Systematic analysis of the $D_J(2580)$, $D'_J(2650)$, $D_J(2740)$, $D'_J(2760)$, $D_J(3000)$ and $D'_J(3000)$ in $D$ meson family

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In this work, we tentatively assign the charmed mesons $D_J(2580)$, $D'_J(2650)$, $D_J(2740)$, $D'_J(2760)$, $D_J(3000)$ and $D'_J(3000)$ observed by the LHCb collaboration according to their spin, parity and masses, then systematically study their strong decays to the ground state charmed mesons plus pseudoscalar mesons with the $^3P_0$ decay model. According to these studies, we assign the $D'_J(2760)$ as the $1D^+_2 S^+$ state, the $D'_J(3000)$ as the $1F^{+}_2^1 S^+$ or $1F^{+}_2^1 P^+$ state, the $D_J(3000)$ as the $1F^{+}_2^3 P^+$ or $2P^{+}_2^1 S^+$ state in the $D$ meson family. As a byproduct, we also study the strong decays of $2P^{+}_2^0 S^+$, $2P^{+}_2^2 S^+$, $3S^{+}_2^1 P^+$, $3S^{+}_2^1 S^+$ etc, states, which will be valuable in searching for the partners of these $D$ mesons.

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1 Introduction

In 2013, the LHCb Collaboration announced several $D_J$ resonances by studying the $D^+\pi^-$, $D^0\pi^+$, $D^{*+}\pi^-$ invariant mass spectra, which were obtained from the $pp$ collisions at a center-of-mass energy of 7TeV [1]. The LHCb Collaboration observed two natural parity resonances $D'_J(2650)^0$, $D'_J(2760)^0$ and two unnatural parity resonances $D_J(2580)^0$, $D_J(2740)^0$ in the $D^{*+}\pi^-$ mass spectrum, and tentatively identified $D_J(2580)$ as the $2S^0$ state, the $D'_J(2650)$ as the $2S^1$ state, the $D_J(2740)$ as the $1D^+_2 S^+$ state, the $D'_J(2760)$ as the $1D^+_2 P^+$ state, respectively. The $D'_J(2760)^0$ observed in the $D^{*+}\pi^-$ and $D^+\pi^-$ decay modes have consistent parameters, their charged partner $D'_J(2760)^+$ was observed in the $D^0\pi^+$ final state [1]. Furthermore, the LHCb collaboration also observed one unnatural parity resonance $D_J(3000)^0$ in the $D^{*+}\pi^-$ final state, and two resonances $D'_J(3000)^0$ and $D'_J(3000)^+$ in the $D^{+}\pi^-$ and $D^0\pi^+$ mass spectra, respectively [1]. The relevant parameters are presented in Table I.

In 2010, the BaBar collaboration observed four excited charmed mesons $D(2550)$, $D(2600)$, $D(2750)$ and $D(2760)$ in the decays $D^0(2550) \rightarrow D^{*+}\pi^-$, $D^0(2600) \rightarrow D^{*+}\pi^-$, $D^0(2750) \rightarrow D^{*+}\pi^-$, $D^0(2760) \rightarrow D^{+}\pi^-$, $D^+(2600) \rightarrow D^0\pi^+$ and $D^+(2760) \rightarrow D^0\pi^+$ respectively in the inclusive $e^+e^- \rightarrow
TABLE I: The experimental results from the LHCb collaboration, where the N and U denote the natural parity and unnatural parity, respectively.

| Mass(MeV)   | Width(MeV) | Decay Channel | Significance |
|-------------|------------|---------------|--------------|
| $D^*_J(2650)^0$ (N) | 2760.1 ± 1.1 ± 3.7 | 74.4 ± 3.4 ± 19.1 | $D^+\pi^-$ | 17.3σ |
| $D^*_J(2670)^0$ (N) | 3008.1 ± 4.0 | 110.5 ± 11.5 | $D^+\pi^-$ | 21.2σ |
| $D^*_J(2760)^0$ (N) | 2971.8 ± 8.7 | 188.1 ± 44.8 | $D^+\pi^-$ | 9.0σ |
| $D^*(2580)^0$ (U) | 2579.5 ± 3.4 ± 5.5 | 177.5 ± 17.8 ± 46.0 | $D^{*+}\pi^-$ | 18.8σ |
| $D_J(2740)^0$ (U) | 2737.0 ± 3.5 ± 11.2 | 73.2 ± 13.4 ± 25.0 | $D^{*+}\pi^-$ | 7.2σ |

TABLE II: The experimental results from the BaBar collaboration, the particles in the bracket are the possible corresponding ones observed by the LHCb collaboration.

| Mass(MeV) | Width(MeV) | Decay Channel | Significance |
|-----------|------------|---------------|--------------|
| $D^0(2550)$ [$D_J(2580)^0$] | 2539.4 ± 4.5 ± 6.8 | 130 ± 12 ± 13 | $D^{*+}\pi^-$ |
| $D^0(2600)$ [$D^*_J(2550)^0$] | 2608.7 ± 2.4 ± 2.5 | 93 ± 6 ± 13 | $D^{+}\pi^-, D^{*+}\pi^-$ |
| $D^0(2750)$ [$D_J(2740)^0$] | 2752.4 ± 1.7 ± 2.7 | 71 ± 6 ± 11 | $D^{*+}\pi^-$ |
| $D^0(2760)$ [$D^*_J(2760)^0$] | 2763.3 ± 2.3 ± 2.3 | 60.9 ± 5.1 ± 3.6 | $D^{+}\pi^-$ |
| $D^*(2600)$ | 2621.3 ± 3.7 ± 4.2 | 93 | $D^0\pi^+$ |
| $D^*(2760)$ [$D^*_J(2760)^+$] | 2769.7 ± 3.8 ± 1.5 | 60.9 | $D^0\pi^+$ |

The BaBar collaboration also analyzed the helicity distributions to determine the spin-parity, and tentatively identified the $(D(2550), D(2600))$ as the 2S doublet ($0^-, 1^-$), the $D(2750)$ and $D(2760)$ as the D-wave states. The relevant parameters are presented in Table II, where we also present the possible correspondences among the particles observed by the LHCb and BaBar collaborations. The physicists have also studied the decay behaviors of these charmed mesons using the heavy meson effective theory [2], constituent quark model [4] and the Eichten-Hill-Quigg's formula [5].

The heavy meson effective theory is a powerful tool in studying the properties of hadrons with a single heavy quark. With this method, P. Colangelo et al. proposed a classification of many observed $c\bar{q}$ and $b\bar{q}$ mesons in doublets [3]. In Ref. [3], we study the strong decays of the charmed mesons $D_J(2580)$, $D^*_J(2650)$, $D_J(2740)$, $D^*_J(2760)$, $D_J(3000)$ and $D^*_J(3000)$ with the heavy meson effective theory in the leading order approximation. And the ratios among decay widths of different channels were calculated. But the exact value of the decay widths were not given out, which constitutes the first motivation of our study. The quark pair creation (QPC) model is another effective method to...
study the strong decays of the mesons, which is also known as the $^3P_0$ decay model. It was originally introduced by L. Micu [8] and further developed by A. Le Yaouanc et al. [9]. This model has been widely used to evaluate the strong decays of hadrons [10–21], since it gives a good description of many observed decay amplitudes and partial widths of the hadrons. Y. Sun et al. [22] studied the strong decays of the $D_J(3000)$ and $D_J^*(3000)$ with the $^3P_0$ decay model, and identified $D_J(3000)$ as the $2P(1^+)$ state, the $D_J^*(3000)$ as the $2^3P_0$ state, respectively. But $D_J(2580)$, $D_J^*(2650)$, $D_J(2740)$ and $D_J^*(2760)$, which were also observed by LHCb Collaboration, were not analyzed in their studies. This is the second motivation of our work. Besides, they chose the simple harmonic oscillator (SHO) wave functions with the effective oscillator parameter $R$ as the meson’s radial wave functions. From Ref. [14], we can see that there are two types of SHO wave functions: SHO wave functions with a common oscillator parameter $R$ and with an effective oscillator parameter $R$. According to a series of least squares fits of the model predictions to the decay widths of 28 of the best known meson decays, it seems that the SHO wave functions with a common $R$ can lead to better results [14]. Thus, in order to identify the $D_J(2580)$, $D_J^*(2650)$, $D_J(2740)$, $D_J^*(2760)$, $D_J(3000)$ and $D_J^*(3000)$, it is necessary and interesting to systematically study the strong decays of these charmed mesons by the $^3P_0$ decay model with the common oscillator parameter $R$.

In the heavy quark limit, the heavy-light mesons $Q^−_n$ can be classified in doublets according to the total angular momentum of the light antiquark $s_q$, $s_q = s + \vec{l}$, where the $s$ and orbital angular momentum of the light antiquark, respectively [22]. In the case of the radial quantum number $n = 1$, the doublet $(P, P^*)$ have the spin-parity $J_{s_q}^P = (0^−, 1^−)_{1/2}$ for $L = 0$; the two doublets $(P^0, P^3)$ and $(P^1, P^2)$ have the spin-parity $J_{s_q}^P = (0^+, 1^+)_{1/2}$ and $(1^+, 2^+)_{3/2}$ respectively for $L = 1$; the two doublets $(P^1, P^2)$ and $(P^2, P^3)$ have the spin-parity $J_{s_q}^P = (1^−, 2^−)_{1/2}$ and $(2^−, 3^−)_{3/2}$ respectively for $L = 2$; the two doublets $(P^3, P^1)$ and $(P^2, P^4)$ have the spin-parity $J_{s_q}^P = (2^+, 3^+)_{1/2}$ and $(3^+, 4^+)_{3/2}$ respectively for $L = 3$, where the superscript $P$ denotes the parity. The $n = 2, 3, 4$, states are clarified by analogous doublets, for example, $n = 2$, the doublet $(P, P^*)$ have the spin-parity $J_{s_q}^P = (0^−, 1^−)_{1/2}$ for $L = 0$.

The $D_J(2580)^0$, $D_J(2740)^0$ and $D_J(3000)^0$ have unnatural parity, and their possible spin-parity assignments are $J^P = 0^−, 1^+, 2^−, 3^+, \cdots$. The $D_J^*(2650)^0$ and $D_J^*(2760)^0$ and $D_J^*(3000)^0$ have natural parity, and their possible spin-parity assignments are $J^P = 0^+, 1^−, 2^+, 3^−, \cdots$. The six low-lying states, $D, D^∗, D_0(2400), D_1(2430), D_1(2420)$ and $D_2(2460)$ have been established [24]. The newly observed charmed mesons $D_J(2580)$, $D_J^*(2650)$, $D_J(2740)$, $D_J^*(2760)$, $D_J(3000)$, $D_J^*(3000)$ can be tentatively identified as the missing states in the $D$ meson family.

The mass is a fundamental parameter in describing a hadron, in TABLE III, we present the predictions from some theoretical models, such as the relativized quark model based on a universal one-gluon exchange plus linear confinement potential [25], the relativistic quark model includes the leading order $1/M_h$ corrections [26], the QCD-motivated relativistic quark model based on the quasipotential
We can identify the $D_J(2580), D_J^*(2650), D_J(2740), D_J^*(2760), D_J(3000), D_J^*(3000)$ tentatively according to the masses.

TABLE III: The masses of the charmed mesons from different quark models compared with experimental data, and the possible assignments of the newly observed charmed mesons. The $N$ and $U$ denote the natural parity and unnatural parity, respectively. All values in units of MeV.

| $nL_s J^P$ | Exp [1, 24] | GI [1, 25] | PE [26] | EFG [27] |
|----------|-------------|-------------|---------|---------|
| $D$      | 1S$^\frac{1}{2}$0$^+$ | 1867 | 1864 | 1868 | 1871 |
| $D^*$    | 1S$^\frac{1}{2}$1$^-$ | 2008 | 2023 | 2005 | 2010 |
| $D^*_0$  | 1P$^\frac{1}{2}$1$^+$ | 2400 | 2380 | 2377 | 2406 |
| $D_1$    | 1P$^\frac{1}{2}$1$^+$ | 2427 | 2419 | 2490 | 2469 |
| $D^*_1$  | 1P$^\frac{1}{2}$2$^+$ | 2420 | 2469 | 2417 | 2426 |
| $D^*_2$  | 1P$^\frac{1}{2}$2$^+$ | 2460 | 2479 | 2460 | 2460 |
| $D_1^*$  | 1D$^\frac{1}{2}$1$^-$ | ?2760(N) | 2796 | 2795 | 2788 |
| $D_2$    | 1D$^\frac{1}{2}$2$^-$ | ?2740(U) | 2801 | 2833 | 2850 |
| $D_2^*$  | 1D$^\frac{1}{2}$2$^-$ | ?2740(U) | 2806 | 2775 | 2806 |
| $D_3^*$  | 1D$^\frac{1}{2}$3$^-$ | ?2760(N) | 2806 | 2799 | 2863 |
| $D_3$    | 1F$^\frac{1}{2}$2$^+$ | ?3000(N) | 3074 | 3101 | 3090 |
| $D_3^*$  | 1F$^\frac{1}{2}$3$^+$ | ?3000(U) | 3074 | 3123 | 3145 |
| $D_4^*$  | 1F$^\frac{1}{2}$4$^+$ | ?3000(N) | 3084 | 3091 | 3187 |
| $D$      | 2S$^\frac{1}{2}$0$^+$ | ?2580(U) | 2558 | 2589 | 2581 |
| $D^*$    | 2S$^\frac{1}{2}$1$^-$ | ?2650(N) | 2618 | 2692 | 2632 |
| $D^*_0$  | 2P$^\frac{1}{2}$1$^+$ | ?3000(N) | | 2949 | 2919 |
| $D_1$    | 2P$^\frac{1}{2}$1$^+$ | ?3000(U) | 3045 | 3021 | |
| $D^*_1$  | 2P$^\frac{1}{2}$2$^+$ | ?3000(U) | 2995 | 2932 | |
| $D^*_2$  | 2P$^\frac{1}{2}$2$^+$ | ?3000(N) | 3035 | 3012 | |
| $D$      | 3S$^\frac{1}{2}$0$^+$ | ?3000(U) | 3141 | 3062 | |
| $D^*$    | 3S$^\frac{1}{2}$1$^-$ | ?3000(N) | 3226 | 3096 | |

In the following, we list out the possible assignments,

$$(D_J(2580), D_J^*(2650)) = (0^-, 1^-)_{\frac{1}{2}} \quad \text{with} \quad n = 2, L = 0,$$

$$(D_J^*(2760), D_J(2740)) = (1^-, 2^-)_{\frac{3}{2}} \quad \text{with} \quad n = 1, L = 2,$$

$$(D_J(2740), D_J^*(2760)) = (2^-, 3^-)_{\frac{3}{2}} \quad \text{with} \quad n = 1, L = 2,$$

$$(D_J^*(3000), D_J(3000)) = (2^+, 3^+)_{\frac{3}{2}} \quad \text{with} \quad n = 1, L = 3,$$
\[(D_f(3000), D_J^*(3000)) = (3^+, 4^+)_{\frac{L}{2}} \quad \text{with} \quad n = 1, L = 3,\]

\[(D_J^*(3000), D_f(3000)) = (0^+, 1^+)_{\frac{L}{2}} \quad \text{with} \quad n = 2, L = 1,\]

\[(D_f(3000), D_J^*(3000)) = (1^+, 2^+)_{\frac{L}{2}} \quad \text{with} \quad n = 2, L = 1,\]

\[(D_J(3000), D_J^*(3000)) = (0^-, 1^-)_{\frac{L}{2}} \quad \text{with} \quad n = 3, L = 0.\]

The article is arranged as follows: In section 2, the brief review of the \(^3P_0\) decay model is given (For the detailed review see Refs. \([9, 11, 12, 14]\)); In section 3, we study the strong decays of the charmed mesons \(D_f(2580), D_J^*(2650), D_f(2740), D_J^*(2760), D_f(3000), D_J^*(3000)\) with the \(^3P_0\) decay model; In section 4, we present our conclusions.

2 METHOD

2.1 The decay model

The main assumption of the \(^3P_0\) decay model is that the strong decays take place via the creation of a \(^3P_0\) quark-antiquark pair from the vacuum. The new produced quark-antiquark pair, together with the \(q\bar{q}\) in the initial meson, regroups into two outgoing mesons in all possible quark rearrangement ways, which corresponds to the two Feynman diagrams as shown in Fig.1 for the strong decay processes \(A \rightarrow B + C\).

The transition operator \(T\) of the decay \(A \rightarrow B + C\) in the \(^3P_0\) decay model is given by

\[
T = -3\gamma \sum \langle m|1 - m|00\rangle \int d^3\vec{p}_3 d^3\vec{p}_4 \delta^3(\vec{p}_3 + \vec{p}_4) \mathcal{Y}_1^m(\frac{\vec{p}_3 - \vec{p}_4}{2}) \chi_{1-m}^{34} \phi_0^{34} \omega_0^{34} b_3^{34}(\vec{p}_3) d_4^j(\vec{p}_4),
\]

where \(\gamma\) is a dimensionless parameter representing the probability of the quark-antiquark pair \(q_3\bar{q}_4\) with \(J^{PC} = 0^{++}\) created from the vacuum, \(\vec{p}_3\) and \(\vec{p}_4\) are the momenta of the created quark \(q_3\) and antiquark \(\bar{q}_4\), respectively. \(\phi_0^{34}, \omega_0^{34}\), and \(\chi_{1-m}^{34}\) are the flavor, color, and spin wave functions of the \(q_3\bar{q}_4\), respectively. The solid harmonic polynomial \(\mathcal{Y}_1^m(\vec{p}) \equiv |\vec{p}| Y_1^m(\theta_p, \phi_p)\) reflects the momentum-space distribution of the \(q_3\bar{q}_4\).
For the meson wave function, we adopt the mock meson state $| A(n_A^{2S_A+1}L_{AM_{A}})(\vec{P}_A) \rangle$ defined by \[28\]

$$| A(n_A^{2S_A+1}L_{AM_{A}})(\vec{P}_A) \rangle \equiv \sqrt{2E_A} \sum_{M_{L_A}M_{S_A}} \langle L_{AM_{L_A}}S_{AM_{S_A}} | J_{AM_{J_A}} \rangle$$

$$\times \int d^3\vec{p}_A\psi_{nAL_{AM_{A}}} (\vec{p}_A) \chi_{S_{AM_{S_A}}}^{12} \phi_A^{12} \omega_A^{12}$$

$$\times | q_1 (m_1 + m_2) \vec{P}_A + \vec{p}_A \rangle q_2 (m_2) \vec{P}_A - \vec{p}_A \rangle ,$$

where $m_1$ and $m_2$ are the masses of the quark $q_1$ with a momentum of $\vec{p}_1$ and the antiquark $\vec{q}_2$ with a momentum of $\vec{p}_2$, respectively, $n_A$ is the radial quantum number of the meson $A$ composed of $q_1\vec{q}_2$, $S_A = s_{q_1} + s_{q_2}$, $J_A = \vec{L}_A + \vec{S}_A$, $s_{q_1}(s_{q_2})$ is the spin of $q_1(\vec{q}_2)$, $\vec{L}_A$ is the relative orbital angular momentum between $q_1$ and $\vec{q}_2$, $\vec{P}_A = \vec{p}_1 + \vec{p}_2$, $\vec{p}_A = \frac{m_2\vec{p}_1 - m_1\vec{p}_2}{m_1 + m_2}$, $\langle L_{AM_{L_A}}S_{AM_{S_A}} | J_{AM_{J_A}} \rangle$ is a Clebsch-Gordan coefficient, and $E_A$ is the total energy of the meson $A$, $\chi_{S_{AM_{S_A}}}^{12}$, $\phi_A^{12}$, $\omega_A^{12}$, and $\psi_{nAL_{AM_{A}}}(\vec{p}_A)$ are the spin, flavor, color, and space wave functions of the meson $A$, respectively.

The $S$-matrix of the process $A \rightarrow BC$ is defined by

$$\langle BC | S | A \rangle = I - 2\pi i\delta(E_A - E_B - E_C) \langle BC | T | A \rangle ,$$

with

$$\langle BC | T | A \rangle = \delta^3(\vec{P}_A - \vec{P}_B - \vec{P}_C) \mathcal{M}^{M_{J_A}M_{J_B}M_{J_C}} ,$$

where $\mathcal{M}^{M_{J_A}M_{J_B}M_{J_C}}$ is the helicity amplitude of $A \rightarrow BC$. In the center of mass frame of the meson $A$, the $\mathcal{M}^{M_{J_A}M_{J_B}M_{J_C}}$ can be written as

$$\mathcal{M}^{M_{J_A}M_{J_B}M_{J_C}}(\vec{P}) = \gamma \sqrt{8E_AE_BE_C} \sum_{M_{L_A}M_{S_A}, M_{L_B}M_{S_B}, M_{L_C}M_{S_C}} \langle L_{AM_{L_A}}S_{AM_{S_A}} | J_{AM_{J_A}} \rangle$$

$$\times \langle L_{BM_{L_B}}S_{BM_{S_B}} | J_{BM_{J_B}} \rangle \langle L_{CM_{L_C}}S_{CM_{S_C}} | J_{CM_{J_C}} \rangle$$

$$\times \langle 1m1 - m | 00 \rangle \langle \chi_{S_{BM_{S_B}}M_{BM_{S_B}}}^{32} \chi_{S_{CM_{S_C}}}^{34} | \chi_{S_{AM_{S_A}}}^{12} \chi_{1-m}^{34} \rangle$$

$$\times \left[ \langle \phi_{C}^{14} \phi_{C}^{32} | \phi_{A}^{12} \phi_{0}^{34} \rangle I(\vec{P}, m_1, m_2, m_3)$$

$$+ (-1)^{1+S_A+S_B+S_C} \langle \phi_{C}^{32} \phi_{C}^{14} | \phi_{A}^{12} \phi_{0}^{34} \rangle I(-\vec{P}, m_2, m_1, m_3) \right] ,$$

where the two terms in the bracket $[ ]$ correspond to the two possible diagrams in Fig.1(a) and 1(b), respectively, and the spatial integral is defined as

$$I(\vec{P}, m_1, m_2, m_3) = \int d^3\vec{p}_B\psi_{nBL_{BM_{B}}}^{*} (\vec{m}_3 \vec{m}_1 + \vec{m}_2 \vec{p}_B + \vec{p}_B)$$

$$\times \psi_{nAL_{AM_{A}}} (\vec{P}_B + \vec{p}) \gamma^{m_3}(\vec{p}) ,$$

$$\times \psi_{nAL_{AM_{A}}} (\vec{P}_B + \vec{p}) \gamma^{m_3}(\vec{p}) ,$$
where $\vec{P} = -\vec{P}_B - \vec{P}_C$, $\vec{p} = \vec{p}_3$, $m_3$ is the mass of the created quark $q_3$, the SHO approximation is used for the meson’s radial wave functions. In momentum-space, the SHO wave function is

$$
\Psi_{nLM_L}(\vec{p}) = (-1)^n (-i)^L R^{L+\frac{1}{2}} \sqrt{\frac{2n!}{\Gamma(n + L + \frac{3}{2})}} \exp(-\frac{R^2 p^2}{2}) Y_{LM_L}(\vec{p}),
$$

(7)

where $Y_{LM_L}(\vec{p}) = |\vec{p}|^L Y_{LM_L}(\Omega_p)$, and $L^{L+\frac{1}{2}}(R^2 p^2)$ is an associated Laguerre polynomial. The overlaps of the flavor and spin wave functions of the mesons and the created pair in the formula (5) can be calculated according to the method in Ref. [14].

With the Jacob-Wick formula the helicity amplitude can be converted into the partial wave amplitude [29]

$$
\mathcal{M}^{JL}(\vec{P}) = \sqrt{\frac{4\pi (2L + 1)}{2J_A + 1}} \sum_{M_{J_A}} \langle L0JM_{J_A} | J_{A} M_{J_A} \rangle \times \langle J_{B} M_{J_B} J_{C} M_{J_C} | J_{M_{J_A}} \rangle \mathcal{M}^{M_{J_A} M_{J_B} M_{J_C}}(\vec{P}).
$$

(8)

The decay width in terms of the partial wave amplitudes using the relativistic phase space is

$$
\Gamma = \frac{\pi}{4} \frac{\mid \vec{P} \mid}{M_A^2} \sum_{JL} |\mathcal{M}^{JL}|^2,
$$

(9)

where $\mid \vec{P} \mid = \sqrt{(M_A^2 - (M_B + M_C)^2) [M_A^2 - (M_B - M_C)^2]}$, $M_A$, $M_B$, and $M_C$ are the masses of the mesons $A$, $B$, and $C$, respectively.

### 2.2 Mixed states

The heavy-light mesons are not charge conjugation eigenstates and so mixing can occur between states with $J = L$ and $S = 1$ or $0$. A general relation between the heavy quark symmetric states and the non-relativistic states $^3L_L$ and $^1L_L$ can be written as [30]

$$
\begin{pmatrix}
|s_L = L - \frac{1}{2}, P_L \rangle \\
|s_L = L + \frac{1}{2}, P_L \rangle
\end{pmatrix} = \frac{1}{\sqrt{2L + 1}} \begin{pmatrix}
\sqrt{L + 1} & -\sqrt{L} \\
\sqrt{L} & \sqrt{L + 1}
\end{pmatrix} \begin{pmatrix}
|^3L_L \rangle \\
|^1L_L \rangle
\end{pmatrix}, P = (-1)^{L+1}.
$$

(10)

Commonly, we express this relation with the mixture. When $J = L = 1$, the corresponding mixture angle is $\theta = -54.7^\circ$ or $\theta = 35.3^\circ$, thus formula (10) transforms into

$$
\begin{pmatrix}
\frac{1}{2}, 1^+ \\
\frac{3}{2}, 1^+
\end{pmatrix} = \begin{pmatrix}
\cos \theta & \sin \theta \\
-\sin \theta & \cos \theta
\end{pmatrix} \begin{pmatrix}
|^3P_1 \rangle \\
|^1P_1 \rangle
\end{pmatrix}.
$$

(11)
In our calculation, the final states are related to $D(2420)/D(2430)$ and $D_s(2460)/D_s(2536)$, which are the $1^+$ states in the $D$ and $D_s$ meson families, respectively. The $D(2420)/D(2430)$ and $D_s(2460)/D_s(2536)$ are the mixings of the $^3P_1$ and $^1P_1$ states, which satisfies the formula (11). In addition, the initial states of $1^+$ are also the mixings of $^3P_1$ and $^1P_1$ states. As far as the $1F_2^23^+/1F_2^23^+$ and $1D_2^22^-/1D_2^22^-$ states are concerned, they are the mixings of the $^3F_3/^1F_3$ and $^3D_2/^1D_2$ states respectively, and the mixture angle can be determined by formula (10).

In order to distinguish $L$ from formula (8), we choose $l$ as the orbital angular momentum of the $D$ mesons in the following three formulas (12-14). If the initial states $A(l^P)$ are the mixings, the partial wave amplitude can be deduced as

$$
\begin{pmatrix}
\mathcal{M}^{JL}_{l^P \rightarrow P} \\
\mathcal{M}^{JL}_{l^P \rightarrow P}
\end{pmatrix}
= \begin{pmatrix}
\cos \theta & -\sin \theta \\
\sin \theta & \cos \theta
\end{pmatrix}
\begin{pmatrix}
\mathcal{M}^{JL}_{l^P \rightarrow P} \\
\mathcal{M}^{JL}_{l^P \rightarrow P}
\end{pmatrix},
$$

(12)
in the case of the mixings of the final states $B(l^P)$

$$
\begin{pmatrix}
\mathcal{M}^{JL}_{A \rightarrow l^P} \\
\mathcal{M}^{JL}_{A \rightarrow l^P}
\end{pmatrix}
= \begin{pmatrix}
\cos \theta' - \sin \theta' \\
\sin \theta' & \cos \theta'
\end{pmatrix}
\begin{pmatrix}
\mathcal{M}^{JL}_{A \rightarrow l^P} \\
\mathcal{M}^{JL}_{A \rightarrow l^P}
\end{pmatrix},
$$

(13)
When the initial and the final states ($A$ and $B$) are both the mixings, we can get the similar relation

$$
\begin{pmatrix}
\mathcal{M}^{JL}_{l^P \rightarrow l^P} \\
\mathcal{M}^{JL}_{l^P \rightarrow l^P}
\end{pmatrix}
= \begin{pmatrix}
\cos \theta \cos \theta' - \sin \theta \sin \theta' \\
\sin \theta \cos \theta' & \cos \theta \sin \theta'
\end{pmatrix}
\begin{pmatrix}
\mathcal{M}^{JL}_{l^P \rightarrow l^P} \\
\mathcal{M}^{JL}_{l^P \rightarrow l^P}
\end{pmatrix},
$$

(14)
where $\theta$ and $\theta'$ are the mixtures of the initial and final states, respectively. Thus the decay width can also be deduced from the general relations of (12-14). For example, in the case of the mixings of the initial states of $1^+$,

$$
\begin{pmatrix}
\mathcal{M}^{JL}_{1^+} \\
\mathcal{M}^{JL}_{1^+}
\end{pmatrix}
= \begin{pmatrix}
\cos \theta - \sin \theta \\
\sin \theta & \cos \theta
\end{pmatrix}
\begin{pmatrix}
\mathcal{M}^{JL}_{1^+} \\
\mathcal{M}^{JL}_{1^+}
\end{pmatrix},
$$

(15)
and the decay width can be expressed as
\[ \Gamma(\frac{1}{2}^+,1^+ \to BC) = \frac{\pi}{4} \frac{|\vec{P}|}{M^2_A} \sum_{JL} |\cos \theta M_{JL}^{(3P_0) \to BC} - \sin \theta M_{JL}^{(3P_0) \to BC}|^2, \]

\[ \Gamma(\frac{3}{2}^+,1^+ \to BC) = \frac{\pi}{4} \frac{|\vec{P}|}{M^2_A} \sum_{JL} |\sin \theta M_{JL}^{(3P_0) \to BC} + \cos \theta M_{JL}^{(3P_0) \to BC}|^2. \] (16)

3 Numerical Results

TABLE IV: The adopted masses of the mesons used in our calculation.

| States | \(M_{s+}\) | \(M_{s0}\) | \(M_{K+}\) | \(M_{K-}\) | \(M_{\eta}\) | \(M_{\eta}'\) | \(M_{D+}\) | \(M_{D^0}\) | \(M_{D^{*+}}\) | \(M_{D^{*0}}\) |
|--------|------------|------------|------------|------------|------------|------------|------------|------------|------------|------------|
| Mass(MeV) | 139.57 | 134.98 | 493.68 | 891.66 | 547.85 | 957.78 | 1869.6 | 1864.83 | 2010.25 | 2006.96 |

| States | \(M_{D^*+}\) | \(M_{D^*0}\) | \(M_{D(2400)}\) | \(M_{D(2420)}\) | \(M_{D(2460)}\) | \(M_{D_{s(2317)}\)} | \(M_{\rho}\) | \(M_{\omega}\) |
|--------|------------|------------|------------|------------|------------|------------|------------|------------|
| Mass(MeV) | 2112.3 | 1968.47 | 2318 | 2427 | 2421.3 | 2464.4 | 2317.8 | 770 | 782 |

The parameters involved in the \(^3P_0\) decay model include the light quark pair \((q\bar{q})\) creation strength \(\gamma\), the SHO wave function scale parameter \(R\), and the masses of the mesons and the constituent quarks. According to Ref. [14], we adopt the SHO wave functions with the common oscillator parameter \(R\) whose value is chosen to be 2.5 GeV\(^{-1}\). Correspondingly, the value of the \(\gamma\) is chosen to be 6.25 for the creation of the \(u/d\) quark [14, 19]. As for the strange quark pair \((s\bar{s})\), its creation strength can be related by \(\gamma_{s\bar{s}} = \gamma/\sqrt{3}\) [10]. The adopted masses of the mesons are listed in TABLE IV, and \(m_u = m_d = 0.22\) GeV, \(m_s = 0.419\) GeV and \(m_c = 1.65\) GeV.

The numerical values of the widths of the strong decays of the charmed mesons \(D_J(2580), D_J^*(2650), D_J(2740), D_J^*(2760), D_J(3000), D_J^*(3000)\) observed by the LHCb collaboration are presented in TABLE V-VII. The measurements of the LHCb collaboration favor the assignment \((D_J(2580), D_J^*(2650)) = (0^-,1^-)_{\frac{1}{2}}\) with \(n = 2\). They also favor the following two possible assignments

\((D_J^*(2760), D_J(2740)) = (1^-,2^-)_{\frac{1}{2}}\) with \(n = 1, L = 2\),

\((D_J(2740), D_J^*(2760)) = (2^-,3^-)_{\frac{3}{2}}\) with \(n = 1, L = 2\).

The partial and total decay widths in the above assignments are listed in TABLE V. Comparing with the experimental data of the LHCb and BaBar collaborations, our results are of the same order in magnitude. We can see that, except for the \(D_J(2580)\), the predicted total widths of the \(D_J(2740)\) and \(D_J^*(2760)\) are somewhat bigger than the experimental values, and the width of the \(D_J^*(2650)\) is roughly in agreement with the total width measured by the BaBar collaboration. In addition, the \(1D_{\frac{3}{2}}^{23^-}\) state may be the optimal assignment of the \(D_J^*(2760)\) since the corresponding total width is close to the experimental value of the LHCb collaboration. However, the LHCb collaboration identify the \(D_J^*(2760)\) as the \(1D_{\frac{3}{2}}^{21^-}\) state, which is incompatible with our results. From TABLE V, we can see...
TABLE V: The strong decay widths of the newly observed charmed mesons \( D_J(2580) \), \( D_J^*(2650) \), \( D_J(2740) \) and \( D_J^*(2760) \) with possible assignments. If the corresponding decay channel is forbidden, we mark it by "-". All values in units of MeV.

| State                  | \( D_J(2580) \) | \( D_J^*(2650) \) | \( D_J(2740) \) | \( D_J(2740) \) | \( D_J^*(2760) \) |
|------------------------|----------------|-----------------|----------------|----------------|----------------|
| \( D^{*+}\pi^- \)      | 49.80          | 34.72           | 16.46          | 17.04          | 48.63          |
| \( D_J^*K^- \)         | -              | 2.02            | 2.86           | 0.38           | 6.95           |
| \( D^{*0}\pi^0 \)      | 25.00          | 17.32           | 8.19           | 8.74           | 24.24          |
| \( D^{*0}\eta \)       | 0.81           | 3.26            | 2.80           | 0.59           | 7.41           |
| \( D^0(2400)\pi^0 \)   | 0.35           | -               | -              | 0.06           | 0.00028        |
| \( D^0(2460)\pi^0 \)   | -              | 0.024           | 0.23           | 0.97           | 23.26          |
| \( D(2420)\pi^0 \)     | -              | 0.12            | 23.92          | 0.26           | 0.089          |
| \( D(2427)\pi^0 \)     | -              | 0.30            | 3.10           | 13.48          | 0.0057         |
| \( D^+\pi^- \)         | -              | 13.57           | 25.15          | -              | 17.02          |
| \( D_J^*\pi^- \)       | -              | 6.56            | 10.34          | -              | 0.70           |
| \( D^0\eta \)          | -              | 6.65            | 12.35          | -              | 8.73           |
| \( D^+\rho \)          | -              | 3.53            | 6.78           | -              | 0.99           |
| \( D_J^*\rho \)        | -              | 1.59            | 37.00          | 36.02          | 0.50           |
| \( D^0\omega \)        | -              | 1.37            | 19.10          | 18.90          | 0.29           |
| Total width            | 75.96          | 91.18           | 186.06         | 113.34         | 111.56         |

that, if the \( D_J^*(2760) \) is the \( 1D_J^{2-3} \) state, the main decay channels are \( D^+\rho \), \( D^+\pi^- \), \( D^0\rho \) and \( D^0\omega \). The decay behavior of the \( 1D_J^{2-1} \) state is very similar to that of the \( 1D_J^{2-3} \) state except for the decay channel \( D(2420)\pi^0 \). This difference can be used to further identify the assignment of the \( D_J^*(2760) \) in the future. Furthermore, we tentatively identify the \( D_J(2740) \) as the \( 1D_J^{2-3} \) state with \( J^P = 2^- \), and we can see that the total widths of the \( 1D_J^{2-2} \) and \( 1D_J^{2-2} \) states are of the same order. However, the decay behaviors of these two states are different from each other. The main decay modes of the \( 1D_J^{2-2} \) state are \( D^+\rho \), \( D^{*+}\pi^- \), \( D^0\rho \), \( D^0\omega \) and \( D(2427)\pi^0 \), while the \( 1D_J^{2-2} \) state mainly decays into \( D^{*+}\pi^- \), \( D^{*0}\pi^0 \) and \( D(2460)\pi^0 \).

As discussed at the end of Section 1, the \( D_J^*(3000) \) is a natural parity state. Thus, we study its decay behavior with the \( 1F_J^{2+} \), \( 1F_J^{4+} \), \( 2P_J^{10+} \), \( 2P_J^{12+} \) and \( 3S_J^{1-} \) assignments. We can see from TABLE VI that the \( D_J^*(3000) \) is most likely to be the \( 1F_J^{2+} \) state or \( 1F_J^{4+} \) state, since the total widths are in good agreement with the experimental data. However, these two assignments lead to different decay modes, which can be used to further identify its quantum numbers. If the \( D_J^*(3000) \) is the \( 1F_J^{2+} \) state, the \( D^{*+}\pi^- \), \( D^+\pi^- \), \( D^+\rho \) and \( D(2420)\pi^0 \) are the main decay modes, on the other hand, if the
$D_j^*(3000)$ is the $1F_2^+\pi^+$ state, the $D^{*+}\rho$, $D^{*0}\rho$, $D^{*0}\omega$, $D^{+}\pi^-$ and $D^{*+}\pi^-$ are the main decay modes. Our results show that the assignments of the $2P_{1/2}^0$, $2P_{3/2}^0$ and $3S_{1/2}^0$ states can be excluded since the corresponding total widths are quite different from the experimental values. Nevertheless, these information are valuable in searching for the partners of the $D_j^*(3000)$. In Ref. [22], Y. Sun et al. identify the $D_j^*(3000)$ as the $2^3P_0$ state with the effective oscillator parameter $R$. In their studies, it is proposed that the main decay channels of the $2^3P_0$ state are $D^{*}\rho$, $D(2420)\pi$, $D(2427)\pi$, $D\eta$, $D\eta K$, and $D^{*}\omega$.

As for the $D_j(3000)$, the possible assignments are the $3S_{1/2}^0\pi^-$, $2P_{1/2}^1\pi^+$, $2P_{3/2}^1\pi^+$, $1F_2^+3\pi^+$ and $1F_2^+3\pi^+$ states. In TABLE VII, the partial and total decay widths of the $D_j(3000)$ in those possible assignments are given. We can see easily from the table that both the widths of the $1F_2^+3\pi^+$ and $2P_{1/2}^1\pi^+$ states are in good agreement with the experimental data. So the $D_j(3000)$ is most likely to be the $1F_2^+3\pi^+$ or $2P_{1/2}^1\pi^+$ state. If the $D_j(3000)$ is the $1F_2^+3\pi^+$ state, it dominantly decays into $D^{*+}(2460)\pi^-$, $D^{*0}(2460)\pi^0$, $D^{+}\pi^-$, $D^{*0}\pi^0$ and $D^{*+}\rho$; on the other hand, if the $D_j(3000)$ is the $2P_{1/2}^1\pi^+$ state, it dominantly decays into $D^{*+}\rho$, $D^{*0}\rho$, $D^{*0}\omega$, $D^{+}\pi^-$, $D^{+}\rho$ and $D^{*0}\pi^0$. These conclusions are consistent with the experimental observation[1], where the $D_j(3000)$ was firstly observed in the $D^{*+}\pi^-$ decay channel. As for the other three assignments $3S_{1/2}^0\pi^-$, $2P_{1/2}^1\pi^+$ and $1F_2^+3\pi^+$, we can also see the main decay modes from TABLE VII, which are valuable in searching for these states experimentally in the future. In Ref.[22], Y. Sun et al. also suggest that the $2P_{1/2}^1\pi^+$ state is the mostly probable assignment of the $D_j(3000)$, which is compatible with our observation. However, the $1F_3^+\pi^+$ assignment is excluded in their studies as the width deviates from the experimental value. The differences between the results of Y. Sun et al. and ours is mainly due to the influence of the input parameter $R$. And we will give a short discussion about the dependence on the $R$ at the end of this section.

From tables V-VII, we can also see that most of the ratios among different decay channels are roughly consistent with the results in Ref. [7]. For example, the ratios $\frac{\Gamma(D_j(2580)\rightarrow D^{*+}\pi^-)}{\Gamma(D_j(2580)\rightarrow D^{*+}\pi^-)}$ and $\frac{\Gamma(D_j(2580)\rightarrow D^{*0}K^-)}{\Gamma(D_j(2580)\rightarrow D^{*+}\pi^-)}$ from the heavy meson effective theory are 0.51 and 0.02, respectively [7], which are consistent with the present results 0.52, and 0.02, respectively. In TABLE VIII, we also present the experimental value of the ratio $\frac{\Gamma(D_j^*(2460)\rightarrow D^{*+}\pi^-)}{\Gamma(D_j^*(2460)\rightarrow D^{*+}\pi^-)}$ for the well established meson $D_j^*(2460)$ from the BaBar [2], CLEO [31, 32], ARGUS [33], and ZEUS [34] collaborations. The result based on the heavy meson effective theory in the leading order approximation is also listed in TABLE VIII. The present prediction 2.29 based on the $3^3P_0$ decay model is in excellent agreement with the average experimental value 2.35 [7]. Furthermore, this result is consistent with the prediction based on the heavy meson effective theory. Finally, it needs to be noticed that the ratios among the decay widths of different charmed mesons based on the $3^3P_0$ decay model are roughly consistent with the experimental data. For example, the predicted ratio $\frac{\Gamma(D_j^*(2760)\rightarrow D_j^*(2760)}{\Gamma(D_j^*(2760)\rightarrow D_j^*(2760)D_j^*(2760)} \approx 0.83$ based on the $3^3P_0$ decay model, the corresponding experimental value is 1.27; the predicted ratio $\frac{\Gamma(D_j^*(2760)\rightarrow D_j^*(2760)}{\Gamma(D_j^*(2760)\rightarrow D_j^*(2760)} \approx 0.86$, the corresponding
experimental value is 1.0.

FIG. 2: The strong decay of $D_J(2580) \rightarrow D^{*+}\pi^-$ with $R_{\pi^-} = 2.5$ GeV$^{-1}$.

FIG. 3: The strong decay of $D_J(2580) \rightarrow D^{*+}\pi^-$ with $R_{D^{*+}} = 2.5$ GeV$^{-1}$.

Now, let us take a short discussion about the uncertainties of the results based on the $^3P_0$ decay model. Since this model is a simplified model of a complicated theory, it is not surprising that the prediction is not very accurate. Especially, the input parameter $R$ has a significant influence on the shapes of the radial wave functions, the spatial integral in equation (6) is sensitive to the parameter $R$, therefore the decay width based on the $^3P_0$ decay model is sensitive to the parameter $R$. We take the decay $D_J(2580) \rightarrow D^{*+}\pi^-$ as an example, and plot the decay width versus the input parameter $R$ in Figs. 2 and 3. From these two figures, we can see easily the dependence of the decay width on the input parameter $R$. If the $R_{D^{*+}}$ and $R_{\pi^-}$ are fixed to be 2.5 GeV$^{-1}$, the decay width of the $D_J(2580)$ changes several times with the value of the $R_{D_J(2580)}$ changing from 1.5 GeV$^{-1}$ to 3.0 GeV$^{-1}$. Similarly, the decay width changes $2 \sim 3$ times, when the $R_{D_J(2580)}$ and $R_{\pi^-}$ (or the $R_{D_J(2580)}$ and $R_{D^{*+}}$) are fixed to be 2.5 GeV$^{-1}$ while the $R_{D^{*+}}$ (or $R_{\pi^-}$) changes. In Ref. [14], H. G. Blundel et al carry out a series of least squares fits of the model predictions to the decay widths of 28 of the best known meson decays. And the common oscillator parameter $R$ with the value of 2.5 GeV$^{-1}$ is suggested to be the optimal value [14]. As for the factor $\gamma$, it describes the strength of quark-antiquark pair creation from the vacuum, which also needs to be fitted according to experimental data, the fitted value is 6.25 [14, 19]. Once the optimal values of the $\gamma$ and $R$ are determined, the best predictions based on the $^3P_0$ decay model are expected to be within a factor of 2. More detailed analysis about the uncertainties of the results in the $^3P_0$ decay model can be found in Ref. [14].

4 Conclusion

In this article, we study the properties of the charmed mesons $D_J(2580)$, $D_J^*(2650)$, $D_J(2740)$, $D_J^*(2760)$, $D_J(3000)$ and $D_J^*(3000)$ with the $^3P_0$ decay model. Our results support the $1D_2^23^-$ assignment of the $D_J^*(2760)$, more experimental data are still needed to identify it. Furthermore, both the mass spectra of the $D$ mesons and the two-body decay behaviors indicate that the $D_J^*(3000)$
maybe the $1F^{2+}_7$ state or $1F^{4+}_7$ state, since the widths in these two assignments are both in good agreement with the experimental data. On the other hand, we tentatively identify the $D_J(3000)$ as the $1F^{2+}_7$ state and $2P^{1+}_2$ state according to the decay widths. It is noted that the $D_J^*(3000)$ and $D_J(3000)$ states are strongly correlated to the background parameters as shown in Ref.[1]. Thus, more experimental data are still needed to draw a more clear conclusion on the existence of these two states. In studying the $D_J(2580)$, $D_J^*(2650)$, $D_J(2740)$, $D_J^*(2760)$, $D_J(3000)$ and $D_J^*(3000)$, we have also obtained their partial decay widths in different channels in the assignments $2P^{1+}_2$, $2P^{2+}_2$, $3S^{1-}_1$, $3S^{0-}_2$, etc, which can be used to confirm or reject the assignments of the newly observed charmed mesons in the future.

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TABLE VI: The strong decay widths of the newly observed charm ed meson $D^*_J(3000)$ with possible assignments. If the corresponding decay channel is forbidden, we mark it by "-". All values in units of MeV.  

| Decay Mode | $1F^\pm 2^+$ | $1F^\pm 4^+$ | $2P^\pm 0^+$ | $2P^\pm 2^+$ | $3S^\pm 1^-$ |
|------------|-------------|-------------|-------------|-------------|-------------|
| $D^+ \pi^-$ | 10.46       | 9.36        | -           | 11.91       | 3.19        |
| $D^+ K^-$  | 1.80        | 0.27        | -           | 6.38        | 1.50        |
| $D^{*0} \pi^0$ | 5.21     | 4.78        | -           | 5.86        | 1.66        |
| $D^{*0} \eta'$ | 1.87      | 0.54        | -           | 3.16        | 0           |
| $D^+ \pi^-$ | 0.10        | -           | -           | 0.25        | 1.84        |
| $D^+_K^-$  | 12.61       | 14.08       | 23.94       | 3.40        | 3.61        |
| $D^{*0} K^-$ | 3.71       | 0.81        | 2.85        | 5.47        | 0.081       |
| $D^{0} \pi^0$ | 6.22      | 7.19        | 11.97       | 1.61        | 1.84        |
| $D^{0} \eta$  | 2.94        | 1.21        | 4.26        | 1.6         | 0.23        |
| $D^{0} \eta'$ | 4.39       | 0.11        | 1.07        | 4.31        | 1.69        |
| $D^{*+} \rho$ | 6.74       | 28.23       | 62.01       | 25.22       | 18.01       |
| $D^{*0} K^*$  | 0.0057     | 0.032       | 3.06        | 12.21       | 0.57        |
| $D^{*0} \rho$ | 3.49        | 14.45       | 31.60       | 12.78       | 8.73        |
| $D^{*0} \omega$ | 3.16      | 13.46       | 29.91       | 12.38       | 9.65        |
| $D^{*+} \rho$ | 11.69       | 2.78        | -           | 20.71       | 0.14        |
| $D^{*0} K^*$  | 0.61        | 0.016       | -           | 2.29        | 3.53        |
| $D^{0} \rho$  | 5.90        | 1.46        | -           | 10.37       | 0.049       |
| $D^{0} \omega$ | 5.81       | 1.33        | -           | 10.38       | 0.11        |
| $D(2420)\pi^0$ | 15.01      | 0.04        | 26.20       | 3.91        | 7.10        |
| $D(2420)\eta$ | 0.61       | $1.82 \times 10^{-7}$ | 1.37 | $1.62 \times 10^{-3}$ | 0.11 |
| $D(2427)\pi^0$ | 2.06        | 0.41        | 6.69        | 1.95        | 0.91        |
| $D(2427)\eta$ | 0.04        | $1.56 \times 10^{-4}$ | 0.35 | 0.13        | 0.77        |
| $D(2400)\pi^0$ | -          | -           | -           | -           | -           |
| $D(2400)\eta$  | -          | -           | -           | -           | -           |
| $D_s(2460)K^-$ | 3.07        | 0.016       | 12.81       | 1.03        | 0.98        |
| $D_s(2536)K^-$ | 1.54        | 0.0081      | 6.40        | 0.64        | 0.49        |
| $D^+(2460)\pi^-$ | 4.85      | 1.14        | -           | 11.08       | 13.57       |
| $D^0(2460)\pi^0$ | 2.45       | 0.59        | -           | 5.59        | 6.87        |
| $D^0(2460)\eta$ | 0.09        | -           | -           | 0.05        | 0.008       |
| $D^+_s(2317)K^-$ | -          | -           | -           | -           | -           |
| Total width  | 116.43      | 102.31      | 224.49      | 174.53      | 87.22       |
TABLE VII: The strong decay widths of the newly observed charmed meson $D_J(3000)$ with possible assignments. If the corresponding decay channel is forbidden, we mark it by "-". All values in units of MeV.

|                  | $1F^+_23^+$ | $1F^-_23^+$ | $2P^+_11^+$ | $2P^-_11^+$ | $3S^0_10^+$ |
|------------------|-------------|-------------|-------------|-------------|-------------|
| $D^+\pi^-$       | 17.02       | 25.95       | 20.32       | 23.62       | 4.78        |
| $D^+_S K^-$      | 0.57        | 4.40        | 9.45        | 1.22        | 2.25        |
| $D^{*0}\pi^0$    | 8.69        | 12.93       | 10.03       | 11.85       | 2.47        |
| $D^{*0}\eta$     | 1.05        | 4.59        | 4.92        | 2.48        | 0           |
| $D^{*0}\eta'$    | 0.0057      | 0.25        | 2.71        | 18.72       | 2.75        |
| $D^+\pi^-$       | -           | -           | -           | -           | -           |
| $D^+_S K^-$      | -           | -           | -           | -           | -           |
| $D^0\pi^0$       | -           | -           | -           | -           | -           |
| $D^0\eta$        | -           | -           | -           | -           | -           |
| $D^0\eta'$       | -           | -           | -           | -           | -           |
| $D^{*+}\rho$     | 12.16       | 12.79       | 41.34       | 36.26       | 15.44       |
| $D^+_S K^*$      | 0.0081      | 0.016       | 2.05        | 4.08        | 0.49        |
| $D^{*0}\rho$     | 6.24        | 6.56        | 21.07       | 18.46       | 7.48        |
| $D^{*0}\omega$   | 5.77        | 6.07        | 19.93       | 17.53       | 8.26        |
| $D^+\rho$        | 29.22       | 5.01        | 10.59       | 34.52       | 0.21        |
| $D^+_S K^*$      | 1.50        | 0.024       | 7.13        | 3.82        | 5.31        |
| $D^0\rho$        | 14.74       | 2.63        | 5.61        | 17.27       | 0.073       |
| $D^0\omega$      | 14.52       | 2.39        | 4.99        | 17.30       | 0.15        |
| $D(2420)\pi^0$   | 0.99        | 0.40        | 0.0081      | 0.024       | -           |
| $D(2420)\eta$    | $1.7 \times 10^{-3}$ | $6.3 \times 10^{-4}$ | $3.0 \times 10^{-3}$ | $6.1 \times 10^{-3}$ | -         |
| $D(2420)\pi^0$   | 0.0081      | $9.7 \times 10^{-3}$ | $9.9 \times 10^{-3}$ | 0.0081      | -           |
| $D(2420)\eta$    | $5.9 \times 10^{-4}$ | $1.8 \times 10^{-4}$ | $1.5 \times 10^{-3}$ | $3.0 \times 10^{-3}$ | -         |
| $D(2400)\pi^0$   | 0.32        | 0.057       | 0.24        | 0.17        | 0.51        |
| $D(2400)\eta$    | 0.011       | 0.0027      | 0.27        | 0.30        | 0.28        |
| $D_S(2460)K^-$    | $1.9 \times 10^{-3}$ | $2.5 \times 10^{-3}$ | 0.0081      | 0.024       | -           |
| $D_S(2536)K^-$    | $3.7 \times 10^{-3}$ | $4.9 \times 10^{-3}$ | 0.024       | 0.049       | -           |
| $D^+(2460)\pi^-$ | 0.99        | 36.52       | 10.52       | 56.21       | 27.15       |
| $D^0(2460)\pi^0$ | 0.50        | 18.32       | 5.39        | 28.05       | 13.74       |
| $D^0(2460)\eta$  | 0.019       | 0.85        | 0.024       | 0.56        | 0.013       |
| $D^+_S(2317)K^-$ | 0.049       | 0.016       | 0.83        | 0.52        | 0.27        |
| **Total width**   | 114.40      | 187.49      | 177.46      | 293.05      | 91.62       |
TABLE VIII: The experimental values and numerical result based on the leading order heavy meson effective theory (HMET) of the ratio $\frac{\Gamma(D_2^*(2460) \to D^+ \pi^-)}{\Gamma(D_2^*(2460) \to D^{*+} \pi^-)}$ compared to our numerical result based on the $^3P_0$ decay model.

|           | BaBar [2] | CLEO [31] | CLEO [32] | ARGUS [33] | ZEUS [34] | HMET [7] | This work |
|-----------|-----------|-----------|-----------|------------|-----------|----------|-----------|
|           | $1.47 \pm 0.03 \pm 0.16$ | $2.2 \pm 0.7 \pm 0.6$ | $2.3 \pm 0.8$ | $3.0 \pm 1.1 \pm 1.5$ | $2.8 \pm 0.8^{+0.5}_{-0.6}$ | $2.29$ | $2.29$ |