Higher radial and orbital excitations in the charmed meson family

Qin-Tao Song\textsuperscript{1,2,4,*} \quad Dian-Yong Chen\textsuperscript{1,2,4} \quad Xiang Liu\textsuperscript{2,3,8} \quad and Takayuki Matsuki\textsuperscript{5,6,**}

\textsuperscript{1}Nuclear Theory Group, Institute of Modern Physics of CAS, Lanzhou 730000, China
\textsuperscript{2}Research Center for Hadron and CSR Physics, Lanzhou University & Institute of Modern Physics of CAS, Lanzhou 730000, China
\textsuperscript{3}School of Physical Science and Technology, Lanzhou University, Lanzhou 730000, China
\textsuperscript{4}University of Chinese Academy of Sciences, Beijing 100049, China
\textsuperscript{5}Tokyo Kasei University, 1-18-1 Kaga, Itabashi, Tokyo 173-8602, Japan
\textsuperscript{6}Theoretical Research Division, Nishina Center, RIKEN, Saitama 351-0198, Japan

Considering abundant experimental information of charmed mesons and the present research status, in this work we systematically study higher radial and orbital excitations in the charmed meson family by analyzing the mass spectrum and calculating their two-body OZI-allowed decay behaviors. This phenomenological analysis not only 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 \(D_J^*(3000)\), but also provides valuable information of the charmed mesons still missing in experiments.

PACS numbers: 14.40.Lb, 12.38.Lg, 13.25.Ft

I. INTRODUCTION

In the past, experiments have made a big progress on observation of charmed mesons. A list of charmed mesons collected in Particle Data Group (PDG) has so far become more and more abundant\cite{1}. As candidates of higher radial and orbital excitations in the charmed meson family, the charmed mesons newly observed are \(D(2550), D^*(2600)\) \(D^*(2760)\) and \(D(2750)\) from BaBar\cite{2}, and \(D_J(2580), D_J^*(2650), D_J^*(2760), D_J^*(2740), D_J^*(3000)\) and \(D_J^*(3000)\) from LHCb\cite{3}. In Table I, experimental information of the observed charmed mesons is given.

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

Although there have been a couple of works studying the heavy-light systems including charmed mesons together with their decay modes\cite{4,5,6,7,8,9,10,11}, in this work we mainly focus on application of the modified Godfrey-Isgur model developed in Ref.\cite{12} to calculate mass spectrum and decay behaviors of charmed mesons. This model is different from the Godfrey-Isgur model (GI) proposed in Ref.\cite{13}. This work is a sequence of the modified Godfrey-Isgur model as an unquenched quark model\cite{13}. This model includes a screening effect in order to reflect the phenomenon that a linear confinement term \(br\) can be screened or softened at large distances by virtual quark pairs and dynamical fermions\cite{14,15}, which is important effect especially to higher radial and orbital excitations. Even though the GI model does not consider the screening effect, it is successful to describe the low-lying states\cite{13}. With the modified GI model, we obtain a quite successful mass spectrum of the charmed meson family. Due to the abundant experimental data, we can compare our theoretical values with the corresponding experimental results, which can not only test the reliability of the modified GI model, but also gives some useful structure information of the observed charmed mesons. In addition, we also predict masses of some missing charmed mesons, which is also an important hint to experimental exploration for these missing states.

One more valuable lesson we learned from the former work Ref.\cite{12} 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, of states with the same \(J^P\) in two spin multiplets, whose result is independent of models. The same consideration can be applied to the charmed meson family in this paper, too and details will be described later.

After analyzing the mass spectrum of charmed meson, in this work we further study two-body OZI-allowed decays of charmed mesons, where the quark pair creation (QPC) model\cite{16,17,18,19,20,21,22} is applied to calculate strong decays. With the modified GI model, we can get the numerical wave functions of charmed mesons, which can be applied to calculation of strong decays of charmed mesons, where partial and total widths of charmed mesons under discussion and some typical ratios relevant to these decays will be given.

Combining the analysis of mass spectrum with calculation of the decay behaviors, 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 these observed charmed states under discussion, which is the main task of this work.

This paper is organized as follows. In Sect. II we give a concise review on the observed charmed mesons. Then, the mass spectrum will be analyzed in Sect. III, where the modified GI model is introduced briefly. In Sect. IV we will give a brief review of the QPC model and calculate the two-body

---

\textsuperscript{1}Corresponding author
\textsuperscript{2}Corresponding author
\textsuperscript{3}Electronic address: songqint@impcas.ac.cn
\textsuperscript{4}Electronic address: chendy@impcas.ac.cn
\textsuperscript{5}Electronic address: xiangliu@lzu.edu.cn
\textsuperscript{6}Electronic address: matsuki@tokyo-kasei.ac.jp

1203-05728v1 [hep-ph] 19 Mar 2015
II. STATUS OF THE OBSERVED CHARMED STATES

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

A. \(D_{s}(2400), D_{1}(2430), D_{s}(2460)\) and \(D_{s}^{*}(2460)\)

As the first observed \(P\)-wave charmed meson, \(D_{1}(2420)\) was reported in the \(D^{\ast}\pi\) invariant mass distribution by the ARGUS Collaboration, where its mass and width are \(M = 2420 \pm 6\) MeV and \(\Gamma = 70 \pm 21\) MeV, respectively [23]. In 1989, the TPS Collaboration confirmed \(D_{1}(2420)\) in its \(D^{\ast}\pi\) decay channel [24]. According to this observed decay modes, its spin-parity quantum number is either \(J^{P} = 1^{+}\) or \(J^{P} = 2^{+}\). Then, the analysis of the angular momentum from the ARGUS Collaboration further shows that the observed \(D_{1}(2420)\) has \(J^{P} = 1^{+}\) [25]. Additionally, \(D_{1}(2420)\) was confirmed by other experiments [2, 26–37].

The Belle Collaboration observed a broad state \(D_{s}(2430)\) with mass \(M = 2427 \pm 26 \pm 20 \pm 15\) MeV and width \(\Gamma = 384_{-75}^{+107} \pm 24 \pm 70\) MeV by analyzing the \(B \to D^{\ast}\pi\pi\) process, where its spin-parity is determined as \(J^{P} = 1^{+}\) from the helicity distributions [32]. In 2006, the BaBar Collaboration studied the \(D^{\ast}\pi\) invariant mass spectrum, where \(D_{1}(2430)\) was confirmed [38].

Besides \(D_{1}(2430)\), Belle announced the observation of another broad state \(D_{s}^{0}(2400)\), which has mass \(M = 2308 \pm 17 \pm 15 \pm 28\) MeV [32]. Here, the spin-parity quantum number was also measured as \(J^{P} = 0^{+}[32]\). \(D_{s}^{0}(2400)\) was confirmed by the FOCUS and BaBar Collaborations with \(M = 2403 \pm 14 \pm 35\) MeV [39] and \(M = 2297 \pm 8 \pm 5 \pm 19\) MeV [40], respectively. Since different experiments gave quite different mass measurements of \(D_{s}^{0}(2400)\), we will discuss the decay of \(D_{s}^{0}(2400)\) dependent on its mass by taking a mass range \((2290 \sim 2350)\) MeV. \(D_{s}^{0}(2400)\) as \(P\)-wave state with \(J^{P} = 0^{+}\) is supported by the theoretical work [4, 5, 8, 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 \(D^{\ast}\pi^{-}\) [24], which shows that this meson has either \(J^{P} = 0^{+}\) or \(J^{P} = 2^{+}\). This observation was confirmed by the ARGUS Collaboration in the \(D^{\ast}\pi^{-}\) channel, and the corresponding angular momentum analysis suggests the \(J^{P} = 2^{+}\) assignment to this state [26]. Thus, this resonance is named \(D_{s}^{*}(2460)\). Later, the CLEO Collaboration again confirmed the existence of \(D_{s}^{*}(2460)\), where it has mass \(M = 2461 \pm 3 \pm 1\) MeV and width \(\Gamma = 20^{+9}_{-10+12}\) MeV. In addition, the ratio

\[
\frac{\mathcal{B}(D_{s}^{*}(2460) \to D^{\ast}\pi^{-})}{\mathcal{B}(D_{s}(2460) \to D^{\ast}\pi^{-})} = 2.3 \pm 0.8
\]

was measured as well in Ref. [27], which is consistent with the theoretical calculations in Refs. [4, 5, 10, 41–44]. In recent years, many other experiments have reported \(D_{s}^{*}(2460)\)
two charmed mesons with \( J^P = 1^+ \). In the heavy quark limit \( m_Q \rightarrow \infty \), \( \bar{J}_L \bar{S}_Q \bar{L} \) is a good quantum number, where \( \bar{S}_Q \) is the spin of a light quark and \( \bar{L} \) is its angular momentum. Thus, heavy-light mesons can be classified by \( \bar{J}_L^P \). Two \( 1S \)-wave charmed mesons forms a \( (0^-, 1^-) \) doublet with \( \bar{J}_L^P = \frac{3}{2}^- \). Four \( 1P \)-wave charmed mesons can be grouped into two doublets, \( (0^-, 1^+) \) and \( (1^+, 2^+) \), with \( \bar{J}_L^P = \frac{3}{2}^+ \) and \( \bar{J}_L^P = \frac{5}{2}^+ \), respectively. Since states with \( J^P = 1^+ \) in \( (0^-, 1^+) \) and \( (1^+, 2^+) \) doublets decay into \( D^* \pi \) via \( S \)-wave and \( D^* \)-wave \([4, 5, 8, 41, 46-48] \) 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 two experimentally observed \( 1^+ \) charmed mesons, i.e., \( D_1(2430) \) and \( D_1(2420) \) belong to the doublets \( (0^-, 1^+) \) and \( (1^+, 2^+) \) \([4, 5, 8, 41, 42, 44] \), respectively.

\[ B(0^+)(2600) \rightarrow D^*\pi^-) = 0.32 \pm 0.02 \pm 0.09. \]  \hspace{1cm} (2)

A natural state \( D_1(2650) \) was found in the \( D^* \pi \) invariant mass spectrum by the LHCb Collaboration through the process \( pp \rightarrow D^* \pi X \) \([3] \), where \( D_1(2650) \) is tentatively identified as a \( J^P = 1^- \) state (a radial excitation of \( D^* \)). Therefore, \( D_1(2650) \) \([3] \) and \( D_1^+(2600) \) \([2] \) are the same state.

In Ref. \([54] \), they predicted that a mass of \( D(2^3S_1) \) is 2620 MeV via the constituent quark model, which is in good agreement with the experimental mass of \( D(2600) \). Moreover, the ratio \( \Gamma(D(2^3S_1)^0 \rightarrow D^*\pi^-)/\Gamma(D(2^3S_1)^0 \rightarrow D^+\pi^-) = 0.47 \) was predicted via the relativistic chiral quark model \([4] \), which is close to the upper limit of Eq. (2). In Ref.\([5] \), 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 obtained 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. \([49-53, 55, 56] \).

\[ D^*(2760), D_1^*(2760), D_1(2750) \text{ and } D_1(2740) \]

\( D^*(2760) \) was observed by the BaBar Collaboration in the \( D^* \) invariant mass spectrum \([2] \), which can be assigned to be a \( D^* \)-wave charmed meson since its mass is consistent with the theoretical prediction in Ref. \([13] \). Later, LHCb announced the observation of a natural state \( D_1^*(2760) \) 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 \( D_1(2760) \) can be regarded as the same state since these two states have the similar widths and masses \([57] \).

Comparison between the prediction in the Ref. \([5] \) 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 \( D(1^3D_1) \) assignment of \( D^*(2760) \) cannot be excluded \([52] \), which is also supported by the following works \([51, 53, 55, 58] \).

Besides \( D^*(2760) \), another state \( D_1(2750) \) 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. \([13] \), the analysis of helicity distribution of \( D(2750) \) does not support the \( D(1^3D_1) \) and \( D(1^3D_3) \) assignments \([2] \). BaBar also gave the ratio \( [2] \)

\[ \frac{B(D(2750)^0 \rightarrow D^*\pi^-)}{B(D(2750)^0 \rightarrow D^{*+}\pi^-)} = 0.42 \pm 0.05 \pm 0.11. \]  \hspace{1cm} (3)

As an unnatural state, \( D_1(2740) \) 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 \( D_1(2740) \), it is possible that \( D(2750) \) and \( D_1(2740) \) are the same state. Before the observation of \( D(2750)/D_1(2740) \), the masses of two \( 2^- \) charmed mesons were predicted in Ref. \([5] \), 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 \( D(2750)/D_1(2740) \) as a \( 2^- \) state with \( J^P = 5/2^- \) is more favorable. However, we also notice that the corresponding theoretical width of this \( 2^- \) state is not consistent with the experimental value. After observations
of $D(2750)/D_s(2740)$, the authors of Ref. [58] calculated the ratio $\Gamma(D^*(2760)^0 \rightarrow D^+\pi^-)/\Gamma(D(2750)^0 \rightarrow D^{*+}\pi^-)$ by adopting an effective Lagrangian approach, which is consistent with the experimental data, where $D^*(2760)$ and $D(2750)$ are identified as the $1^+D_3$ 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 $D^\ast \pi$ invariant mass spectrum [3], where its resonance parameters are

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

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 Ref. [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

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

The $D_J^*(3000)$ was explained differently as $D(2^1P_0)$ [59], $D(1^1F_2)$ [56] and $D(1^3F_0)$ [50, 56, 60].

Until now, there have been so many observations of charmed mesons. It is a suitable time to carry out a systematical study of higher radial and orbital excitations in the charmed meson family by combining these experimental informations with theoretical results. In the following sections, we focus on this interesting research topic by performing the analysis of mass spectrum and calculation of the strong decay behaviors.

III. MASS SPECTRUM

For heavy-light meson systems, 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 proposed by Godfrey and Isgur can well describe the meson spectrum [13], 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 greater than about one fermi [15], which is known as the screening effect. The screening effect has been proven by the unquenched Lattice QCD and holographic models [71–73]. The mass suppression can be caused by both the screening effect and coupled channel effect. Although the screening effect can be almost equivalent description of 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].

In Refs. [12, 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. provide description of a highly excited light-quark meson spectrum by flattening the confining potential $br$ at distances greater than $r_s$ [75]. The screened potential model [77, 78] was adopted to compute the charmonium spectrum [76]. In our recent work [12], the screening effect was introduced to modify the GI model, where the mass spectrum of charmed-strange meson family with this treatment is greatly improved compared with the results of the GI model. As a sister work of Ref. [12], the present work focuses on the charmed mesons applying the modified GI model [12] to obtain their mass spectrum.

In order to take account of the screening effect in the GI model, the confining potential $br$ is replaced with [77, 78]

$$br \to V_{\text{scr}}(r) = \frac{b(1 - e^{-\mu r})}{\mu},$$  

where $V_{\text{scr}}(r)$ behaves like $br$ at short distances and constant $b/\mu$ at large distances. Furthermore, the smearing function is introduced to take into account nonlocality property of potentials [13], i.e.,

$$V_{\text{scr}}(r) = \int d^3r' \rho_{\text{sc}}(r - r') \frac{b(1 - e^{-\mu r'})}{\mu}.  

The detailed explanation of how to introduce the screening effect into the GI model can be found in Ref. [12].

The mass spectrum of charmed mesons are 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 [13] except for the additional parameter $\mu$ in $V_{\text{scr}}(r)$. In our work, we take several values of $\mu$, 0.01 GeV, 0.02 GeV, 0.03 GeV, and 0.04 GeV. Our result shows that the obtained masses of charmed mesons with $\mu = 0.03$ GeV can well reproduce the corresponding experimental data, where adoption of the modified GI model can improve description of the charmed meson mass spectrum compared with the GI model (see Table III for more details).

1 In order to choose the suitable value of $\mu$, in Table III we compare the theoretical results with experimental data by listing $\chi^2$ values, where the concrete expression for $\chi^2$ is

$$\chi^2 = \sum_i \frac{(\mathcal{A}_{\text{th}}(i) - \mathcal{A}_{\text{exp}}(i))^2}{\text{Error}(i)}.$$  

$\mathcal{A}_{\text{th}}(i)$ and $\mathcal{A}_{\text{exp}}(i)$ are theoretical and experimental data, respectively. Error(i) denotes the experimental error of the mass of a charmed meson. Among four $\chi^2$ values corresponding to four $\mu$ values, there is a minimum of $\chi^2$ when $\mu^2 = 0.3$ GeV.
In Table I, we further make 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 via 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 as a candidate of $D(2^3S_1)$. Our result shows that $D^*(2600)$ is more close 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 $D(1^3D_1)$ 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, 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 $D_J(3000)$ and $D_J^*(3000)$ are about 100 MeV smaller than the corresponding experimental data of the $2P$ states.

In order to definitely 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**

Studying the two-body Okubo-Zweig-Iizuka (OZI) allowed strong decay behaviors of the observed and the predicted charmed mesons can provide abundant information of 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 Sect. III can be further tested here.

As an effective approach to study the OZI allowed strong...
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 $\mu$ values, $\mu = 0.01, 0.02, 0.03$, and 0.04 GeV to show the results of the modified GI model. Values in brackets for the GI model and $\mu = 0.03$ are of $R = 1/\beta$, which can be determined by solving $\int \Psi_{slm}^*(p)\gamma^2\gamma^2d^4p = \int \Phi(p)\gamma^2\gamma^2d^4p$, where $\Psi_{slm}^*(p)$ is an SHO wave function and $\Phi(p)$ 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. $\mu$ is in units of GeV, while $R$ is in units of GeV$^{-1}$.

| GI model | Modified GI model |
|----------|-------------------|
| $1^1S_0$ | 1874(1.52) |
| $2^3S_1$ | 2583(2.08) |
| $3^3S_1$ | 3068(2.33) |
| $1^3S_1$ | 2038(1.85) |
| $2^3S_1$ | 2645(2.17) |
| $3^3S_1$ | 3111(2.38) |
| $1^1P_1$ | 2457(2.00) |
| $2^3P_1$ | 2933(2.27) |
| $3^3P_1$ | 2398(1.85) |
| $4^3P_1$ | 2932(2.22) |
| $1^3P_1$ | 2465(2.00) |
| $2^3P_1$ | 2952(2.27) |
| $3^3P_1$ | 2501(2.22) |
| $4^3P_1$ | 2957(2.38) |
| $1^1D_2$ | 2827(2.27) |
| $2^3D_2$ | 3225(2.44) |
| $3^3D_2$ | 3193(2.63) |
| $1^3D_2$ | 2816(2.13) |
| $2^3D_2$ | 3231(2.33) |
| $3^3D_2$ | 2834(2.27) |
| $1^1F_4$ | 3235(2.44) |
| $2^3F_4$ | 3823(2.38) |
| $3^3F_4$ | 3194(2.50) |
| $1^3F_4$ | 3123(2.44) |
| $2^3F_4$ | 3132(2.33) |
| $3^3F_4$ | 3139(2.50) |
| $1^3F_4$ | 3113(2.50) |

where $\gamma$ is a dimensionless constant which reflects the strength of creation of a quark-antiquark pair from the vacuum. In Ref. [79], $\gamma = 8.7$ is obtained for the $u\bar{u}+d\bar{d}$ pair creation by fitting with the experimental data, while $\gamma = 8.7/\sqrt{3}$ for the $s\bar{s}$ pair creation [17]. $P_1$ and $P_2$ stand for momenta of quark and antiquark, respectively. $S_{lm}(p) = |P|Y_{lm}(p)$ is the solid harmonic polynomial and $\chi_{1,-m}$ is the spin triplet state. The quantum number of a quark-antiquark pair is $J^PC = 0^+$ 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. $\phi^{34}_0 = (u\bar{u}+d\bar{d}+s\bar{s})/\sqrt{3}$ and $(\omega^{34})_{ij} = \delta_{ij}/\sqrt{3}$ are the flavor and color functions, respectively, with $i$ and $j$ being the color indices.

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

$$\langle BP\rangle^{(n)} = \delta^A_{(B+C)}|M_{A\rightarrow BC}|^2,$$

where $P_A$ and $P_B$ are the momenta of mesons $B$ and $C$, respectively. $|A\rangle$, $|B\rangle$ and $|C\rangle$ denote mock states [80]. The mock state of a meson $A$ can be defined as

$$|A\rangle = \int \Psi_{nLM}d^4p|A,p\rangle = \int \Psi_{nLM}d^4p|A,L\rangle|J\rangle_{L\rightarrow P}.$$

where $\chi_A^{LS}M_J$, $\phi_A$ and $\omega_A$ are spin, flavor and color wave functions of a meson $A$, respectively. $\Psi_{nLM}^{(A)}(p_1,p_2)$ is a spatial wave function of meson $A$, which can be obtained in the modified GI model. Furthermore, the amplitude $M_{A\rightarrow BC}$ is related to the partial wave amplitude $M^{\ell\ell}$ via the Jacob-Wick formula [81], i.e.,

$$M^{\ell\ell}(A \rightarrow BC) = \frac{\sqrt{2\ell+1}}{2\lambda + 1}\sum_{M_{\ell\ell}}\langle L\ell; JM_JA|JAM_{\ell\ell}\rangle \times \langle J_BM_{\ell\ell}; J_CM_{\ell\ell}|JM_JA\rangle M^{M_{\ell\ell}M_{\ell\ell}M_{\ell\ell}}.$$

Therefore, the total decay width can be expressed as

$$\Gamma = \pi^2|P|\sum_{\ell\ell}^\infty |M_{\ell\ell}|^2.$$

After this brief introduction of the QPC model, in the following we perform a phenomenological analysis of charmed mesons. When calculating a decay width, we adopt the numerical wave function for a charmed meson calculated in this work and the one for charmed-strange meson from Ref. [12]. Additionally, we still employ the simple harmonic oscillator wave function for light mesons such as $\pi$ and $K$, where the corresponding $\beta$ 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) or Fig. 1) as an input.
TABLE III: Comparison of experimental data and the theoretical results. Here, we also list the $\chi^2$ values corresponding to different cases. 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 $\chi^2$ value among several $\mu$.

| $n^{2S+1}L_J$ | Experimental values [1] | GI model [13] | Modified GI model |
|---------------|--------------------------|--------------|------------------|
| $D$           | $^1S_0$                  | 1864.84 ± 0.07 | 1874             | 1861             |
| $D^*$         | $^3S_1$                  | 2010.26 ± 0.07 | 2038             | 2020             |
| $D_s(2400)$   | $^1P_0$                  | 2318 ± 29    | 2398             | 2365             |
| $D_s(2420)$   | $^1P_1$                  | 2421.4 ± 0.6  | 2467             | 2434             |
| $D_s(2430)$   | $^1P_1$                  | 2427 ± 26 ± 25 | 2455             | 2424             |
| $D_s^*(2460)$ | $^1P_2$                  | 2464.3 ± 1.6  | 2501             | 2468             |
| $D(2550)$     | $^2S_0$                  | 2539.4 ± 4.5 ± 6.8 [2] | 2583             | 2534             |
| $D^*(2600)$   | $^2S_1$                  | 2608.7 ± 2.4 ± 2.5 [2] | 2645             | 2593             |
| $D(2750)$     | $^1D_2$                  | 2752.4 ± 1.7 ± 2.7 [2] | 2845             | 2789             |
| $D^*(2760)$   | $^3D_3$                  | 2763.3 ± 2.3 ± 2.3 [2] | 2833             | 2779             |

$\chi^2$ is 45677 in the modified GI model.

1. $1P$ states

As the $^1P_0$ state, $D_s^*(2400)$ has been observed by three different experiments. However, the experimental masses are quite different from each other as shown in Table I. Therefore, in this work we take the mass range (2.29~2.35 GeV) of $D_s^*(2400)$ to discuss a mass-dependence of the calculated decay width. Here, $D_s^*(2400)$ only decays into $D\pi$. In Fig. 2, we present the mass-dependence of the decay width of $D_s^*(2400)$. We find that our result is consistent with experimental data $\Gamma = 276 ± 21 ± 63$ [32], $\Gamma = 240 ± 55 ± 59$ [39], and $\Gamma = 273 ± 12 ± 48$ [40].

In the following, we study $D_1(2420)$ and $D_1(2430)$, which are mixtures of the $^1P_1$ and $^1P_2$ states. $D_1(2420)$ and $D_1(2430)$ satisfy the relation

$$\begin{align*}
\left(\begin{array}{c}
|D_1(2430)\rangle \\
|D_1(2420)\rangle
\end{array}\right) &= \left(\begin{array}{cc}
\cos \theta_{1P} & \sin \theta_{1P} \\
-\sin \theta_{1P} & \cos \theta_{1P}
\end{array}\right) \left(\begin{array}{c}
|1^1P_1\rangle \\
|1^3P_1\rangle
\end{array}\right),
\end{align*}$$

(11)

where the mixing angle is $\theta_{1P} = -54.7^\circ$ which is determined by the heavy quark limit [41, 82, 83].

The width of $D_1(2420)$ ($\Gamma = 70 ± 21$) was first measured by the ARGUS Collaboration [23]. However, different experiments provided different widths as $\Gamma = 13 ± 6^{+10}_{-5} \text{ MeV}$ [25], $\Gamma = 23^{+5+10}_{-5-3} \text{ MeV}$ [27], and $\Gamma = 21 ± 5 ± 8 \text{ MeV}$ [33]. Here, we take the middle value as the width, i.e., the measurement $\Gamma = 21 ± 5 ± 8 \text{ MeV}$ from the Belle Collaboration [33], $D_1(2430)$ is a broad state, which has the width $\Gamma = 38^{+100}_{-70} ± 75 \text{ MeV}$ given by Belle [32] and $\Gamma = 266 ± 96 \text{ MeV}$ by BaBar [38]. Both $D_1(2430)$ and $D_1(2420)$ only decay into $D\pi$. In Fig. 3, we show the decay widths of $D_1(2430)$ and $D_1(2420)$ dependent on the mixing angle $\theta_{1P}$, where our results are consistent with the experimental data when taking $-45.6^\circ < \theta_{1P} < -37.2^\circ$, which is close to $\theta_{1P} = -54.7^\circ = -\arcsin(\sqrt{2}/3)$ in the heavy quark limit [41, 82, 83].

The $D_s^*(2460)$ is considered as the $^3P_2$ state. Its decay channels are $D\pi$, $D^*\pi$, $D_s\pi$, and $D_sK$, whose theoretical values are shown in Table IV. The total width is 14.86 MeV and the branching ratio $B(D_s^*(2460)^0 \rightarrow D^*\pi^-)/B(D_s^*(2460)^0 \rightarrow D^{*+}\pi^+)$ is 1.96. For $D_1^*(2460)$, there are several different experimental widths, i.e., $\Gamma = 20 ± 10 ± 5 \text{ MeV}$ from the TPS Collaboration [24], $\Gamma = 20^{+10+9}_{-10-12} \text{ MeV}$ from the CLEO Collaboration [27] and 45.6±4.4±6.7 MeV from the Belle Collaboration [32]. Our theoretical width is consistent with the TPS data [24] and the CLEO data [27]. Furthermore, our ratio is in good agreement with experimental values $B(D^*\pi^-)/B(D^{*+}\pi^+) = 2.3 ± 0.8$ [27] and $B(D^*\pi^-)/B(D^{*+}\pi^+) = 1.9 ± 0.5$ [32] measured by CLEO and Belle, respectively.
have been tested, which makes us safely adopt the QPC model.

$\Delta$ are parameters, we label them with “–”. If the channels depend on other parameters, we label them with “□”. All values are in units of MeV.

| Channels | $D(2460)$ | $D(2550)/D_J(2580)$ | $D(2600)/D_J(2650)$ |
|----------|------------|----------------------|----------------------|
| $D\pi$   | 9.17       | –                    | □                    |
| $D\eta$  | 0.02       | –                    | □                    |
| $D, K$   | $1.0 \times 10^{-4}$ | – | □ |
| $D^*\pi$ | 4.67       | 67.56                | □                    |
| $D^*\eta$| –          | –                    | □                    |
| $D, K$   | –          | –                    | □                    |
| $D_J(2400)\pi$ | – | 4.09 | – |
| $D_J(2460)\pi$ | – | – | □ |
| $D_J(2420)\pi$ | – | – | □ |
| $D_J(2430)\pi$ | – | – | □ |
| Total width | 14.86 | 71.65 | – |

In this subsection, $D_J(2400)$, $D_J(2420)$, $D_J(2430)$ and $D_J(2460)$ which are well established as $1P$ charged mesons have been tested, which makes us safely adopt the QPC model and the related model parameters to further study the following charged mesons under discussion.

Fig. 3: The $\theta_{1P}$ dependence of the decay widths of $D_J(2420)$ and $D_J(2430)$.

Fig. 4: The $\theta_{5D}$ dependence of the total and partial decay widths and the ratio $\Gamma(D\pi)/\Gamma(D^*\pi)$ of $D^*(2600)$.

$D^*\pi$ channel. Additionally, the obtained total width is 71.65 MeV which is comparable with the lower limit of the BaBar data [2] and is smaller than the LHCb data [3]. Due to this situation, we also suggest more precise measurement of the resonance parameters of $D(2550)/D_J(2580)$ needs to be done, which will be helpful for further testing the $2^3S_0$ assignment to $D(2550)/D_J(2580)$.

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

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

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

The $\theta_{5D}$ dependence of the total width, partial decay widths, and ratio $B(D^*(2600) \to D^*\pi) / B(D(2600) \to D^*\pi)$ of $D^*(2600)$ is shown in Fig. 4, where two tiny partial widths $\Gamma(D^*(2600) \to D^*K)$ and $\Gamma(D^*(2600) \to D_J(2460)\pi)$ are not listed. When taking the range $-3.6^\circ < \theta_{5D} < 1.8^\circ$, 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 $D^*(2600)$ is $D\pi$ ($9 \sim 15$ 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 $\theta_{SD}$ is due to the obvious, large mass difference between $D(2600)$ and its partner $D^*(2760)$, which is consistent with the suggestion in Ref. [13].

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

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

$2S$ and $1D$ 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 $D_J(2400)\pi$ (see Table IV), which can explain why BaBar and LHCb first observed $D(2550)/D_J(2580)$ in the
where $\theta_{1D}$ is the mixing angle which can be fixed as $\theta_{1D} = -50.8^\circ$ in the heavy quark limit [41, 82, 84].

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. Here the calculated total width is consistent with a central value of the experimental data when taking $\theta_{1D} = -50.8^\circ$ predicted by the heavy quark limit [41, 82, 84], which is included in the range $-73.8^\circ < \theta_{1D} < -35.7^\circ$ in Fig. 5. Thus, $D(2750)/D_j(2740)$ as a $1D'(2^-)$ state is suitable. In addition, we also predict the main decay modes of $D(1D(2^-))$, which include $D^*\pi (10 \sim 25$ MeV), $D_\rho (37 \sim 55$ MeV), $D_\omega (12 \sim 17$ MeV) and $D_j(2460)\pi (0 \sim 25$ MeV).

We need to indicate 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 $\theta_{1D} = 90^\circ$ is equal to that of $1D(2^-)$ with the mixing angle $\theta_{1D}$. Here, we give more predictions for the mixing $D(1D(2^-))^\pi$. Its total width can reach $265 \sim 290$ MeV and its main decay modes are $D^*\pi (96 \sim 110$ MeV) and $D^*_j(2460)\pi (135 \sim 160$ MeV) when taking the range $-73.8^\circ < \theta_{1D} < -35.7^\circ$. Here, we take the mass $2762$ MeV for $D(1D(2^-))^\pi$ as an input, which is taken from calculation presented in Sect. III.

There are two possible assignments of $D^*(2760)/D_j^*(2760)$, i.e. an orthogonal partner of $D^*(2600)$ and a $1^{3}D_{1}$ state. Since the mixing angle $\theta_{5D}$ defined in Eq. (12) is quite small, $-3.6^\circ < \theta_{5D} < 1.8^\circ$, shown in Fig. 4, so it is legitimate to consider that $D^*(2760)/D_j^*(2760)$ is dominated by a pure $1^{3}D_{1}$ state.

The decay modes of $D(1^{3}D_{1})$ and $D(1^{3}D_{3})$ states are listed in Table V. The theoretical widths of the $D(1^{3}D_{1})$ and $D(1^{3}D_{3})$ 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 for the $D(1^{3}D_{1})$ and $D(1^{3}D_{3})$ assignment of $D^*(2760)/D_j^*(2760)$.

Apart from the problem of their total decay width, in this work we show the ratio $\mathcal{B}(D'(2600)^0 \to D^*\pi\gamma)/\mathcal{B}(D(2760)^0 \to D^*\pi\gamma)$ to compare 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 $1^{3}D_{3}$ state, the theoretical ratio is $0.34 \sim 0.86$ with the $-73.8^\circ < \theta_{1D} < -35.7^\circ$ range, which is in good agreement with experimental measurement [2]. As a consequence, $D^*(2760)/D_j^*(2760)$ can be tentatively identified as the $1^{3}D_{3}$ state. However, the future experimental study of measurement of the resonance parameters for $D^*(2760)/D_j^*(2760)$ is an important topic, which will be helpful for finally giving a 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 $D_j(2420)\pi$. Here, the ratio

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

is also predicted.

3. 3S states

The mass spectrum analysis suggests the $D(3^{1}S_{0})$ assignment of $D_j(3000)$ (see the discussion in Sect. 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 $\Gamma = \ldots$
188.1 ± 44.8 [3]. The partial decay width of $D(3^1S_0) \rightarrow D^*\pi$ is 43.17 MeV which contributes to almost 50% of the total decay width. This consists with the fact that $D_J'(3000)$ is observed in the channel of $D^*\pi$. As a consequence, $D_J(3000)$ can be a good candidate of $D(3^1S_0)$. Besides $D^*\pi$, $D^\rho$ and $D^\omega$ are its two important decay modes.

We further discuss $D_J'(3000)$ as $D(3^1S_1)$. 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 $D(3^1S_1) \rightarrow D\pi$ contribute to about 17% of 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 $D(3^1S_1)$ is suitable. In addition, we also predict the ratio

$$\frac{\mathcal{B}(D_J(3^1S_0) \rightarrow D\pi)}{\mathcal{B}(D_J(3^1S_1) \rightarrow D^*\pi)} = 0.53,$$

which can be tested in future.

There exist four $1F$ states. In Table VI, we list their decay behaviors.

For the $D(1^3F_2)$ state, the mass by the modified GI model is 3053 MeV predicted in Table II. The newly observed meson $D_J'(3000)$ 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 $D(1^3F_2)\pi$ 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

$$\frac{\mathcal{B}(D(1^3F_2) \rightarrow D\pi)}{\mathcal{B}(D(1^3F_2) \rightarrow D^*\pi)} = 1.39.$$  

(16)

is also obtained, which provides a 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

### 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 by ‘−’. All mixing angles are given in the heavy quark limit and all values are in units of MeV.

| Channels | $3^1S_0$ | $3^1S_1$ | $1^1F_2$ | $1F(3^+)$ | $1F^*(3^+)$ | $1^3F_4$ | $2^3P_0$ | $2P(1^+)$ | $2P^*(1^+)$ | $2^3P_2$ |
|----------|----------|----------|----------|-----------|-----------|----------|----------|-----------|-----------|----------|
| $D\pi$   | 13.53    | 26.09    | –        | 4.97      | 72.51     | –        | –        | 1.46      |          |          |
| $D\eta$  | 1.37     | 2.76     | –        | 0.29      | 6.96      | –        | –        | 0.003     |          |          |
| $D\eta'$ | 0.54     | 1.71     | –        | 0.02      | 1.11      | –        | –        | 0.17      |          |          |
| $D, K$   | 2.01     | 2.78     | –        | 0.15      | 7.46      | –        | –        | $1.2 \times 10^{-4}$ |          |          |
| $D^\pi$  | 43.17    | 25.68    | 18.83    | 42.23     | 8.39      | 5.31     | –        | 61.73     | 6.46      | 0.12     |
| $D^\eta$ | 2.37     | 1.78     | 1.76     | 3.75      | 0.35      | 0.21     | –        | 4.30      | 1.26      | 0.23     |
| $D^\eta'$| 0.004    | $1.1 \times 10^{-5}$ | 0.06    | $4.9 \times 10^{-5}$ | $8.8 \times 10^{-6}$ | $7.4 \times 10^{-5}$ | – | 0.90      | 0.001     | 0.04     |
| $D_J K$  | 3.10     | 2.24     | 1.53     | 3.06      | 0.16      | 0.09     | –        | 3.77      | 1.33      | 0.26     |
| $D_J^\rho$ | 10.22  | 12.16    | 19.71    | 4.10      | 42.86     | 2.95     | –        | 36.44     | 8.80      | 13.57    |
| $D_J^\omega$ | 3.26 | 4.31     | 6.80     | 1.28      | 12.99     | 0.94     | –        | 12.56     | 2.75      | 4.34     |
| $D_J K^*$ | 0.004    | 0.71     | 0.47     | 0.01      | 0.64      | 0.007    | –        | 1.94      | 6.75      | 0.72     |
| $D_J^\rho$ | 2.54    | 0.02     | 6.41     | 16.62     | 16.41     | 56.94    | 138.25   | 41.94     | 23.78     | 5.60     |
| $D_J^\omega$ | 0.83   | 0.006    | 2.29     | 5.08      | 5.45      | 18.37    | 43.89    | 13.95     | 7.78      | 1.81     |
| $D_J K^*$ | –       | $1.1 \times 10^{-4}$ | 6.3 $\times 10^{-5}$ | –        | $5.8 \times 10^{-4}$ | 3.59     | –        | –        | 4.29      |          |
| $D_J'(3000)\pi$ | 11.27 | –        | –        | 0.23      | 0.98      | –        | –        | 7.08      | 14.01     |          |
| $D_J'(3000)\eta$ | 2.79 | –        | –        | 0.002     | 0.005     | –        | –        | 0.39      | 0.90      | –        |
| $D_J(2317)K$ | 5.05 | –        | –        | 0.004     | 0.02      | –        | –        | 0.84      | 2.09      | –        |
| $D_J(2460)\pi$ | 5.67 | 6.93     | 11.97    | 109.45    | 3.27      | 2.37     | –        | 81.44     | 9.46      | 5.51     |
| $D_J(2420)\pi$ | –       | 4.04     | 116.51   | 1.26      | 1.82      | 0.33     | 11.78    | 13.03     | 6.85      | 7.08     |
| $D_J(2420)\eta$ | –       | 0.03     | 2.21     | 0         | 0         | $4.0 \times 10^{-6}$ | 0.32     | 0.01      | 0.008     | 0.02     |
| $D_J(2430)\pi$ | –       | 1.32     | 0.31     | 0.12      | 0.41      | 1.55     | 11.64    | 9.00      | 5.03      | 21.36    |
| $D_J(2430)\eta$ | –       | 1.40     | $6.8 \times 10^{-4}$ | 0        | 0         | $5.1 \times 10^{-4}$ | 0.27     | 0.006     | 0.003     | 0.43     |
| $D_J(2460)K$ | –       | 2.28     | 0.002    | $3.3 \times 10^{-6}$ | $1.2 \times 10^{-5}$ | 0.002    | 0.57     | 0.08      | 0.05      | 0.88     |

Total width: 90.28 MeV, 80.36 MeV, 222.02 MeV, 187.20 MeV, 93.76 MeV, 94.50 MeV, 298.35 MeV, 289.41 MeV, 97.31 MeV, 68.89 MeV.
where the mixing angle $\theta_{1\ell}$ can be fixed as $\theta_{1\ell} = -49.1^\circ = -\arcsin(2/\sqrt{7})$ in the heavy quark limit [41, 82] 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 conformity with the experimental measurement $\Gamma = 188.1 \pm 44.8$ MeV [3]. The main decay modes are $D^*\pi$, $D\rho$ and $D_1(2460)\pi$, 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. 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].

There are four 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 $D'_J(3000)$ only according to 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 $D(1^3F_4) \rightarrow D^*\pi$ is only 4.97 MeV which contributes to 5% of 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.,

$$\frac{B(D(1^3F_4) \rightarrow D\pi)}{B(D(1^3F_4) \rightarrow D^*\pi)} = 0.94,$$

although these are not main decay modes.

5. 2P 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 mass 2856 MeV predicted 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 $D(2^3P(1^+))$ or $D(2^3P'(1^+))$ is considered here. As mixed states, $D(2^3P(1^+))$ and $D(2^3P'(1^+))$ have a relation

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

with a mixing angle $\theta_{2\rho}$, where we take $\theta_{2\rho} = -54.7^\circ$ [41, 82] to list the numerical results of the decay widths of $D(2^3P(1^+))$ or $D(2^3P'(1^+))$ in Table VI.

If $D_J(3000)$ is a $D(2^3P(1^+))$ state, $D^*\pi$. $D\rho$. $D^*\rho$ and $D_1(2460)\pi$ 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 $D(2^3P(1^+))$ is 2853 MeV, which is about 120 MeV lower than experimental value of $D_J(3000)$, the above results show that there is still a possibility of $D_J(3000)$ as $D(2^3P(1^+))$.

If $D_J(3000)$ is $D(2^3P'(1^+))$, 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 $D_1(2460)\pi$ are the main decay modes. However, $D^*\pi$ is not main decay channel since it only contributes 6.6% to the total decay width, where $D(2^3P'(1^+)) \rightarrow D^*\pi$ occurs via a $D$-wave contribution 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 $D(2^3P'(1^+))$ assignment of $D_J(3000)$, which is also supported by the mass spectrum analysis since the theoretical mass of $D(2^3P'(1^+))$ 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 by 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 decay width of $D(2^3P_2) \rightarrow D\tau$ is a sub-ordinate 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 hint to search for the missing 2P charmed mesons and to test these meson assignments to $D'_J(3000)$ and $D_J(3000)$.

6. 2D states

The mass of $D(2^3D_1)$ is 3136 MeV predicted through the modified GI model. In Table VII, we show the decay behavior of $D(2^3D_1)$, 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

$$\frac{\mathcal{B}(D(2^3D_1) \to D^*\pi)}{\mathcal{B}(D(2^3D_1) \to D\pi)} = 0.37. \quad (20)$$

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

$$\begin{pmatrix} 2D(2^-) \rangle \\ 2D'(2^-) \rangle \end{pmatrix} = \begin{pmatrix} \cos \theta_{2D} & \sin \theta_{2D} \\ -\sin \theta_{2D} & \cos \theta_{2D} \end{pmatrix} \begin{pmatrix} 2^1D_2 \rangle \\ 2^3D_2 \rangle \end{pmatrix}, \quad (21)$$

where $\theta_{2D}$ is the mixing angle, which in the heavy quark limit we can fix as $\theta_{2D} = -50.8^\circ$ \[41, 82, 84\].

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 $D_1'(2460)\pi$ 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 via 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 purely $P$-wave decay while $D(2D'(2^-) \to D^*\pi)$ is purely $F$-wave decay \[84\], 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, $D(2^3D_3)$ is a narrow charmed meson, where $D\pi$, $D_1'(2460)\pi$, $D_1(2420)\pi$ and $D_1(2430)\pi$ are the main decay channels. We also obtain the ratio

$$\frac{\mathcal{B}(D(2^3D_3) \to D^*\pi)}{\mathcal{B}(D(2^3D_3) \to D\pi)} = 0.29, \quad (22)$$

which can be tested in future experiments.

## V. SUMMARY

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

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 $D(2550)$, $D^*(2600)$, $D(2750)$, $D^*(2760)$, $D_1(2740)$, $D_1'(2760)$, $D_1(3000)$, and $D_1'(3000)$. Additionally, we have provided more abundant their properties including some typical decay ratios and partial decay widths, which is critical to test the 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 in Belle, LHCb, and 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 observations of charmed mesons in future.

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

| Channels | $2^1D_1$ | $2D(2^-)$ | $2D'(2^-)$ | $2^3D_3$ |
|----------|------------|-----------|------------|----------|
| $D\pi$   | 36.10      | –         | –          | 3.09     |
| $D\eta$  | 3.49       | –         | –          | 0.11     |
| $D\eta'$ | 2.13       | –         | –          | 0.003    |
| $D_1K$   | 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     |
| $D^*_1K$ | 0.74       | 3.51      | 0.04       | $1.3 \times 10^{-5}$ |
| $D_1\rho$| 2.19       | 5.36      | 14.75      | 1.02     |
| $D_1\omega$| 0.71     | 1.73      | 4.76       | 0.32     |
| $D_1K^*$| 0.15       | 0.28      | 0.01       | 0.11     |
| $D_1\omega$| 0.01     | 0.29      | 1.35       | 10.11    |
| $D^*_1K^*$| 0.04       | 0.09      | 0.42       | 3.35     |
| $D_{10}(2400)\pi$| –       | 2.54      | 2.89       | –        |
| $D_{10}(2400)\eta$| –     | 0.18      | 0.31       | –        |
| $D_{10}(2317)K$| –     | 0.24      | 0.36       | –        |
| $D_1(2460)\pi$| 7.19    | 39.92     | 0.60       | 2.38     |
| $D_1(2573)K$| 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     |
| $D_{10}(2460)K$| 0.34    | 0.14      | 0.16       | 0.27     |
| $D_{10}(2536)K$| 0.22    | 0.03      | 0.05       | 0.007    |
| Total width | 121.75 | 111.67 | 30.17 | 29.33 |
Acknowledgments

This project is supported by the National Natural Science Foundation of China under Grants No. 1122547, No. 11175073, and No. 11375240, the Ministry of Education of China (SRFDP under Grant No. 2012021111000), and the Fok Ying Tung Education Foundation (No. 131006).
[59] Y. Sun, X. Liu and T. Matsuki, Phys. Rev. D 88 (2013) 9, 094020 [arXiv:1309.2203 [hep-ph]].
[60] L. Y. Xiao and X. H. Zhong, arXiv:1407.7408 [hep-ph].
[61] B. Aubert et al. [BaBar Collaboration], Phys. Rev. Lett. 90 (2003) 242001 [hep-ex/0304021].
[62] D. Besson et al. [CLEO Collaboration], Phys. Rev. D 68 (2003) 032002 [Erratum-ibid. D 75 (2007) 119908] [hep-ex/0305100].
[63] K. Abe et al. [Belle Collaboration], Phys. Rev. Lett. 92 (2004) 012002 [hep-ex/0307052].
[64] B. Aubert et al. [BaBar Collaboration], Phys. Rev. D 74 (2006) 032007 [hep-ex/0604030].
[65] B. Aubert et al. [BaBar Collaboration], Phys. Rev. D 69 (2004) 031101 [hep-ex/0310050].
[66] S. K. Choi et al. [Belle Collaboration], Phys. Rev. Lett. 91 (2003) 262001 [hep-ex/0309032].
[67] E. J. Eichten, K. Lane and C. Quigg, Phys. Rev. D 69 (2004) 094019 [hep-ph/0401210].
[68] E. van Beveren and G. Rupp, Phys. Rev. Lett. 91 (2003) 012003 [hep-ph/0305035].
[69] Y. B. Dai, X. Q. Li, S. L. Zhu and Y. B. Zuo, Eur. Phys. J. C 55 (2008) 249 [hep-ph/0610327].
[70] Y. R. Liu, X. Liu and S. L. Zhu, Phys. Rev. D 79 (2009) 094026 [arXiv:0904.1770 [hep-ph]].
[71] G. S. Bali et al. [SESAM Collaboration], Phys. Rev. D 71 (2005) 114513 [hep-lat/0505012].
[72] A. Armoni, Phys. Rev. D 78 (2008) 065017 [arXiv:0805.1339 [hep-th]].
[73] F. Bigazzi, A. L. Cotrone, C. Nunez and A. Paredes, Phys. Rev. D 78 (2008) 114012 [arXiv:0806.1741 [hep-th]].
[74] B. Q. Li, C. Meng and K. T. Chao, Phys. Rev. D 80 (2009) 014012 [arXiv:0904.4068 [hep-ph]].
[75] E. H. Mezoir and P. Gonzalez, Phys. Rev. Lett. 101 (2008) 232001 [arXiv:0810.5651 [hep-ph]].
[76] B. -Q. Li and K. -T. Chao, Phys. Rev. D 79 (2009) 094004 [arXiv:0903.5506 [hep-ph]].
[77] K. T. Chao, Y. B. Ding and D. H. Qin, Commun. Theor. Phys. 18 (1992) 321.
[78] Y. B. Ding, K. T. Chao and D. H. Qin, Chin. Phys. Lett. 10 (1993) 460.
[79] Z. -C. Ye, X. Wang, X. Liu and Q. Zhao, Phys. Rev. D 86 (2012) 054025 [arXiv:1206.0097 [hep-ph]].
[80] C. Hayne and N. Isgur, Phys. Rev. D 25, 1944 (1982).
[81] M. Jacob and G. C. Wick, Annals Phys. 7, 404 (1959) [Annals Phys. 281, 774 (2000)].
[82] T. Matsuki, T. Mori and K. Seo, Prog. Theor. Phys. 124 (2010) 285 [arXiv:1001.4248 [hep-ph]].
[83] T. Barnes, N. Black and P. R. Page, Phys. Rev. D 68 (2003) 054014 [nucl-th/0208072].
[84] S. Godfrey and I. T. Jardine, Phys. Rev. D 89 (2014) 074023 [arXiv:1312.6181 [hep-ph]].