Analysis of the charmed mesons $D_1^*(2680)$, $D_3^*(2760)$, and $D_2^*(3000)$

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In this work, we systematically study the strong decay behavior of the charmed mesons $D_1^*(2680)$, $D_3^*(2760)$, and $D_2^*(3000)$ reported by the LHCb Collaboration. By comparing the masses and the decay properties with the results of the experiment, we assign these newly observed mesons as the $2S\frac{1}{2}1^-$, $1D\frac{5}{2}3^-$, and $1F\frac{5}{2}2^+$ states, respectively. As a byproduct, we also study the strong decays of the unobserved $2P\frac{3}{2}2^+$, $2F\frac{5}{2}2^+$, and $3P\frac{3}{2}2^+$ charmed mesons, which is useful for future experiments in searching for these charmed mesons.

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I. INTRODUCTION

Recently, the LHCb Collaboration studied the resonant substructures of $B^- \to D^+\pi^-\pi^-$ decays in a data sample corresponding to 3.0 fb^{-1} of pp collision data recorded by the LHCb experiment during 2011 and 2012. By a Dalitz plot analysis technique, the presence of resonances with spins 1, 2, and 3 at the $D^+\pi^-$ mass spectrum were confirmed [1]. Their analysis indicated that these resonances are mainly from the contributions of $D_2^*(2460)$, $D_1^*(2680)$, $D_3^*(2760)$, and $D_2^*(3000)$ charmed mesons. The masses and decay widths of these mesons are

$$
\begin{aligned}
D_2^*(2460):\ & M = 2463.7 \pm 0.4 \pm 0.4 \pm 0.6\ \text{MeV},\\
& \Gamma = 47.0 \pm 0.8 \pm 0.9 \pm 0.3\ \text{MeV}\\
D_1^*(2680):\ & M = 2681.1 \pm 5.6 \pm 4.9 \pm 13.1\ \text{MeV},\\
& \Gamma = 186.7 \pm 8.5 \pm 8.6 \pm 8.2\ \text{MeV}\\
D_3^*(2760):\ & M = 2775.5 \pm 4.5 \pm 4.5 \pm 4.7\ \text{MeV},\\
& \Gamma = 95.3 \pm 9.6 \pm 7.9 \pm 33.1\ \text{MeV}\\
D_2^*(3000):\ & M = 3214 \pm 29 \pm 33 \pm 36\ \text{MeV},\\
& \Gamma = 186 \pm 38 \pm 34 \pm 63\ \text{MeV}.
\end{aligned}
$$

Actually, people have found many other charmed mesons before these discoveries [2–9], which have greatly enriched the charmonium spectra. On the other hand, these discoveries also shed more light on our knowledge about the essence of the elementary particles in the microworld. For $D_2^*(2460)$ as an example, it has been well established previously, and the $1P\frac{3}{2}2^+$ assignment is strongly favored [10]. We studied the nature of the states $D_1^*(2680)$, $D_3^*(2760)$, and $D_2^*(3000)$ in our previous work using the heavy-meson effective theory [11]. Some of the strong decay behavior in which the calculated ratios among the decay widths can be used to confirm or reject the assignments of the newly observed charmed mesons has also been studied. The decay behavior of the $D_2^*(3000)$ charmed meson was also analyzed in Ref. [12], where it was assigned as the 2^3F_2 or 3^3P_2 states. To identify the $D_1^*(2680)$, $D_3^*(2760)$, and $D_2^*(3000)$ and give more specific decay widths and the ratios, we further analyze the strong decay properties of these newly observed charmed mesons using the $^3P_0$ decay model.

The $^3P_0$ decay model is known as quark pair creation model which was first introduced by Micu [13] in 1969. An important feature of the this decay model, apart from its simplicity, is that it provides the gross features of several transitions with two parameters, the pair-crestion strength γ and the oscillator parameter R, which can be fitted to the experimental data. Soon after the introduction of the $^3P_0$ model, it was further developed by other collaborations [14,15]. This model, extensively applied to the decays of light mesons and baryons [16–25], has been applied to evaluate the strong decays of heavy meson in the charmonium [26–28], bottomonium [28,29], and open-charm sectors [30,31].

Just as what we have analyzed [11], the mesons of $D_1^*(2680)$, $D^*(2600)$, and $D_J^*(2650)$ have a similar mass and width [32,33] and can be assigned to be the same states $2S\frac{1}{2}1^-$ [34–38]. Based on the same analysis, $D_3^*(2760)^0$, $D^*(2760)^0$, and $D_J^*(2760)^0$ may be the same particle and can be assigned to be the $1D\frac{5}{2}3^-$ state [32–40]. As for $D_2^*(3000)$, it can be a P-wave and F-wave charmed meson. Its mass can be calculated by different theoretical models, such as the relativized quark model based on a universal one-gluon exchange plus linear confinement potential [41], the relativistic quark model includes the leading order

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$1/M_h$ corrections [42], the QCD-motivated relativistic quark model based on the quasipotential approach [43]. According to these calculations, $1F\frac{5}{2}2^+$, $2P\frac{3}{2}2^+$, $2F\frac{5}{2}2^+$, and $3P\frac{3}{2}2^+$ can also be assigned as the candidates of the possible states of the charmed meson $D_2^*(3000)$.

To further verify the states of $D_1^*(2680)$ and $D_3^*(2760)$ and check the possibilities of different assignments of the $D_2^*(3000)$, we give a systematic analysis of the decay behaviors about these charmed mesons. The article is arranged as follows. In Sec. II, the brief review of the $^3P_0$ decay model is given (for the detailed review, see Refs. [15,17,18,20]). In Sec. III, we study the strong decays of the charmed mesons $D_1^*(2680)$, $D_3^*(2760)$, and $D_2^*(3000)$ observed by the LHCb Collaboration with the $^3P_0$ decay model. In Sec. IV, we present our conclusions.

II. METHOD

A. Decay model

The $^3P_0$ decay model assumes that a quark-antiquark pair is created from the vacuum with the corresponding quantum number 0^{++}. This new $q\bar{q}$ together with the $q\bar{q}$ within the initial meson regroups into two outgoing mesons in all possible arrangements for the meson decay process $A \to BC$ as shown in Fig. 1.

In the nonrelativistic limit, the transition operator of this process can be expressed as

$$T = -3\gamma \sum_m \langle 1m1-m|00\rangle \int d^3\vec{p}_3 d^3\vec{p}_4 \delta^3(\vec{p}_3+\vec{p}_4)\mathcal{Y}_1^m \times \left(\frac{\vec{p}_3-\vec{p}_4}{2}\right)\chi_{1-m}^{34}\varphi_0^{34}\omega_0^{34} b_3^\dagger(\vec{p}_3)d_4^\dagger(\vec{p}_4), \tag{1}$$

where γ is a dimensionless parameter which denotes the creation strength of the quark-antiquark $q_3\bar{q}_4$ pair. $\vec{p}_3$ and $\vec{p}_4$ are the momenta of this quark-antiquark pair. Its flavor, color, and spin wave functions are represented by φ_0^{34}, ω_0^{34}, and χ_{1-m}^{34}, respectively. The solid harmonic polynomial $\mathcal{Y}_1^m(\vec{p}) \equiv |\vec{p}|^1 Y_1^m(\theta_p, \phi_p)$ reflects the momentum-space distribution of the $q_3\bar{q}_4$.

In the center-of-mass frame of parent meson A, the helicity amplitude $\mathcal{M}^{M_{J_A}M_{J_B}M_{J_C}}$ of the decay process $A \to BC$ is written as

$$\mathcal{M}^{M_{J_A}M_{J_B}M_{J_C}}(\vec{P}) = \gamma\sqrt{8E_AE_BE_C} \sum_{\substack{M_{L_A},M_{S_A},\\ M_{L_B},M_{S_B},\\ M_{L_C},M_{S_C},m}} \langle L_AM_{L_A}S_AM_{S_A}|J_AM_{J_A}\rangle \langle L_BM_{L_B}S_BM_{S_B}|J_BM_{J_B}\rangle \times \langle L_CM_{L_C}S_CM_{S_C}|J_CM_{J_C}\rangle \langle 1m1-m|00\rangle \langle \chi_{S_BM_{S_B}}^{14}\chi_{S_CM_{S_C}}^{32}|\chi_{S_AM_{S_A}}^{12}\chi_{1-m}^{34}\rangle \times [\langle\phi_B^{14}\phi_C^{32}|\phi_A^{12}\phi_0^{34}\rangle I(\vec{P},m_1,m_2,m_3) + (-1)^{1+S_A+S_B+S_C}\langle\phi_B^{32}\phi_C^{14}|\phi_A^{12}\phi_0^{34}\rangle I(-\vec{P},m_2,m_1,m_3)], \tag{2}$$

where the spatial integral is defined as

$$I(\vec{P},m_1,m_2,m_3) = \int d^3\vec{p}\,\psi_{n_BL_BM_{L_B}}^*\left(\frac{m_3}{m_1+m_2}\vec{P}_B+\vec{p}\right)\psi_{n_CL_CM_{L_C}}^*\left(\frac{m_3}{m_2+m_3}\vec{P}_B+\vec{p}\right)\psi_{n_AL_AM_{L_A}}(\vec{P}_B+\vec{p})\mathcal{Y}_1^m(\vec{p}), \tag{3}$$

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, and the simple harmonic oscillator (SHO) approximation is used for the meson space wave functions:

$$\Psi_{nLM_L}(\vec{p}) = (-1)^n(-i)^L R^{L+\frac{3}{2}}\sqrt{\frac{2n!}{\Gamma(n+L+\frac{3}{2})}}\exp\left(-\frac{R^2p^2}{2}\right)L_n^{L+\frac{1}{2}}(R^2p^2)\mathcal{Y}_{LM_L}(\vec{p}). \tag{4}$$

The partial wave amplitudes are related to the helicity amplitudes by [44]

$$\mathcal{M}^{JL}(\vec{P}) = \frac{\sqrt{4\pi(2L+1)}}{2J_A+1}\sum_{M_{J_B}M_{J_C}}\langle L0JM_{J_A}|J_AM_{J_A}\rangle\langle J_BM_{J_B}J_CM_{J_C}|JM_{J_A}\rangle\mathcal{M}^{M_{J_A}M_{J_B}M_{J_C}}(\vec{P}), \tag{5}$$

where $M_{J_A} = M_{J_B} + M_{J_C}$, $\mathbf{J_A} = \mathbf{J_B} + \mathbf{J_C}$, and $\mathbf{J_A} + \mathbf{J_P} = \mathbf{J_B} + \mathbf{J_C} + \mathbf{J_L}$. The transition in terms of partial wave amplitudes is

$$\Gamma = \frac{\pi}{4}\frac{|\vec{P}|}{M_A^2}\sum_{JL}|\mathcal{M}^{JL}|^2, \tag{6}$$

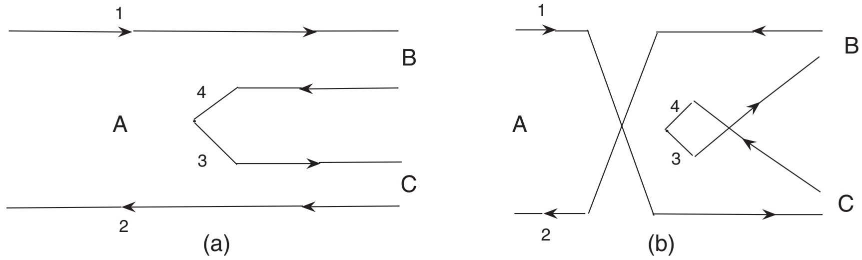

FIG. 1. The two possible diagrams contributing to $A \to BC$ in the $^3P_0$ model.

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

B. Mixed states

Heavy-light mesons are not charge conjugation eigenstates, and so mixing can occur among states with the same J^P that are forbidden for neutral states [45]. These occur between states with $J = L$ and $S = 1$ or 0 [45,46]. When $J = L = 1$, the corresponding mixture angle is $\theta = -54.7°$ or $\theta = 35.3°$ [45,46]. The two 1^+ charmed mesons are the mixtures of the $^3P_1$ and $^1P_1$ states:

$$\begin{pmatrix} |\frac{1}{2},1^+\rangle \\ |\frac{3}{2},1^+\rangle \end{pmatrix} = \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} |^3P_1\rangle \\ |^1P_1\rangle \end{pmatrix}. \tag{7}$$

In our calculation, the final states are related to $D(2420)/D(2430)$ and $D_{s_1}(2460)/D_{s_1}(2536)$, which are the 1^+ states in the D and D_s meson families, respectively. $D(2420)/D(2430)$ and $D_{s_1}(2460)/D_{s_1}(2536)$ are the mixing of the $^3P_1$ and $^1P_1$ states, which satisfy the above relation [see Eq. (7)]. Thus, the helicity amplitude can also be deduced as

$$\begin{pmatrix} \mathcal{M}^{JL}_{|A\rangle \to \frac{1}{2},1^+\rangle C} \\ \mathcal{M}^{JL}_{|A\rangle \to \frac{3}{2},1^+\rangle C} \end{pmatrix} = \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix} \times \begin{pmatrix} \mathcal{M}^{JL}_{|A\rangle \to ^3P_1\rangle C} \\ \mathcal{M}^{JL}_{|A\rangle \to ^1P_1\rangle C} \end{pmatrix}, \tag{8}$$

and the decay width can be expressed as

$$\Gamma\left(|A\rangle \to \frac{1}{2},1^+\rangle C\right) = \sum_{JL} \left| \cos\theta \mathcal{M}^{JL}_{|A\rangle \to ^3P_1\rangle C} - \sin\theta \mathcal{M}^{JL}_{|A\rangle \to ^1P_1\rangle C} \right|^2$$
$$\Gamma\left(|A\rangle \to \frac{3}{2},1^+\rangle C\right) = \sum_{JL} \left| \sin\theta \mathcal{M}^{JL}_{|A\rangle \to ^3P_1\rangle C} + \cos\theta \mathcal{M}^{JL}_{|A\rangle \to ^1P_1\rangle C} \right|^2. \tag{9}$$

III. NUMERICAL RESULTS

The input parameters in the $^3P_0$ model mainly include the light-quark pair ($q\bar{q}$) creation strength γ, the SHO wave function scale parameter R, and the masses of the mesons and the constituent quarks. The adopted masses of the mesons are listed in Table I, and $m_u = m_d = 0.22$ GeV, $m_s = 0.419$ GeV, and $m_c = 1.65$ GeV [47].

The scale parameter R has a significant influence on the shapes of the radial wave functions. The spatial integral in Eq. (3) is sensitive to the parameter R, and therefore the decay width based on the $^3P_0$ model is sensitive to the parameter R. Taking the decay $D_1^*(2680) \to D^{*+}\pi^-$ as an example, we plot the decay width vs the input parameter R in Figs. 2 and 3. From these two figures, we can easily see the dependence of the decay width on the input parameter R. If $R_{D^{*+}}$ and R_{π^-} are all fixed to be 2.5 GeV^{-1} (the lines with triangles in Figs. 2 and 3), the decay width of the $D_1^*(2680)$ changes several times with the value of $R_{D_1^*(2680)}$ from 1.5 to 3.0 GeV^{-1}. Similarly, the decay width changes two to three times, when $R_{D_1^*(2680)}$ and R_{π^-} (or $R_{D_1^*(2680)}$ and $R_{D^{*+}}$) are fixed to be 2.5 GeV^{-1} while the value of $R_{D^{*+}}$ (or R_{π^-}) changes.

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

States	M_{π^+}	M_{π^0}	M_{K^+}	M_{K^*}	M_η	$M_{\eta'}$	M_{D^+}	M_{D^0}
Mass (MeV)	139.57	134.9766	493.677	891.66	547.853	957.78	1869.6	1864.83
States	$M_{D_s^{*+}}$	$M_{D_s^+}$	$M_{D_0^*(2400)}$	$M_{D(2430)}$	$M_{D(2420)}$	$M_{D_{s0}^{*\pm}(2317)}$	M_ρ	M_ω
Mass (MeV)	2112.3	1968.47	2318	2427	2421.3	2317.8	770	782
States	$M_{D^{*+}}$	$M_{D^{*0}}$	$M_{D_2^*(2460)}$	$M_{D_{s_1}(2460)}$	$M_{D_{s_1}(2536)}$			
Mass (MeV)	2010.25	2006.96	2464.4	2459.5	2535.11			

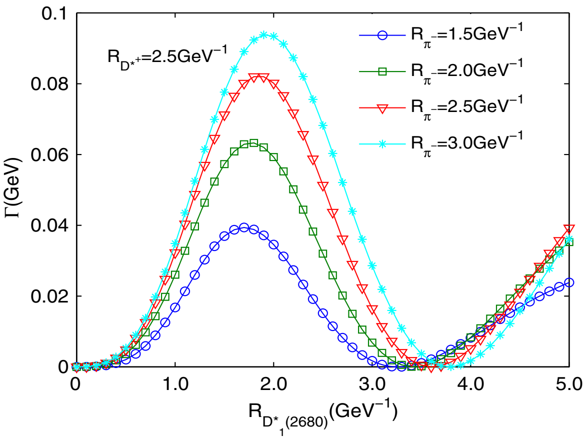

FIG. 2. The strong decay of $D_1^*(2680) \to D^{*+}\pi^-$ with $R_{D^{*+}} = 2.5\ \text{GeV}^{-1}$.

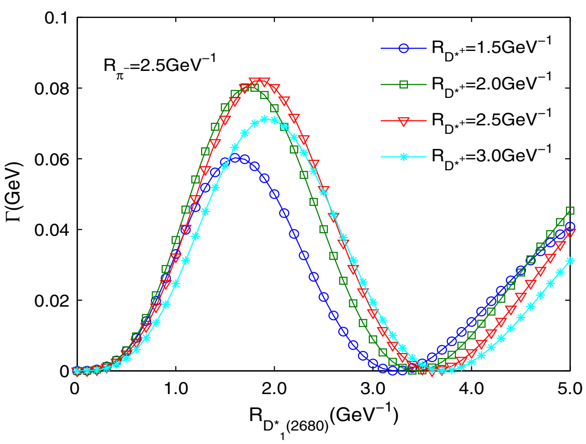

FIG. 3. The strong decay of $D_1^*(2680) \to D^{*+}\pi^-$ with $R_{\pi^-} = 2.5\ \text{GeV}^{-1}$.

Once the optimal values of γ and R are determined, the best predictions based on the $^3P_0$ decay model are expected. In Ref. [20], H. G. Blundel *et al.* carried 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 a value of $2.5\ \text{GeV}^{-1}$ was suggested to be the optimal value. As for the factor γ, it was also fitted at the same time according to experimental data, giving a fitted value of 6.25 [20]. More detailed analysis of the input parameters in the $^3P_0$ model can be found in Ref. [20]. Thus, we adopt the SHO wave function with common R of which the value is chosen to be $2.5\ \text{GeV}^{-1}$. Correspondingly, the γ value is chosen to be 6.25 for the creation of the u/d quark [20]. As for the strange quark pair ($s\bar{s}$), its creation strength can be related by $\gamma_{s\bar{s}} = \gamma/\sqrt{3}$ [16]. As a simple test, we also calculate the decay ratio $\frac{\Gamma(D_2^*(2460)\to D^+\pi^-)}{\Gamma(D_2^*(2460)\to D^{*+}\pi^-)}$ of the $D_2^*(2460)$ meson with the above parameters. The corresponding experimental data from the *BABAR* [48], CLEO [49,50], ARGUS [51], and ZEUS [52] collaborations are listed in Table II. The present calculation 2.29 based on the $^3P_0$ model agrees well with the average experimental value 2.35. Certainly, we can also predict the decay ratio $\frac{\Gamma(D_2^*(2460)\to D^+\pi^-)}{\Gamma(D_2^*(2460)\to D^{*+}\pi^-)}$ with some other methods such as the heavy-quark symmetry theory [53] and the heavy-meson effective theory [54]. With the assumption that the transition is dominated by $\bar{u} \to \pi^- d$, the heavy-quark symmetry theory gives the expression of the decay ratio $r = \frac{2}{3}(\frac{p}{p^*})^5 = 2.44$, where $p = 507$ MeV and $p^* = 391$ MeV are the c.m. 3-momenta in the decays $D_2^{*0} \to D^+\pi^-$ and $D_2^{*0} \to D^{*+}\pi^-$, respectively. In Ref. [54], the heavy-meson effective theory almost gives the same expression as that of the heavy-quark symmetry theory. Thus, our calculation is just a primary verification, which indicates that the $^3P_0$ model with the above parameters can reproduce the experimental data to some extent.

The numerical values of the decay widths and ratios of the charmed mesons $D_1^*(2680)$, $D_3^*(2760)$, and $D_2^*(3000)$ observed by the LHCb Collaboration are presented in Tables III and IV. It can be seen from Table III that the total width of $D_3^*(2760)$ is quite consistent with the experimental data of the LHCb Collaboration, which indicates $D_3^*(2760)$ is most probably the $1D\frac{5}{2}3^-$ meson. Besides the decay channel $D^+\pi^-$, the decay ratios in Table IV indicate that the other probable decay channels include $D^{*+}\pi^-$, $D^{*0}\pi^0$, $D_S^+K^-$, $D^{*0}\eta$, $D^0\eta$, and $D^+\rho$. As for $D_1^*(2680)$, the total width is predicted to be 208.91 MeV, which is about 21 MeV above the central value of the experimental data. Considering the total uncertainties of the experimental data, our result is also in agreement with it, which suggests that $D_1^*(2680)$ can be assigned as the $2S\frac{1}{2}1^-$ state. Besides $D^+\pi^-$ decay mode, its dominant decay channels also include $D^{*+}\pi^-$, $D^0\pi^0$, $D^{*0}\eta$ and $D^{*0}\pi^0$.

Experiments indicate $D_2^*(3000)$ is a 2^+ state charmed meson [1]. Thus, we study its decay behavior with the $1F\frac{5}{2}2^+$, $2P\frac{3}{2}2^+$, $2F\frac{5}{2}2^+$, and $3P\frac{3}{2}2^+$ assignments. As the candidate of $D_2^*(3000)$, the total width of $2F\frac{5}{2}2^+$ is predicted to be only 32.09 MeV, which is about 150 MeV smaller than the central value of the experimental data. Thus, it can be completely excluded from the probable

TABLE II. The experimental values and numerical result based on the $^3P_0$ decay model of the ratio $\frac{\Gamma(D_2^*(2460)\to D^+\pi^-)}{\Gamma(D_2^*(2460)\to D^{*+}\pi^-)}$.

BABAR [48]	CLEO [49]	CLEO [50]	ARGUS [51]	ZEUS [52]	3P0
$1.47 \pm 0.03 \pm 0.16$	$2.2 \pm 0.7 \pm 0.6$	2.3 ± 0.8	$3.0 \pm 1.1 \pm 1.5$	$2.8 \pm 0.8^{+0.5}_{-0.6}$	2.29

TABLE III. The strong decay widths of $D_1^*(2680)$, $D_3^*(2760)$, and $D_2^*(3000)$ with possible assignments. If the corresponding decay channel is forbidden, we mark it by "-." All values are in units of MeV.

	$D_1^*(2680)$	$D_3^*(2760)$	$D_2^*(3000)$			
	$2S\frac{1}{2}1^-$	$1D\frac{5}{2}3^-$	$1F\frac{5}{2}2^+$	$2P\frac{3}{2}2^+$	$2F\frac{5}{2}2^+$	$3P\frac{3}{2}2^+$
$D^{*+}\pi^-$	50.92	17.24	9.67	0.97	1.45	3.02
$D_S^{*+}K^-$	12.68	0.38	7.97	24.21	0.53	1.37
$D^{*0}\pi^0$	25.53	8.85	4.76	0.43	0.75	1.55
$D^{*0}\eta$	20.01	13.86	8.05	5.52	0.06	0.18
$D^{*0}\eta'$	⋯	⋯	7.75	16.58	0.87	2.10
$D^+\pi^-$	18.17	27.51	7.17	1.11	4.85	3.86
$D_S^+K^-$	22.68	2.52	10.35	11.17	0.08	0.09
$D^0\pi^0$	8.86	14.10	3.46	0.63	2.47	1.96
$D^0\eta$	16.37	5.13	7.88	0.37	1.13	1.04
$D^0\eta'$	⋯	⋯	15.82	9.84	0.46	0.33
$D^{*+}\rho$	⋯	⋯	15.70	100.10	0.41	7.23
$D_S^{*+}K^*$	⋯	⋯	3.27	34.87	1.09	5.74
$D^{*0}\rho$	⋯	⋯	7.85	50.10	0.19	3.51
$D^{*0}\omega$	⋯	⋯	7.87	50.11	0.23	3.82
$D^+\rho$	15.97	1.18	17.44	12.51	0.09	0.28
$D_S^+K^*$	⋯	⋯	8.01	28.72	1.31	3.39
$D^0\rho$	9.22	0.66	8.63	6.00	0.06	0.17
$D^0\omega$	6.28	0.51	8.82	6.49	0.04	0.12
$D(2420)\pi^0$	2.21	0.01	5.88	5.13	0.22	0.02
$D(2420)\eta$	⋯	⋯	9.31	1.49	0.58	0.50
$D(2430)\pi^0$	0.01	0	0.82	0.79	0.01	1.28
$D(2430)\eta$	⋯	⋯	1.49	1.99	1.32	0.69
$D_0^*(2400)\pi^0$	⋯	⋯	0	0	0	0
$D_0^*(2400)\eta$	⋯	⋯	0	0	0	0
$D_S(2460)K^-$	⋯	⋯	1.61	3.45	0.52	0.34
$D_S(2536)K^-$	⋯	⋯	10.14	1.39	2.78	1.47
$D_2^{*+}(2460)\pi^-$	⋯	0.65	16.73	39.69	5.93	10.46
$D_2^{*0}(2460)\pi^0$	⋯	0.32	8.38	19.88	2.97	5.24
$D_2^{*0}(2460)\eta$	⋯	4.49	5.22	11.82	1.69	2.81
$D_{s_0}^{*+}(2317)K^-$	⋯	⋯	0	0	0	0
Total width	208.91	97.41	220.05	442.36	32.09	62.57

assignments. In addition, it can be seen from Table III that the width of $2P\frac{3}{2}2^+$ is about 120 MeV above the upper limit of the experimental data. Thus, it is also impossible for $D_2^*(3000)$ to be the $2P\frac{3}{2}2^+$ state. In addition, if $D_2^*(3000)$ is the $3P\frac{3}{2}2^+$ state, its predicted cross section is 62.57 MeV, which is smaller by about 123 MeV than the central value of the experimental data. Although the calculated total width is just above the lower limit of the experimental data, its branching ratio of the $D^+\pi^-$ decay channel is very small. Thus, the $3P\frac{3}{2}2^+$ state is also less likely to be the assignment of $D_2^*(3000)$.

Although the predicted value of the total width of $1F\frac{5}{2}2^+$ is somewhat bigger than the central value of experimental data, it is within the error range. This indicates $1F\frac{5}{2}2^+$ is most likely to be the assignment of $D_2^*(3000)$. However, this determination needs to be further verified according to experiments in the future. We can see from Table IV that no decay channel show an obvious advantage over another, while the $D_2^*(3000)$ resonance is observed by the LHCb Collaboration in the $D^+\pi^-$ channel. One possible explanation about this behavior is that the production cross section of $D_2^*(3000)$ is so large that the fairly small branching ratio is still observable. If the decay ratios of different decay channels are measured in experiments in the future, this determination can be exactly verified. At present, we can temporarily assign the $D_2^*(3000)$ charmed meson as the $1F\frac{5}{2}2^+$ state, while $2F\frac{5}{2}2^+$, $2P\frac{3}{2}2^+$, and $3P\frac{3}{2}2^+$ states can be excluded temporarily. Nevertheless, these decay predictions for the $2F\frac{5}{2}2^+$, $2P\frac{3}{2}2^+$, and $3P\frac{3}{2}2^+$ states are valuable in further searches for the partners of $D_2^*(3000)$. For $2P\frac{3}{2}2^+$ as an example, its decay ratios of $D^{*+}\rho$, $D^{*0}\rho$, and $D^{*0}\omega$ are much more obvious than the other decay modes, which can be used as a valuable judgement of this meson.

TABLE IV. The decay ratios of the partial decay width Γ_p/Γ_T of $D_1^*(2680)$, $D_3^*(2760)$, and $D_2^*(3000)$ with possible assignments.

	$D_1^*(2680)$	$D_3^*(2760)$	$D_2^*(3000)$			
	$2S\frac{1}{2}1^-$	$1D\frac{5}{2}3^-$	$1F\frac{5}{2}2^+$	$2P\frac{3}{2}2^+$	$2F\frac{5}{2}2^+$	$3P\frac{3}{2}2^+$
$D^{*+}\pi^-$	0.24	0.18	0.04	0.002	0.05	0.05
$D_S^{*+}K^-$	0.06	0.004	0.04	0.05	0.02	0.02
$D^{*0}\pi^0$	0.12	0.09	0.02	0.001	0.02	0.02
$D^{*0}\eta$	0.10	0.14	0.04	0.01	0.002	0.003
$D^{*0}\eta'$	...	...	0.04	0.04	0.03	0.03
$D^+\pi^-$	0.09	0.28	0.03	0.003	0.15	0.06
$D_S^+K^-$	0.11	0.03	0.05	0.03	0.003	0.001
$D^0\pi^0$	0.04	0.14	0.02	0.001	0.08	0.03
$D^0\eta$	0.08	0.05	0.04	0.0008	0.04	0.02
$D^0\eta'$	...	...	0.07	0.02	0.01	0.005
$D^{*+}\rho$	...	...	0.07	0.23	0.01	0.12
$D_S^{*+}K^*$	...	...	0.01	0.08	0.03	0.09
$D^{*0}\rho$	...	...	0.04	0.11	0.006	0.06
$D^{*0}\omega$	...	...	0.04	0.11	0.007	0.06
$D^+\rho$	0.08	0.01	0.08	0.03	0.003	0.004
$D_S^+K^*$	...	...	0.04	0.06	0.04	0.05
$D^0\rho$	0.04	0.007	0.04	0.01	0.002	0.003
$D^0\omega$	0.03	0.005	0.04	0.01	0.001	0.002
$D(2420)\pi^0$	0.01	0.0001	0.03	0.01	0.007	0.0003
$D(2420)\eta$	...	...	0.04	0.003	0.02	0.008
$D(2430)\pi^0$	0	0	0.004	0.002	0.0003	0.02
$D(2430)\eta$	...	...	0.007	0.005	0.04	0.01
$D_0^*(2400)\pi^0$	...	...	0	0	0	0
$D_0^*(2400)\eta$	...	...	0	0	0	0
$D_S(2460)K^-$	...	...	0.007	0.008	0.02	0.005
$D_S(2536)K^-$	...	...	0.05	0.003	0.09	0.02
$D_2^{*+}(2460)\pi^-$	...	0.007	0.08	0.08	0.18	0.17
$D_2^{*0}(2460)\pi^0$	...	0.003	0.04	0.04	0.09	0.08
$D_2^{*0}(2460)\eta$	...	0.05	0.02	0.03	0.05	0.04
$D_{s_0}^{*+}(2317)K^-$	...	...	0	0	0	0

In Ref. [12], the decay behavior of $D_2^*(3000)$ was also analyzed using the $^3P_0$ decay model. The $3P\frac{3}{2}2^+$ state was predicted as the most possible assignment of the $D_2^*(3000)$ in their work, while the assignment of the $2F\frac{5}{2}2^+$ charmed meson could not be fully excluded. The primary difference between our analysis and theirs in Ref. [12] about the $D_2^*(3000)$ charmed meson is that they employed the SHO wave function with the effective scale parameter R [12], while we adopt the common valve of the scale parameter R which was calculated by fitting the experimental data in Ref. [20]. Thus, the difference between the results in Ref. [12] and ours is mainly due to the influence of the input parameter R, which needs further confirmation by future experimental data from LHCb and the forthcoming Belle II.

IV. CONCLUSION

In this article, we carry out an analysis of the newly observed charmed mesons $D_1^*(2680)$, $D_3^*(2760)$, and $D_2^*(3000)$ reported by LHCb Collaboration with the $^3P_0$ decay model. Our analysis supports $D_1^*(2680)$ and $D_3^*(2760)$ to be the $2S\frac{1}{2}1^-$ and $1D\frac{5}{2}3^+$ assignments separately. In addition, the partial width and ratios are obtained, further shedding light on the nature of these two mesons. The total width predicted by the $^3P_0$ decay model supports the $1F\frac{5}{2}2^+$ for the $D_2^*(3000)$ meson, which needs further confirmation from the measured partial decay ratios. When investigating $D_2^*(3000)$, we have also analyzed the decay behavior of the $2P\frac{3}{2}2^+$, $2F\frac{5}{2}2^+$, and $2P\frac{3}{2}2^+$ states, which can be used as valuable judgements for the assignments of the newly observed charmed mesons in the future.

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