tiny partial widths $\Gamma(D^*(2600) \to D_s^*K)$ and $\Gamma(D^*(2600) \to D_2^*(2460)\pi)$ are not listed. When taking the range $-3.6° < \theta_{SD} < 1.8°$, the theoretical ratio is consistent with the *BABAR* measurement of Eq. (2). The obtained total width is about 60 MeV, which is comparable to the experimental data $\Gamma = 93 \pm 6 \pm 13$ MeV [2]. We also find that the main decay modes of $D^*(2600)$ are $D\pi$ ($9 \sim 15$ MeV) and $D^*\pi$ ($32 \sim 38$ MeV), which also explains why $D^*(2600)$ was first reported in these two decay channels [2]. We need to stress that the small mixing angle θ_{SD} is expected because of the large mass difference between $D^*(2600)$ and its partner $D^*(2760)$, which is consistent with the suggestion in Ref. [19].

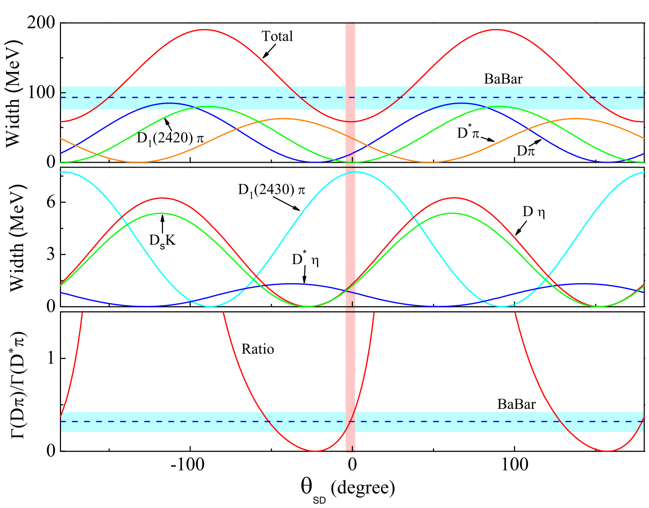

FIG. 4 (color online). The θ_{SD} dependence of the total and partial decay widths and the ratio $\Gamma(D\pi)/\Gamma(D^*\pi)$ of $D^*(2600)$.

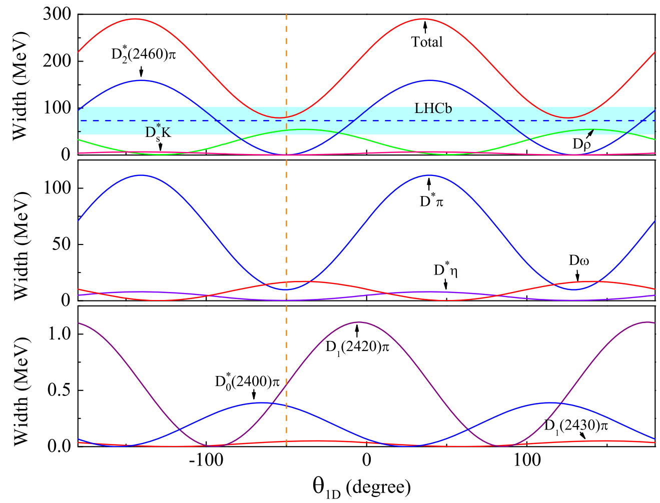

FIG. 5 (color online). The θ_{1D} dependence of the total and partial decay widths of $D(2750)/D_J(2740)$. Here, the vertical dashed line corresponds to the mixing angle $\theta_{1D} = -50.8°$.

As the D-wave charmed meson with $J^P = 2^-$, $D(2750)/D_J(2740)$ is probably either a $1D(2^-)$ or $1D'(2^-)$ state, which satisfies the following relation,

$$\begin{pmatrix} |1D(2^-)\rangle \\ |1D'(2^-)\rangle \end{pmatrix} = \begin{pmatrix} \cos\theta_{1D} & \sin\theta_{1D} \\ -\sin\theta_{1D} & \cos\theta_{1D} \end{pmatrix} \begin{pmatrix} |1^1D_2\rangle \\ |1^3D_2\rangle \end{pmatrix}, \tag{14}$$

where θ_{1D} is the mixing angle and can be fixed as $\theta_{1D} = -50.8° = -\arcsin(\sqrt{3/5})$ in the heavy quark limit [41,83,85].

TABLE V. The calculated partial and total decay widths of $1D$ states with several possible assignments. If a decay channel is forbidden, we mark it with the "⋯" symbol. As for the channels which depend on other parameters, we label them with "□" and show the widths in Figs. 4 and 5. All values are in units of MeV.

Channels	1^3D_1	$1D(2^-)/1D'(2^-)$	1^3D_3
$D\pi$	76.13	⋯	8.47
$D\eta$	9.01	⋯	0.31
D_sK	11.66	⋯	0.17
$D^*\pi$	35.16	□	7.05
$D^*\eta$	2.68	□	0.11
D_s^*K	2.92	□	0.04
$D\rho$	26.34	□	0.61
$D\omega$	8.87	□	0.21
$D_0^*(2400)\pi$	⋯	□	⋯
$D_2^*(2460)\pi$	0.56	□	0.63
$D_1(2420)\pi$	211.72	□	0.21
$D_1(2430)\pi$	0.007	□	0.26
Total width	385.06	⋯	18.07

The decay modes of $1D(2^-)/1D'(2^-)$ are shown in Table V. If $D(2750)/D_J(2740)$ is $1D'(2^-)$, the mixing angle dependence of the corresponding partial and total decay widths is given in Fig. 5. The range of a mixing angle is obtained as $-73.8° < \theta_{1D} < -35.7°$ in Fig. 5 so that the calculated total width is consistent with a central value of the experimental data, which includes the above heavy quark limit, $\theta_{1D} = -50.8°$. Thus, a $1D'(2^-)$ state is suitable for $D(2750)/D_J(2740)$. In addition, the main decay modes of $D(1D'(2^-))$ are predicted to be $D^*\pi$ ($10 \sim 25$ MeV), $D\rho$ ($37 \sim 55$ MeV), $D\omega$ ($12 \sim 17$ MeV), and $D_2^*(2460)\pi$ ($0 \sim 25$ MeV).

We need to mention that the widths of $1D'(2^-)$ can be easily transformed into those of $1D(2^-)$, since the width expression for $1D'(2^-)$ with mixing angle θ_{1D} is equal to that of $1D(2^-)$ with the mixing angle $\theta_{1D} + 90°$. Here, we give more predictions for the missing $D(1D(2^-))$. Its total width can reach $265 \sim 290$ MeV and its main decay modes are $D^*\pi$ ($96 \sim 110$ MeV) and $D_2^*(2460)\pi$ ($135 \sim 160$ MeV) when taking the range $-73.8° < \theta_{1D} < -35.7°$. Here, we take the mass 2737 MeV for $D(1D(2^-))$ as an input, which is taken from the experimental data of $D_J(2740)$ [3].

There are two possible assignments of $D^*(2760)/D_J^*(2760)$, i.e., either an orthogonal partner of $D^*(2600)$) as given by Eq. (13) or a 1^3D_3 state. Since the mixing angle θ_{SD} defined in Eq. (13) is quite small, $-3.6° < \theta_{SD} < 1.8°$, as shown in Fig. 4, so it is legitimate to consider that $D^*(2760)/D_J^*(2760)$ is dominated by a pure 1^3D_1 state.

The decay modes of the $D(1^3D_1)$ and $D(1^3D_3)$ states are listed in Table V. The theoretical widths of the $D(1^3D_1)$ and $D(1^3D_3)$ states are 385.06 MeV and 18.07 MeV, respectively, both of which deviate from the experimental data, $\Gamma = 60.9 \pm 5.1 \pm 3.6$ [2] and $\Gamma = 74.4 \pm 3.4 \pm 37.0$ MeV [3]. This is the obstacle to assign the $D(1^3D_1)$ and $D(1^3D_3)$ to $D^*(2760)/D_J^*(2760)$.

Apart from the problem of their total decay width, in this work we compare the ratio $\mathcal{B}(D^*(2760)^0 \to D^+\pi^-)/\mathcal{B}(D(2750)^0 \to D^{*+}\pi^-)$ with the *BABAR* data [2]. Here, $D(2750)$ is considered as the $1D'(2^-)$ state. If we assign $D^*(2760)/D_J^*(2760)$ to the 1^3D_3 state, the theoretical ratio is $0.34 \sim 0.86$ with the $-73.8° < \theta_{1D} < -35.7°$ range, which is in good agreement with experimental measurement [2]. As a consequence, $D^*(2760)/D_J^*(2760)$ can be tentatively identified as the 1^3D_3 state. However, the future experimental measurement of the resonance parameters for $D^*(2760)/D_J^*(2760)$ is an important topic, which will be helpful for giving a final and definite answer to the assignment of $D^*(2760)/D_J^*(2760)$.

Our calculation also shows that the orthogonal partner of $D^*(2600)$ should be a broad state with the total width 385 MeV and its main decay channels are $D\pi$, $D^*\pi$, $D\rho$, and $D_1(2420)\pi$. Here, the ratio

$$\frac{\mathcal{B}(D^{*\prime}(1^-) \to D^*\pi)}{\mathcal{B}(D^{*\prime}(1^-) \to D\pi)} = 0.46 \tag{15}$$

is also predicted.[2]

C. 3*S* states

The mass spectrum analysis suggests the $D(3^1S_0)$ assignment for $D_J(3000)$ (see the discussion in Sec. III). Under this assignment, we present the decay behaviors of $D_J(3000)$ in Table VI. Here, its total width is 90.28 MeV, which is comparable to the lower limit of the experimental data $\Gamma = 188.1 \pm 44.8$ [3]. The partial decay width of $D(3^1S_0) \to D^*\pi$ is 43.17 MeV, which contributes almost 50% to the total decay width. This is consistent with the fact that $D_J(3000)$ is observed in the channel $D^*\pi$. As a consequence, $D_J(3000)$ can be a good candidate of $D(3^1S_0)$. Besides $D^*\pi$, $D\rho$ and $D_0^*(2400)\pi$ are two other important decay modes.

We further discuss $D_J^*(3000)$ as $D(3^3S_1)$. In Table VI, the total width of $D(3^1S_1)$ is 80.36 MeV, which is pretty close to the lower limit of experimental measurement for $D_J^*(3000)$, $\Gamma = 110.5 \pm 11.5$ MeV [3]. The main decay modes of $D(3^1S_0)$ are $D\pi$, $D^*\pi$, and $D\rho$, where the partial decay width of $D(3^3S_1) \to D\pi$ contributes about 17% to the total decay width, which naturally explains why the observed decay mode of $D_J^*(3000)$ is $D\pi$. By the above study, we conclude that $D_J^*(3000)$ as $D(3^3S_1)$ is suitable. In addition, we also predict the ratio

$$\frac{\mathcal{B}(D(3^3S_1) \to D\pi)}{\mathcal{B}(D(3^3S_1) \to D^*\pi)} = 0.53, \tag{16}$$

which can be tested in future experiments.

In this work we do not consider the mixing effect between 2^3S_1 and 3^3S_1 since the mass gap between these is as large as 400 MeV as shown in Table II, which is a different situation from the case of mixing between 2^3S_1 and 1^3D_1 discussed in Sec. IV B.

D. 1*F* states

There exist four $1F$ states in the charmed meson family. We list their decay behaviors in Table VI.

As for the $D(1^3F_2)$ state, the mass by the modified GI model is 3053 MeV predicted in Table II. The $D_J^*(3000)$

[2]We also notice recent results of LHCb, where a new resonance $D_1^*(2760)$ [86] with spin-1 was observed. Its resonance parameters are

$$M = 2781 \pm 18 \pm 11 \pm 6 \text{ MeV}, \qquad \Gamma = 177 \pm 32 \pm 20 \pm 7 \text{ MeV},$$

which are comparable with the theoretical mass (2762 MeV) and width (385 MeV) of $D^{*\prime}(1^-)$. This means that $D_1^*(2760)$ can be the orthogonal partner of $D^*(2600)$.

TABLE VI. The calculated partial and total decay widths of $D_J^*(3000)$ and $D_J(3000)$ with several possible assignments. If a decay channel is forbidden, we mark it with the "$\cdots$" symbol. All mixing angles are given in the heavy quark limit and all values are in units of MeV.

Channels	3^1S_0	3^3S_1	1^3F_2	$1F(3^+)$	$1F'(3^+)$	1^3F_4	2^3P_0	$2P(1^+)$	$2P'(1^+)$	2^3P_2
$D\pi$	$\cdots$	13.53	26.09	$\cdots$	$\cdots$	4.97	72.51	$\cdots$	$\cdots$	1.46
$D\eta$	$\cdots$	1.37	2.76	$\cdots$	$\cdots$	0.29	6.96	$\cdots$	$\cdots$	0.003
$D\eta'$	$\cdots$	0.54	1.71	$\cdots$	$\cdots$	0.02	1.11	$\cdots$	$\cdots$	0.17
D_sK	$\cdots$	2.01	2.78	$\cdots$	$\cdots$	0.15	7.46	$\cdots$	$\cdots$	1.2×10^{-4}
$D^*\pi$	43.17	25.68	18.83	42.23	8.39	5.31	$\cdots$	61.73	6.46	0.12
$D^*\eta$	2.37	1.78	1.76	3.75	0.35	0.21	$\cdots$	4.30	1.26	0.23
$D^*\eta'$	0.004	1.1×10^{-5}	0.06	4.9×10^{-4}	8.8×10^{-6}	7.4×10^{-5}	$\cdots$	0.90	0.001	0.04
D_s^*K	3.10	2.24	1.53	3.06	0.16	0.09	$\cdots$	3.77	1.33	0.26
$D\rho$	10.22	12.16	19.71	4.10	42.86	2.95	$\cdots$	36.44	8.80	13.57
$D\omega$	3.26	4.31	6.80	1.28	12.99	0.94	$\cdots$	12.56	2.75	4.34
D_sK^*	0.004	0.71	0.47	0.01	0.64	0.007	$\cdots$	1.94	6.75	0.72
$D^*\rho$	2.54	0.02	6.41	16.62	16.41	56.94	138.25	41.94	23.78	5.60
$D^*\omega$	0.83	0.006	2.29	5.08	5.45	18.37	43.89	13.95	7.78	1.81
$D_s^*K^*$	$\cdots$	1.1×10^{-4}	6.3×10^{-5}	$\cdots$	$\cdots$	5.8×10^{-4}	3.59	$\cdots$	$\cdots$	4.29
$D_0^*(2400)\pi$	11.27	$\cdots$	$\cdots$	0.23	0.98	$\cdots$	$\cdots$	7.08	14.01	$\cdots$
$D_0^*(2400)\eta$	2.79	$\cdots$	$\cdots$	0.002	0.005	$\cdots$	$\cdots$	0.39	0.90	$\cdots$
$D_s(2317)K$	5.05	$\cdots$	$\cdots$	0.004	0.02	$\cdots$	$\cdots$	0.84	2.09	$\cdots$
$D_2^*(2460)\pi$	5.67	6.93	11.97	109.45	3.27	2.37	$\cdots$	81.44	9.46	5.51
$D_1(2420)\pi$	$\cdots$	4.04	116.51	1.26	1.82	0.33	11.78	13.03	6.85	7.08
$D_1(2420)\eta$	$\cdots$	0.03	2.21	0	0	4.0×10^{-6}	0.32	0.01	0.008	0.02
$D_1(2430)\pi$	$\cdots$	1.32	0.31	0.12	0.41	1.55	11.64	9.00	5.03	21.36
$D_1(2430)\eta$	$\cdots$	1.40	6.8×10^{-4}	0	0	5.1×10^{-4}	0.27	0.006	0.003	0.43
$D_s(2460)K$	$\cdots$	2.28	0.002	3.3×10^{-6}	1.2×10^{-5}	0.002	0.57	0.08	0.05	0.88
Total width	90.28	80.36	222.02	187.20	93.76	94.50	298.35	289.41	97.31	68.89

recently observed can be a possible candidate of $D(1^3F_2)$ according to the mass spectrum analysis. The main decay channels of $D(1^3F_2)$ are $D\pi$, $D^*\pi$, $D\rho$, and $D_1(2420)\pi$ and the total width is 222.02 MeV, which is about two times larger than the experimental data, $\Gamma = 110.5 \pm 11.5$ MeV [3]. Therefore, $D_J^*(3000)$ is not a suitable candidate for $D(1^3F_2)$. Here, the ratio

$$\frac{\mathcal{B}(D(1^3F_2)\to D\pi)}{\mathcal{B}(D(1^3F_2)\to D^*\pi)} = 1.39 \tag{17}$$

is also obtained, which provides crucial information to further test whether the $D(1^3F_2)$ assignment to $D_J^*(3000)$ is reasonable.

$D(1F(3^+))$ and $D(1F'(3^+))$ are mixtures of the 1^1F_3 and 1^3F_3 states, i.e.,

$$\begin{pmatrix} |1F(3^+)\rangle \\ |1F'(3^+)\rangle \end{pmatrix} = \begin{pmatrix} \cos\theta_{1F} & \sin\theta_{1F} \\ -\sin\theta_{1F} & \cos\theta_{1F} \end{pmatrix} \begin{pmatrix} |1^1F_3\rangle \\ |1^3F_3\rangle \end{pmatrix}, \tag{18}$$

where the mixing angle θ_{1F} can be fixed as $\theta_{1F} = -49.1° = -\arcsin(2/\sqrt{7})$ in the heavy quark limit [41,83] when further discussing their decay properties.

The predicted mass of $D(1F(3^+))$ is 3032 MeV. If we take the assignment $D(1F(3^+))$ to $D_J(3000)$, the obtained total decay width is 187.20 MeV, which is in good agreement with the experimental measurement $\Gamma = 188.1 \pm 44.8$ MeV [3]. The main decay modes are $D^*\pi$ and $D_2^*(2460)\pi$, which can explain why $D_J(3000)$ was first observed by experiment in the $D^*\pi$ channel [3]. As a consequence, $D_J(3000)$ can be reasonably regarded as the $D(1F(3^+))$ charmed meson.

As an orthogonal partner of $D(1F(3^+))$, the theoretical mass of $D(1F'(3^+))$ by the modified GI model is 3063 MeV, which is about 100 MeV above the experimental data of $D_J(3000)$. Thus, we also discuss the $D(1F'(3^+))$ assignment of $D_J(3000)$. The results shown in Table VI indicate that $D^*\pi$, $D\rho$, $D\omega$, and $D^*\rho$ are the main decay channels and the total width is 93.76 MeV, comparable with the lower limit of the experimental data [3]. Therefore, we cannot fully exclude the possibility that $D_J(3000)$ is a candidate of $D(1'F(3^+))$. In order to distinguish possible assignments $D(1F(3^+))$ and $D(1F'(3^+))$ of $D_J(3000)$, a precise measurement of the total and partial widths of $D_J(3000)$ will be a main task in future experiments.

$D(1^3F_4)$ is a possible assignment to $D_J^*(3000)$ according to only the mass spectrum analysis, since the mass of $D(1^3F_4)$ is calculated as 3037 MeV close to the experimental data of $D_J^*(3000)$. In Table VI, we list the decay channels of $D(1^3F_4)$. Here, $D^*\rho$ and $D^*\omega$ are the main decay channels, and the total width is 94.50 MeV, which is consistent with the experimental data $\Gamma = 110.5 \pm 11.5$ MeV [3]. However, the decay width of $D(1^3F_4) \to D^*\pi$ is only 4.97 MeV, which contributes 5% to the total decay width. Thus, it is difficult to explain why the observed channel of $D_J^*(3000)$ is $D^*\pi$. By this analysis, we can conclude that $D_J^*(3000)$ is not a good candidate of $D(1^3F_4)$. We also give extra information of the typical ratio, i.e.,

$$\frac{\mathcal{B}(D(1^3F_4) \to D\pi)}{\mathcal{B}(D(1^3F_4) \to D^*\pi)} = 0.94, \tag{19}$$

although these are not main decay modes.

E. 2*P* states

In the following, we discuss whether $D_J(3000)$ and $D_J^*(3000)$ can be categorized into the $2P$ states.

In Table VI, we list the decay modes of $D(2^3P_0)$, where the main decay modes are $D\pi$, $D^*\rho$, and $D^*\omega$ and the total width is 298.35 MeV, which is far larger than the experimental data $\Gamma = 110.5 \pm 11.5$ MeV [3]. $D(2^3P_0)$ has a predicted mass of 2856 MeV in the modified GI model, which is about 150 MeV lower than the experimental mass of $D_J^*(3000)$. Hence, if we consider this mass spectrum analysis together with the present calculation of the decay behaviors, the $D(2^3P_0)$ assignment to $D_J^*(3000)$ cannot be supported by our study.

$D_J(3000)$ as a candidate of $D(2P(1^+))$ or $D(2P'(1^+))$ is considered here. As mixed states, $D(2P(1^+))$ and $D(2P'(1^+))$ have a relation

$$\begin{pmatrix} |2P(1^+)\rangle \\ |2P'(1^+)\rangle \end{pmatrix} = \begin{pmatrix} \cos\theta_{2P} & \sin\theta_{2P} \\ -\sin\theta_{2P} & \cos\theta_{2P} \end{pmatrix} \begin{pmatrix} |2^1P_1\rangle \\ |2^3P_1\rangle \end{pmatrix} \tag{20}$$

with a mixing angle θ_{2P}, where we take $\theta_{2P} = \theta_{1P} = -54.7°$ [41,83] to list the numerical results of the decay widths of $D(2P(1^+))$ or $D(2P'(1^+))$ in Table VI.

If $D_J(3000)$ is a $D(2P(1^+))$ state, $D^*\pi.D\rho$, $D^*\rho$, and $D_2^*(2460)\pi$ are its main decay modes, and its total width can reach 289.41 MeV comparable with the experimental width $\Gamma = 188.1 \pm 44.8$ MeV [3]. Although the predicted mass of $D(2P(1^+))$ is 2853 MeV, which is about 120 MeV lower than the experimental value of $D_J(3000)$, the above results show that there is still a possibility of $D_J(3000)$ as $D(2P(1^+))$.

If $D_J(3000)$ is $D(2P'(1^+))$, the obtained total width is 97.31 MeV, which is comparable to the lower limit of the experimental width of $D_J(3000)$. In addition, $D^*\rho$ and $D_0^*(2400)\pi$ are the main decay modes. However, $D^*\pi$ is not a main decay channel since it only contributes 6.6% to the total decay width, where $D(2P'(1^+)) \to D^*\pi$ occurs via a D-wave in the heavy quark limit. By remembering that $D_J(3000)$ was first observed in its $D^*\pi$ channel, our results do not favor the $D(2P'(1^+))$ assignment of $D_J(3000)$, which is also supported by the mass spectrum analysis since the theoretical mass of $D(2P'(1^+))$ by the modified GI model is 2885 MeV, far below the experimental data.

$D_J^*(3000)$ is not a good candidate of the $D(2^3P_2)$ state, which is concluded from the mass spectrum analysis and the study of its decay behaviors. In the modified GI model, the mass of $D(2^3P_2)$ is predicted to be 2884 MeV, which is inconsistent with the mass of $D_J^*(3000)$. Under the $D(2^3P_2)$ assignment to $D_J^*(3000)$, the total and partial decay widths are presented in Table VI, where $D\rho$ and $D_1(2430)\pi$ are the main decay modes and the total width is 68.89 MeV, which is comparable to the lower limit of experimental measurement $\Gamma = 110.5 \pm 11.5$ MeV [3] released by the LHCb Collaboration. However, the process $D(2^3P_2) \to D\pi$ is a subordinate decay channel, which just contributes 2% to the total decay width. Accordingly, we conclude that $D_J^*(3000)$ is not a good candidate of the $D(2^3P_2)$ state.

In Table VI, we predict abundant information of decay behaviors of the $2P$ states in the charmed meson family, which provides valuable hints to search for the missing $2P$ charmed mesons and to test these meson assignments to $D_J^*(3000)$ and $D_J(3000)$.

TABLE VII. Decay behaviors of four $2D$ charmed mesons. Values are in units of MeV.

Channels	2^3D_1	$2D(2^-)$	$2D'(2^-)$	2^3D_3
$D\pi$	36.10	...	...	3.09
$D\eta$	3.49	...	...	0.11
$D\eta'$	2.13	...	...	0.003
D_sK	3.46	...	...	0.06
$D^*\pi$	13.26	47.39	0.29	0.89
$D^*\eta$	0.99	3.86	0.02	0.001
$D^*\eta'$	0.02	0.28	0.13	0.03
D_s^*K	0.74	3.51	0.04	1.3×10^{-5}
$D\rho$	2.19	5.36	14.75	1.02
$D\omega$	0.71	1.73	4.76	0.32
D_sK^*	0.15	0.28	0.01	0.11
$D^*\rho$	0.01	0.29	1.35	10.11
$D^*\omega$	0.004	0.09	0.42	3.35
$D_s^*K^*$	0.41	0.47	0.50	0.39
$D_0^*(2400)\pi$	...	2.54	2.89	...
$D_0^*(2400)\eta$	...	0.18	0.31	...
$D_{s0}^*(2317)K$	...	0.24	0.36	...
$D_2^*(2460)\pi$	7.19	39.92	0.60	2.38
$D_{s2}^*(2573)K$	0.07	0.37	0.02	0.02
$D_1(2420)\pi$	43.32	1.41	0.81	2.24
$D_1(2420)\eta$	0.63	0.10	0.12	0.03
$D_1(2430)\pi$	6.05	3.36	2.28	4.65
$D_1(2430)\eta$	0.27	0.12	0.14	0.25
$D_{s1}(2460)K$	0.34	0.14	0.16	0.27
$D_{s1}(2536)K$	0.22	0.03	0.05	0.007
Total width	121.75	111.67	30.17	29.33

TABLE VIII. A summary of the possible assignments for $D_J^*(3000)$ and $D_J(3000)$. Comparing the experimental and theoretical data, we rate the possibility of each assignment with stars.

	Assignments	Mass (MeV)	Width (MeV)	Main channels	
	$D(3^3S_1)$	3015	80.36	$D\pi, D^*\pi, D\rho$	★★★★★
	$D(1^3F_2)$	3053	222.02	$D\pi, D^*\pi, D\rho, D_1(2420)\pi$	★
$D_J^*(3000)$	$D(1^3F_4)$	3037	94.50	$D^*\rho, D^*\omega$	★★
	$D(2^3P_0)$	2856	298.35	$D\pi, D^*\rho, D^*\omega$	★
	$D(2^3P_2)$	2884	68.89	$D\rho, D_1(2430)\pi$	★
	$D(3^1S_0)$	2976	90.28	$D^*\pi, D\rho, D_0^*(2400)\pi$	★★★★
	$D(1F(3^+))$	3032	187.20	$D^*\pi, D_2^*(2460)\pi$	★★★★
$D_J(3000)$	$D(1F'(3^+))$	3063	93.76	$D^*\pi, D\rho, D^*\rho, D\omega$	★★
	$D(2P(1^+))$	2853	289.41	$D^*\pi, D\rho, D^*\rho, D_2^*(2460)\pi$	★★
	$D(2P'(1^+))$	2885	97.31	$D^*\rho, D_0^*(2400)\pi$	★

F. 2*D* states

The mass of $D(2^3D_1)$ is 3131 MeV, predicted through the modified GI model in Table II. We show the decay behaviors of $D(2^3D_1)$ in Table VII, which indicates that $D(2^3D_1)$ is a broad state since the obtained total width is 121.75 MeV. Its main decay modes contain $D\pi$, $D^*\pi$, and $D_1(2420)\pi$. We also predict the branching ratio

$$\frac{\mathcal{B}(D(2^3D_1)\to D^*\pi)}{\mathcal{B}(D(2^3D_1)\to D\pi)} = 0.37. \tag{21}$$

The charmed mesons, $D(2D(2^-))$ and $D(2D'(2^-))$, satisfy the following relation,

$$\begin{pmatrix} |2D(2^-)\rangle \\ |2D'(2^-)\rangle \end{pmatrix} = \begin{pmatrix} \cos\theta_{2D} & \sin\theta_{2D} \\ -\sin\theta_{2D} & \cos\theta_{2D} \end{pmatrix} \begin{pmatrix} |2^1D_2\rangle \\ |2^3D_2\rangle \end{pmatrix}, \tag{22}$$

where θ_{2D} is the mixing angle, which in the heavy quark limit we can fix as $\theta_{2D} = -50.8°$ [41,83,85].

The $D(2D(2^-))$ has the predicted mass 3115 MeV and has the broad total decay width, whose value can reach 111.67 MeV. Additionally, $D^*\pi$ and $D_2^*(2460)\pi$ are the main decay channels, and the decay width of $D(2D(2^-))\to D^*\pi$ can contribute more than 40% to the total decay width.

With the modified GI model, we get the theoretical mass of $D(2D'(2^-))$ to be 3148 MeV. In Table VII, we list the decay channels of $D(2D'(2^-))$, the total width is 30.17 MeV, and the main decay channels contain $D\rho$ and $D\omega$.

The masses of $D(2D(2^-))$ and $D(2D'(2^-))$ are similar to each other and have the same decay modes but with different values. However, we can still distinguish them in experiments in two aspects. Firstly, $D(2D(2^-))$ and $D(2D'(2^-))$ are broad and narrow states. Secondly, in the heavy quark limit $D(2D(2^-))\to D^*\pi$ is a purely P-wave decay while $D(2D'(2^-))\to D^*\pi$ is a purely F-wave decay [85], which is the reason why the total decay widths of $D(2D(2^-))$ and $D(2D'(2^-))$ are largely different.

The mass prediction of $D(2^3D_3)$ is 3129 MeV in the modified GI model. Since the calculated total width of $D(2^3D_3)$ is 29.33 MeV, $D(2^3D_1)$ is a narrow charmed meson, where $D\pi$, $D_2^*(2460)\pi$, $D_1(2420)\pi$, and $D_1(2430)\pi$ are the main decay channels. We also obtain the ratio

$$\frac{\mathcal{B}(D(2^3D_3)\to D^*\pi)}{\mathcal{B}(D(2^3D_3)\to D\pi)} = 0.29, \tag{23}$$

which can be tested in future experiments.

V. SUMMARY

Looking at the observed charmed mesons shown in Table I, the charmed meson family has become more and more abundant, which has stimulated us to perform a more systematic phenomenological analysis of higher radial and orbital excitations in the charmed meson family with great interest.

In the present work we have done two major tasks. Firstly, a mass spectrum analysis has been given by adopting the modified GI model, where the screening effect is taken into account. Secondly, the OZI-allowed two-body strong decays of charmed mesons under discussion have been obtained via the QPC model.

In this work, we have revealed the underlying structures of the observed charmed states $D(2550)$, $D^*(2600)$, $D(2750)$, $D^*(2760)$, $D_J(2740)$, $D_J^*(2760)$, $D_J(3000)$, and $D_J^*(3000)$. In Table VIII we give a summary of possible assignments for $D_J^*(3000)$ and $D_J(3000)$. Comparing the theoretical and experimental data, we rate the possibility of each assignment with stars. Additionally, we have provided more abundant properties of these particles, including some typical decay ratios and partial decay widths, which are critical to test these possible assignments of charmed mesons.

In the following years, exploration of higher radial and orbital excitations in the charmed meson family will be one of the main projects for Belle, LHCb, and the forthcoming BelleII. In this work, we have also predicted some missing charmed mesons, where their masses and decay behaviors have been provided. This information is helpful for experimental study of the missing states in the charmed meson family. We also expect more experimental observation of charmed mesons in the future.

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