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Strong decays of the newly observed $D(2550)$, $D(2600)$, $D(2750)$, and $D(2760)$

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The strong decay properties of the newly observed $D(2550)$, $D(2600)$, $D(2750)$, and $D(2760)$ are studied in a constituent quark model. It is predicted that the $D(2760)$ and $D(2750)$ seem to be two overlapping resonances. The $D(2760)$ could be identified as the 1^3D_3 with $J^P = 3^-$, while the $D(2750)$ is most likely to be the high-mass mixed state $|1D_2{}'\rangle_H$ ($J^P = 2^-$) via the 1^1D_2-1^3D_2 mixing. The $D(2600)$ favors the low-mass mixed state $|(SD)_1\rangle_L$ ($J^P = 1^-$) via the 1^3D_1-2^3S_1 mixing. The $D(2550)$ as the 2^1S_0 assignment bears controversies for its too-broad width given in experiments.

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I. INTRODUCTION

Recently, four new charmed mesons, the $D(2550)$, $D(2600)$, $D(2750)$, and $D(2760)$, were observed by the *BABAR* Collaboration [1]. The $D(2600)^0$ and $D(2760)^0$ with neutral charge were first found in the $D^+\pi^-$ channel. Then, their isospin partners $D(2600)^+$ and $D(2760)^+$ were observed in $D^0\pi^+$, as well. Further analysis of the $D^{*+}\pi^-$ invariant mass spectrum confirmed the $D(2600)^0$. Furthermore, two additional new charmed mesons, the $D(2550)^0$ and $D(2750)^0$, were found in the $D^{*+}\pi^-$ channel. The measured branching ratio fractions are

$$\frac{D(2600)^0 \to D^+\pi^-}{D(2600)^0 \to D^{*+}\pi^-} = 0.32 \pm 0.02_{\text{stat}} \pm 0.09_{\text{syst}}, \quad (1)$$

$$\frac{D(2760)^0 \to D^+\pi^-}{D(2750)^0 \to D^{*+}\pi^-} = 0.42 \pm 0.05_{\text{stat}} \pm 0.11_{\text{syst}}. \quad (2)$$

The other observed results are summarized in Table I. To determine the spin-parity J^P of these newly observed charmed mesons, the *BABAR* Collaboration also analyzed their helicity distributions.

These newly observed charmed mesons make great progress in the establishment of the charmed meson spectroscopy. From the Particle Data Group book [2], it is seen that only six low-lying states, the D, D^*, $D_0(2400)$, $D_1(2430)$, $D_1(2420)$, and $D_2(2460)$, have been established. The higher excitations, $2S$ and $1D$ waves, are still absent. Thus, the find of the $D(2550)$, $D(2600)$, $D(2750)$, and $D(2760)$ provides us a good opportunity to establish the missing $2S$ and $1D$ states.

The $D(2550)^0$ may be identified as the radial excitation of the D^0 (i.e., 2^1S_0) [1], for its quark-model-predicted mass $\sim$2.58 GeV [3–5], helicity distribution ($\propto \cos^2\theta_H$) [1], and dominated decay mode $D^*\pi$ consist with the observations.

The $D(2600)$ is observed in both the $D\pi$ and $D^*\pi$ channels; thus, its possible J^P's are 1^- and 3^- in the $2S$ and $1D$ states. The *BABAR* analysis of helicity distribution ($\propto \sin^2\theta_H$) [1] also indicates that the $D(2600)$ may be 1^- or 3^- assignments [3]. The typical quark-model-predicted mass of the 1^3D_3 is $\sim$2.83 GeV [3,4], which is much larger than that of the $D(2600)$. Thus, the $D(2600)$ as the $J^P = 3^-$ assignment should be excluded.

The $D(2750)$ and $D(2760)$ may be good candidates of D-wave states, for their masses are close to those of D waves predicted in various quark models [3–5]. Since the $D(2750)^0$ is observed in the $D^{*+}\pi^-$ channel, its possible J^P's are 1^-, 2^-, and 3^-. The helicity distribution of the $J^P = 1^-$ and 3^- assignments is a simple $\sin^2\theta_H$ distribution [3], which is inconsistent with the *BABAR* observation that the $D(2750)^0$ does not show a simple helicity distribution [1]. Although the mass of the $D(2760)$ is very close to that of the $D(2750)$, they may be two different states, for their mass and width values differ by 2.6σ and 1.5σ, respectively [1]. The observation of the $D(2760)$ in the $D\pi$ channel indicates it may be a candidate of the 1^3D_1 or 1^3D_3.

To distinguish the different candidates for these newly observed charmed mesons, in this work, we study their strong decay properties in a constituent quark model, which has been developed and successfully used to deal with the strong decays of heavy-light mesons and charmed baryons [6–8]. Very recently, the strong decays of the $D(2550)$, $D(2600)$, and $D(2760)$ were studied by Liu *et al.* in a $^3P_0$ model [9]. For the $D(2550)$ and $D(2600)$, the main $^3P_0$-model predictions are compatible with our quark-model predictions. In [9], two candidates are suggested for the $D(2760)$. They are the mixed state via 2^3S_1-1^3D_1 mixing and the 1^3D_3, respectively. In our predictions, only the 1^3D_3 is the favored assignment to the $D(2760)$.

The paper is organized as follows. In the subsequent section, a brief review of the model is given. The numerical results are presented and discussed in Sec. III. Finally, a summary is given in Sec. IV.

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TABLE I. Summary of the experimental results.

Resonance	Mass	Width	Decay channel
$D(2550)^0$	$2539.4 \pm 4.5 \pm 6.8$	$130 \pm 12 \pm 13$	$D^{*+}\pi^-$
$D(2600)^0$	$2608.7 \pm 2.4 \pm 2.5$	$93 \pm 6 \pm 13$	$D^+\pi^-$, $D^{*+}\pi^-$
$D(2760)^0$	$2763.3 \pm 2.3 \pm 2.3$	$60.9 \pm 5.1 \pm 3.6$	$D^+\pi^-$
$D(2750)^0$	$2752.4 \pm 1.7 \pm 2.7$	$71 \pm 6 \pm 11$	$D^{*+}\pi^-$
$D(2600)^+$	$2621.3 \pm 3.7 \pm 4.2$	93	$D^0\pi^+$
$D(2760)^+$	$2769.7 \pm 3.8 \pm 1.5$	60.9	$D^0\pi^+$

II. THE MODEL

In the chiral quark model [10], the low-energy quark-pseudoscalar-meson interactions in the SU(3)-flavor basis are described by the effective Lagrangian [11–13]

$$\mathcal{L}_{Pqq} = \sum_j \frac{1}{f_m}\bar{\psi}_j\gamma^j_\mu\gamma^j_5\psi_j\partial^\mu\phi_m, \qquad (3)$$

where ψ_j represents the jth quark field in the hadron, ϕ_m is the pseudoscalar-meson field, and f_m is the pseudoscalar-meson decay constant.

The effective Lagrangian for quark-vector-meson interactions in the SU(3)-flavor basis is [14–16]

$$\mathcal{L}_{Vqq} = \sum_j \bar{\psi}_j\left(a\gamma^j_\mu + \frac{ib}{2m_j}\sigma_{\mu\nu}q^\nu\right)V^\mu\psi_j, \qquad (4)$$

where V^μ represents the vector-meson field with four-vector moment q. The parameters a and b denote the vector and tensor coupling strength, respectively.

To match the nonrelativistic harmonic-oscillator wave function of the heavy-light meson $\psi^n_{lm} = R_{nl}Y_{lm}$ adopted in the calculation of the strong decay amplitudes, we should provide the quark-pseudoscalar and quark-vector-meson coupling operators in a nonrelativistic form. Considering light-meson emission in heavy-light-meson strong decays, the effective quark-pseudoscalar-meson coupling operator in the center-of-mass system of the initial meson is [6,7,11–13]

$$H_m = \sum_j\left[A\boldsymbol{\sigma}_j\cdot\mathbf{q} + \frac{\omega_m}{2\mu_q}\boldsymbol{\sigma}_j\cdot\mathbf{p}_j\right]I_j\varphi_m, \qquad (5)$$

where $A \equiv -(1 + \frac{\omega_m}{E_f+M_f})$. In a case when a light-vector meson is emitted, the transition operators for producing a transversely or longitudinally polarized vector meson are as follows [14–16]:

$$H^T_m = \sum_j\left\{i\frac{b'}{2m_q}\boldsymbol{\sigma}_j\cdot(\mathbf{q}\times\epsilon) + \frac{a}{2\mu_q}\mathbf{p}_j\cdot\epsilon\right\}I_j\varphi_m \qquad (6)$$

and

$$H^L_m = \sum_j \frac{aM_v}{|\mathbf{q}|}I_j\varphi_m. \qquad (7)$$

In the above three equations, $\mathbf{q}$ and ω_m are the three-vector momentum and energy of the final-state light meson, respectively. $\mathbf{p}_j$ is the internal momentum operator of the jth quark in the heavy-light-meson rest frame. $\boldsymbol{\sigma}_j$ is the spin operator on the jth quark of the heavy-light system, and μ_q is a reduced mass given by $1/\mu_q = 1/m_j + 1/m'_j$, with m_j and m'_j for the masses of the jth quark in the initial and final mesons, respectively. Here, the jth quark is referred to as the active quark involved at the quark-meson coupling vertex. M_v is the mass of the emitted vector meson. The plane-wave part of the emitted light meson is $\varphi_m = e^{-i\mathbf{q}\cdot\mathbf{r}_j}$, and I_j is the flavor operator defined for the transitions in the SU(3)-flavor space [6–8,12–16]. The parameter b' in Eq. (6) is defined as $b' \equiv b - a$.

For a light-pseudoscalar-meson emission in a heavy-light-meson strong decay, the partial decay width can be calculated with

$$\Gamma = \left(\frac{\delta}{f_m}\right)^2\frac{(E_f + M_f)|\mathbf{q}|}{4\pi M_i(2J_i + 1)}\sum_{J_{iz},J_{fz}}|\mathcal{M}_{J_{iz},J_{fz}}|^2, \qquad (8)$$

where $\mathcal{M}_{J_{iz},J_{fz}}$ is the transition amplitude, and J_{iz} and J_{fz} stand for the third components of the total angular momenta of the initial and final heavy-light mesons, respectively. δ as a global parameter accounts for the strength of the quark-meson couplings. In the heavy-light-meson transitions, the flavor symmetry does not hold any more. Treating the light-pseudoscalar meson as a chiral field while treating the heavy-light mesons as a constituent quark system is an approximation. This will bring uncertainties to coupling vertices and form factors. The parameter δ is introduced to take into account such an effect. It has been determined in our previous study of the strong decays of the charmed baryons and heavy-light mesons [7,8]. Here, we fix its value the same as that in Refs. [7,8], i.e., $\delta = 0.557$.

In the calculation, the standard quark-model parameters are adopted. Namely, we set $m_u = m_d = 330$ MeV, $m_s = 450$ MeV, and $m_c = 1700$ MeV for the constituent quark masses. The harmonic-oscillator parameter β in the wave function $\psi^n_{lm} = R_{nl}Y_{lm}$ is taken as $\beta = 0.40$ GeV. The decay constants for the π, K, and η mesons are taken as $f_\pi = 132$ MeV and $f_K = f_\eta = 160$ MeV, respectively. For the quark-vector-meson coupling strength, which still suffers relatively large uncertainties, we adopt the values extracted from vector-meson photoproduction, i.e.,

$a \simeq -3$ and $b' \simeq 5$ [14–18]. The masses of the mesons used in the calculations are adopted from the Particle Data Group [2]. With these parameters, the strong decay properties of the well-known heavy-light mesons and charmed baryons have been described reasonably [6–8].

Our approach is similar to Pierro and Eichten's model [4] in the calculation of the strong decay. Both of the models adopt the chiral quark-pseudoscalar-meson interactions in the quark-model framework. On the other hand, there are obvious differences between these two models. Our model is a nonrelativistic quark model, where the nonrelativistic harmonic-oscillator wave function of the heavy-light meson is adopted, with which the decay amplitudes can be presented analytically. Pierro and Eichten's model is a relativistic quark model, in which the total wave function is obtained by solving the relativistic Dirac equation for the heavy-light system.

III. RESULTS AND DISCUSSIONS

A. *D*(2550)

The $D(2550)^0$ is observed in the $D^{*+}\pi^-$ channel with a broad width $\Gamma \simeq 130$ MeV [1]. The decay modes, the *BABAR* analysis of angle distributions, and the predicted mass of various theoretical models [3–5] indicate that it should be classified as the 2^1S_0. If the $D(2550)$ is considered as the 2^1S_0 assignment, it has two decay modes: the $D^*\pi$ and $D_0(2400)\pi$. The calculated partial decay widths and total width are listed in Table II, which shows that the predicted width $\Gamma \simeq 22$ MeV is too narrow to compare with the data. The $^3P_0$-model [9] and relativistic quark-model [4] calculations also predicted that the 2^1S_0 is a narrow width state. The width of the $D(2550)$ may be overestimated if it is the 2^1S_0 assignment, indeed. To confirm the $D(2550)$, further experimental study is needed.

B. *D*(2600)

The $D(2600)$ is observed in both the $D\pi$ and $D^*\pi$ channels [1]. Our analysis in Sec. I suggests its quantum number should be $J^P = 1^-$. There are two states, the 2^3S_1 and 1^3D_1, with $J^P = 1^-$ in the S and D waves. The quark-model-predicted masses of the 2^3S_1 and 1^3D_1 are around 2.6 and 2.76 GeV, respectively [3,4]. The 2^3S_1-1^3D_1 mixing is also possible, for their comparable masses.

TABLE II. The partial decay widths and total width (MeV) for the $D(2550)$ as the 2^1S_0 candidate, where the mass of the $D_0(2400)$ is set with 2338 MeV [1].

	$D^*\pi$	$D_0(2400)\pi$	Total	$\Gamma[D_0(2400)\pi]/\Gamma(D^*\pi)$
2^1S_0	7.2	14.9	22.1	2.1

First, we consider the $D(2600)$ as the 2^3S_1 assignment. The decay modes and corresponding partial decay widths are listed in Table III. The strong decays of this state are dominated by the $D_1(2430)\pi$ and $D^*\pi$. The total decay width and the partial decay width ratio between the $D\pi$ and $D^*\pi$ channels are

$$\Gamma \simeq 42 \text{ MeV}, \qquad \frac{\Gamma(D\pi)}{\Gamma(D^*\pi)} \simeq 0.2. \tag{9}$$

It shows that the predicted width $\Gamma \simeq 42$ MeV is too narrow to compare with the data, although the ratio $\Gamma(D\pi)/\Gamma(D^*\pi)$ is compatible with that of measurement. Thus, with the pure 2^3S_1, we cannot well explain observations of the $D(2600)$. Our conclusion is consistent with that of the $^3P_0$ model [9]. Furthermore, the relativistic quark-model calculations also indicate that the 2^3S_1 is a narrow width state [with the determined value $g_A^8 = 0.53 \sim 0.82$, the predicted decay width is $\Gamma \simeq (23 \sim 57)$ MeV] [4]. The strong decay properties of the 2^3S_1 in D mesons were studied by Colangelo *et al.*, as well, with the heavy quark effective theory [19]. In their framework, when the $D(2600)$ is considered as the 2^3S_1 assignment, its decay width, $\Gamma \simeq (128 \pm 61)$ MeV, is compatible with that of measurement, while the predicted ratio, $\Gamma(D\pi)/\Gamma(D^*\pi) \simeq 0.82$, is obviously larger than the measured value $\Gamma(D\pi)/\Gamma(D^*\pi) = 0.32 \pm 0.02 \pm 0.09$.

Since the $D(2600)$ can not be well-explained with the pure 2^3S_1 assignment, we consider the possibility of the $D(2600)$ as the 1^3D_1; the predicted partial widths and total width are shown in Table III, as well. It is seen that the predicted width $\Gamma \simeq 250$ MeV is about a factor 3 larger than the data, while the predicted ratio $\Gamma(D\pi)/\Gamma(D^*\pi) \simeq 3.1$ is also inconsistent with the data. Thus, the possibility of the $D(2600)$ as the pure 1^3D_1 is excluded as well.

Finally, we consider the possibility of the $D(2600)$ as a mixed state via the 2^3S_1-1^3D_1 mixing, for which the physical states can be expressed as

$$|(SD)_1\rangle_L = +\cos(\phi)|2^3S_1\rangle + \sin(\phi)|1^3D_1\rangle, \tag{10}$$

$$|(SD)_1'\rangle_H = -\sin(\phi)|2^3S_1\rangle + \cos(\phi)|1^3D_1\rangle, \tag{11}$$

where the physical partner in the mixing is included. Assuming that the low-mass state $|(SD)_1\rangle_L$ corresponds to the $D(2600)$, we plot the decay width of $|(SD)_1\rangle_L$ as a

TABLE III. The partial decay widths and total width (MeV) for the $D(2600)$ as the 2^3S_1 and 1^3D_1 candidates, respectively.

	$D\pi$	D_sK	$D\eta$	$D^*\pi$	$D^*\eta$	D_s^*K	$D_1(2430)\pi$	$D_1(2420)\pi$	$D_2(2460)\pi$	Total
2^3S_1	1.9	2.4	2.7	9.9	1.3	0.02	23.3	0.01	0.002	41.5
1^3D_1	119.9	17.9	23.1	39.0	1.8	0.03	7.9	43.6	0.00	253.2

function of the mixing angle ϕ in Fig. 1. It is shown that when we take the mixing angle $\phi \simeq -(36 \pm 6)^\circ$, the measured decay width

$$\Gamma \simeq (93 \pm 6 \pm 13)\ \mathrm{MeV} \tag{12}$$

can be well-explained. The predicted partial width ratio is

$$\frac{\Gamma(D\pi)}{\Gamma(D^*\pi)} \simeq 0.63 \pm 0.21, \tag{13}$$

which is compatible with the measurement ratio $\Gamma(D\pi)/\Gamma(D^*\pi) = 0.32 \pm 0.02 \pm 0.09$, within its uncertainties. Thus, the $D(2600)$ may be identified as the mixed state $|(SD)_1\rangle_L$. Its main strong decay channels are the $D^*\pi$, $D\pi$, $D_1(2420)\pi$, and $D_1(2430)\pi$.

Recently, the $D(2600)$ as an admixture of 2^3S_1 and 1^3D_1 has also been suggested by Liu *et al.* [9]. They adopted a different mixing scheme from ours. In our mixing scheme, their predicted mixing angle, $-86^\circ \le \phi \le -51^\circ$, is roughly comparable with our prediction $\phi \simeq -(36 \pm 6)^\circ$. However, we have noted that the ratio $\Gamma(D\pi)/\Gamma(D^*\pi) \simeq 2.13 \sim 2.86$ predicted by Liu *et al.* [9] is too large to compare with the observation $\Gamma(D\pi)/\Gamma(D^*\pi) = 0.32 \pm 0.02 \pm 0.09$.

It should be mentioned that in our previous work [6], we have discussed the 2^3S_1-1^3D_1 mixing in the study of the D_{sJ} mesons. We predicted that the $D_s(2710)$ is most likely to be the low-mass state $|(SD)_1\rangle_L$ with a mixing angle $\phi \simeq -(54 \pm 7)^\circ$; similar predictions also were obtained in [20,21]. This mixing angle is close to that of the $D(2600)$. If both the $D(2600)$ and $D_s(2710)$ correspond to the mixed state $|(SD)_1\rangle_L$, indeed, the 2^3S_1-1^3D_1 mixing might be a common character in the heavy-light mesons. The future search for the $|(SD)_1\rangle_L$ in B and B_s spectroscopies will clarify this assumption. Finally, we should point out that there still exist controversies in the $D_s(2710)$ about the extent of the mixing. The $D_s(2710)$ is also interpreted as the first radial excitation of the D_s^* (i.e., 2^3S_1) [19], which just corresponds to the limit of zero mixing of the $|(SD)_1\rangle_L$. A combined study of the $D(2600)$ and $D_s(2710)$ may be helpful to clarify these controversies.

Following this mixing scheme, one can examine the high-mass partner $|(SD)'_1\rangle_H$. Supposing that the mass of the $|(SD)'_1\rangle_H$ is in the range of $(2.65 \sim 2.80)$ GeV, in Fig. 2, we plot the decay width as a function of the mass with the mixing angle $\phi = -36^\circ$ fixed by the $D(2600)$. It is shown that the $|(SD)'_1\rangle_H$ should be a broad state with a width of $\Gamma = (300 \sim 550)$ MeV. Its decay modes are dominated by the $D\pi$ and $D^*\pi$; with the increasing mass, the $D_1(2420)\pi$ and $D_1(2430)\pi$ decay channels become dominant as well.

C. *D*(2760)

The $D(2760)$ is a good candidate of D waves [1] in which the $J^P = 2^-$ states [i.e., the ${}^1D_2(2^-)$ and ${}^3D_2(2^-)$] are excluded for the observation of the $D\pi$ decay mode. Thus, only the $1^3D_1(1^-)$ and $1^3D_3(3^-)$ are possible candidates for the $D(2760)$. Assuming the $D(2760)$ as a candidate of the $1^3D_1(1^-)$ or $1^3D_3(3^-)$, it can decay into $D\pi$, D_sK, $D\eta$, $D^*\pi$, $D^*\eta$, D_s^*K, $D_1(2430)\pi$, $D_1(2420)\pi$, $D_2(2460)\pi$, $D\omega$, and $D\rho$. We calculate these partial decay widths and list the results in Table IV.

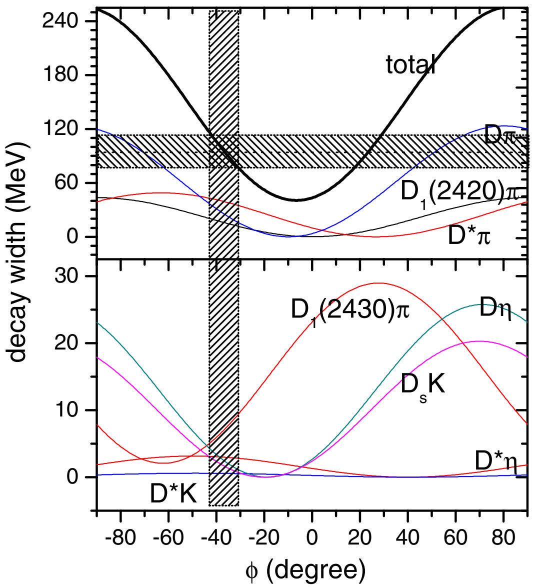

FIG. 1 (color online). The partial decay widths and total decay width of the $|(SD)_1\rangle_L$, with a mass of 2609 MeV as a function of mixing angle ϕ. The tiny contributions of the $D_2(2460)\pi$ and D_s^*K are not shown in the figure.

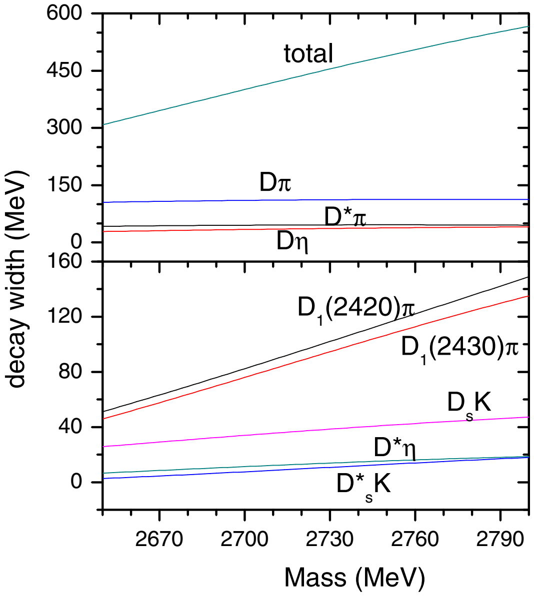

FIG. 2 (color online). The partial decay widths and total width of the $|(SD)'_1\rangle_H$ as a function of mass, with the mixing angle $\phi = -36^\circ$. The tiny contributions of the $D\rho$, $D\omega$, and $D_2(2460)\pi$ are not shown in the figure.

TABLE IV. The decay partial decay widths and total width (MeV) for the $D(2760)$ as the 1^3D_3 and 1^3D_1 candidates, respectively.

	$D\pi$	D_sK	$D\eta$	$D^*\pi$	$D^*\eta$	D_s^*K	$D_1(2430)\pi$	$D_1(2420)\pi$	$D_2(2460)\pi$	$D\omega$	$D\rho$	Total
1^3D_3	32.5	2.1	2.6	20.6	0.7	0.3	5.2	1.7	1.7	0.1	0.4	67.9
1^3D_1	156.8	45.8	43.2	64.9	12.9	10.3	29.4	187.1	2.7	0.05	0.2	553.3

As the assignment of the $1^3D_1(1^-)$, from Table IV it is seen that the strong decays of the $D(2760)$ are dominated by the $D\pi$ and $D_1(2420)\pi$. The dominant roles of the $D\pi$ and $D_1(2420)\pi$ decay modes in the strong decays of the $1^3D_1(1^-)$ were also predicted in [4,22]. It is found that the total decay width, $\Gamma \simeq 550$ MeV, is too broad to compare with the data. Thus, the $D(2760)$ as the $1^3D_1(1^-)$ assignment should be excluded.

As the assignment of the $1^3D_3(3^-)$, the $D(2760)$ has two dominant decay channels, the $D\pi$ and $D^*\pi$, which is compatible with the predictions in [4,22]. The other decay modes, such as the $D_1(2430)\pi$, D_sK, and $D\eta$, have sizeable contributions. The decay width and partial decay width ratio are

$$\Gamma \simeq 68 \text{ MeV}, \qquad \frac{\Gamma(D\pi)}{\Gamma(D^*\pi)} \simeq 1.58. \tag{14}$$

Our predicted ratio is compatible with the ratio $\Gamma(D\pi)/\Gamma(D^*\pi) \simeq 1.36$ predicted in [4], while our predicted width $\Gamma \simeq 68$ MeV is in agreement with the data $\Gamma \simeq 60.9$ MeV. Furthermore, the typical quark-model-predicted mass of the $1^3D_3(3^-)$ is ~ 2.8 GeV [3,4], which is close to the mass of the $D(2760)$. Thus, the $D(2760)$ is most likely to be the $1^3D_3(3^-)$ assignment.

Finally, it should be mentioned that in Ref. [9], two possible assignments to the $D(2760)$ are suggested, which are the $1^3D_3(3^-)$ and the high-mass partner $|(SD)_1'\rangle_H$ via the 2^3S_1-1^3D_1 mixing, respectively. Our calculations exclude the $D(2760)$ as the $|(SD)_1'\rangle_H$ assignment. It is shown in Fig. 2 that as the assignment of the $|(SD)_1'\rangle_H$, the $D(2760)$ should be a broad resonance with a width of $\Gamma \simeq 500$ MeV. The $D\pi$, $D_1(2420)\pi$, $D_1(2430)\pi$, $D^*\pi$, and $D\eta$ are the main decay modes. For the too-broad decay width to compare with the data, the $D(2760)$ as a mixed state of 2^3S_1-1^3D_1 is excluded. The differences in the predicted width of the $|(SD)_1'\rangle_H$ between our model and that in Ref. [9] mainly come from the different predictions of the strong decay properties of the 1^3D_1. In our model, the decays of the $|(SD)_1'\rangle_H$ are dominated by both the $D\pi$ and $D_1(2420)\pi$ channels. We find that the main contributor to the partial widths of the $D\pi$ and $D_1(2420)\pi$ is the 1^3D_1, whose decay modes are dominated by the $D\pi$ and $D_1(2420)\pi$. However, in Ref. [9], the strong decays of the 1^3D_1 are predicted to be dominated by the $D_1(2430)\pi$. It should be pointed out that with the $^3P_0$ model, Close and Swanson predicted that the dominant decay modes of the 1^3D_1 are the $D_1(2420)\pi$ and $D\pi$ [22]. In fact, it is easy to distinguish the two different assignments to the $D(2760)$ in experiments by measuring the ratio $\Gamma(D^*\pi)/\Gamma(D\pi)$ for its very different value in the two cases.

D. *D*(2750)

The $D(2750)^0$ is observed in the $D^{*+}\pi^-$. Although its mass is very close to that of the $D(2760)$, they might be two different resonances due to the following three reasons: (i) If they are the same charmed meson state, according to our analysis in Sec. III C, they should be the 1^3D_3 assignment. However, the simple helicity distribution of the 1^3D_3, $\propto \sin^2\theta_H$ [3], is inconsistent with the observation that the $D(2750)^0$ does not show a simple helicity distribution [1]; (ii) Furthermore, the predicted ratio $\Gamma(D\pi)/\Gamma(D^*\pi) \simeq 1.58$ is inconsistent with the measured value $\Gamma(D\pi)/\Gamma(D^*\pi) \simeq 0.42$ if they are the same state; (iii) Their measured mass and width values differ by 2.6σ and 1.5σ, respectively [1]. The recent study of the strong decays of the $D(2750)$ and $D(2760)$ with the heavy quark effective theory agrees with our conclusion [23].

Thus, the $D(2750)$ is most likely to be the $J^P = 2^-$ assignments. There are three cases, the 1^1D_2, 1^3D_2, and their admixtures of 1^1D_2-1^3D_2, that should be considered. First, we consider the $D(2750)^0$ as a mixed state of the 1^1D_2-1^3D_2 by the following mixing scheme:

$$|1D_2\rangle_L = +\cos(\phi)|1^1D_2\rangle + \sin(\phi)|1^3D_2\rangle, \tag{15}$$

$$|1D_2{}'\rangle_H = -\sin(\phi)|1^1D_2\rangle + \cos(\phi)|1^3D_2\rangle, \tag{16}$$

where the subscripts L and H denote the low-mass and high-mass state due to the mixing. Usually, the $|1D_2{}'\rangle_H$ has a narrow width [22,24,25]. We thus consider the $D(2750)$ as the $|1D_2{}'\rangle_H$. In Fig. 3, the decay properties of the $|1D_2{}'\rangle_H$ as a function of the mixing angle ϕ are plotted. We see that when we take the mixing angle $\phi \simeq -(50 \pm 15)^\circ$, the predicted decay width is in the range of the *BABAR* observation $\Gamma = (71 \pm 6 \pm 11)$ MeV. The decay modes are dominated by the $D^*\pi$, which can explain why the $D(2750)^0$ is first observed in $D^{*+}\pi^-$ channel. It is also interestedly found that the mixing angle is consistent with that ($\phi = 50.7^\circ$) obtained in the heavy quark effective theory [5,22,24,25]. Considering the $D(2760)$ as the 1^3D_3, we predicted the ratio

$$\frac{D(2760) \to D\pi}{D(2750) \to D^*\pi} \simeq 0.37 \sim 0.57, \tag{17}$$

which is in good agreement with the observed value as well. As a whole, the $D(2750)$ is favorably interpreted as the mixed state $|1D_2{}'\rangle_H$, with a mixing angle

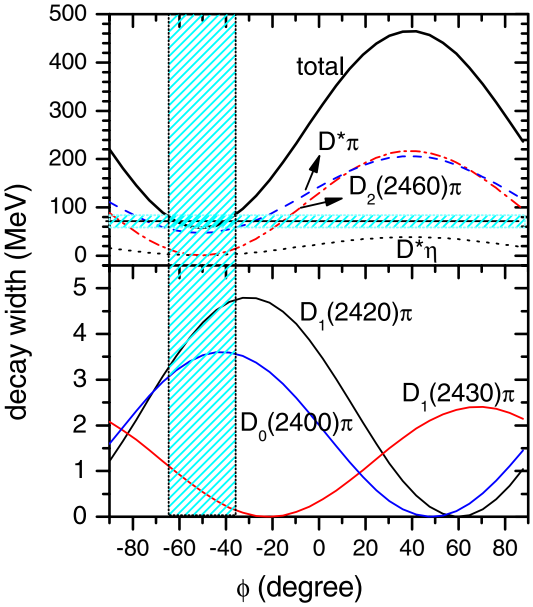

FIG. 3 (color online). The partial decay widths and total width of the $|1D_2'\rangle_H$, with a mass of 2750 MeV as a function of the mixing angle ϕ. The tiny contributions of the $D\rho$ and $D\omega$ are not shown in the figure.

$\phi \simeq -(50 \pm 15)°$. The $D(2750)$ might be observed in the $D_1(2420)\pi$, $D_0(2400)\pi$, $D^*\eta$, and $D_1(2430)\pi$ channels for their sizeable partial widths.

The $D(2750)$ cannot be interpreted as either a pure 1^1D_2 state or a pure 1^3D_2 state, for their widths are too broad to compare with the data. It is shown in Fig. 3 that the decay widths of the 1^1D_2 and 1^3D_2 are $\Gamma \simeq 220$ MeV (taking $\phi = 90°$) and $\Gamma \simeq 330$ MeV (taking $\phi = 0°$), respectively.

Since the $D(2750)$ can be interpreted as the mixed state $|1D_2'\rangle_H$, its low-mass partner $|1D_2\rangle_L$ may be observed in experiments as well. It is predicted that the mass of the low-mass partner $|1D_2\rangle_L$ is about 50 MeV lighter than that of the $|1D_2'\rangle_H$ [5]. Thus, the mass of the $|1D_2\rangle_L$ is likely to be $\sim$2.7 GeV. To know about the decay properties of the $|1D_2\rangle_L$, in Fig. 4, we plot its decay width as a function of mass in the range of $(2.65 \sim 2.75)$ GeV, with a mixing angle $\phi = -50°$ fixed by the $D(2750)$. From the figure, we see that the $|1D_2\rangle_L$ should be a broad state with a width of $\Gamma \simeq (250 \sim 500)$ MeV. Its strong decays are dominated by the $D^*\pi$ and $D_2(2460)\pi$. Furthermore, the $D^*\eta$ and D_s^*K also have sizeable contributions to the strong decays of the $|1D_2\rangle_L$. The $|1D_2\rangle_L$ may be too broad to be observed in experiments.

E. Sensitivity to β

The harmonic-oscillator parameter β is the most important parameter in the quark model. It controls the size effect or coupling form factor from the convolution of the heavy-light-meson wave functions. The uncertainties of β may affect our conclusions. The typical quark-model value of β is $\sim$0.4 GeV. To examine the sensitivity of the calculation to β, we plot the decay widths, partial decay widths, and partial decay width ratios of the 2^1S_0, 1^3D_3, the mixed state $|(SD)_1\rangle_L$ of the 2^3S_1-1^3D_1 and the mixed state $|1D_2'\rangle_H$ of the 1^3D_2-1^1D_2 as a function of β in Fig. 5.

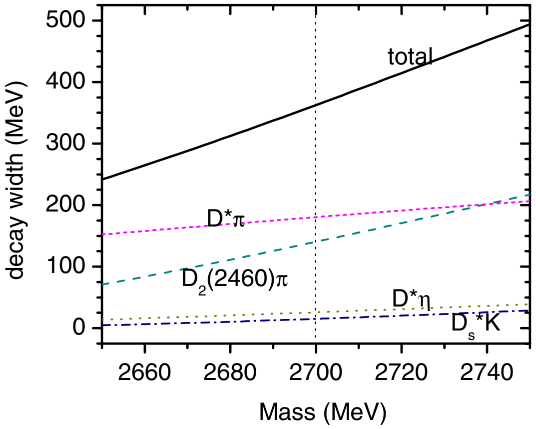

FIG. 4 (color online). The partial decay widths and total width of the $|1D_2\rangle_L$ as a function of mass, with the mixing angle $\phi = -50°$. The tiny contributions of the $D\rho$, $D\omega$, $D_0(2400)\pi$, $D_1(2420)\pi$, and $D_1(2430)\pi$ are not shown in the figure.

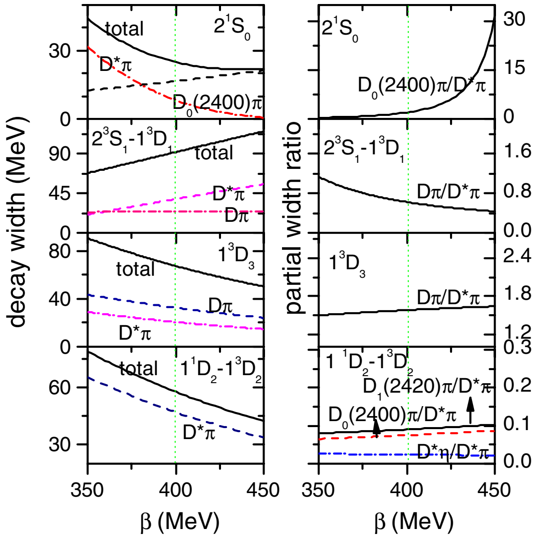

FIG. 5 (color online). The partial decay widths, total widths, and partial decay width ratios of different configuration assignments as a function of β, which have been labeled in the figure, where we only plot the dominant decay channels of these assignments. The 2^3S_1-1^3D_1 and 2^3S_1-1^3D_1 stand for the mixed states $|(SD)_1\rangle_L$ and $|1D_2'\rangle_H$, respectively. The mixing angle of the $|(SD)_1\rangle_L$ is fixed with $\phi = -36°$, while the mixing angle of the $|1D_2'\rangle_H$ is set with $\phi = -50°$. The masses of the 2^1S_0, $|(SD)_1\rangle_L$, $|1D_2'\rangle_H$, and 1^3D_3 are set with 2539, 2609, 2750, and 2760 MeV, respectively.

Figure 5 shows that the decay widths of these excited charmed mesons exhibit some sensitivities to the parameter β. The uncertainties of the width of the 1^3D_3 mainly come from the $D\pi$ and $D^*\pi$ channels, while for the 2^1S_0, the $|(SD)_1\rangle_L$, and the $|1D_2{}'\rangle_H$, the uncertainties of their decay widths mainly come from the $D^*\pi$ channel. Within the range of $\beta = (400 \pm 50)$ MeV, about a 30% uncertainty of the decay widths would be expected, which consists with our previous analysis [6]. This is a typical order of accuracy for the constituent quark model and can be regarded as reasonable.

From the figure, we see that the ratios $\Gamma(D_0(2400)\pi)/\Gamma(D\pi)$ of the 2^1S_0 and $\Gamma(D\pi)/\Gamma(D^*\pi)$ of the mixed state of $|(SD)_1\rangle_L$ are sensitive to β. In contrast, the ratios of the D waves, 1^3D_3 and $|1D_2{}'\rangle_H$, are insensitive to β.

In brief, although the harmonic-oscillator parameter β can bring some uncertainties to the final results, within the range of $\beta = (400 \pm 50)$ MeV, our major conclusions will still hold.

Finally, it should be mentioned that the relatively large uncertainties of the quark-vector-meson couplings, a and b', might affect our conclusions as well. Fortunately, they only affect the decay channels of a light-vector-meson emission, such as the $D\rho$ and $D\omega$ channels. From Table IV, we see that although the $D\rho$ and $D\omega$ are allowed for $D(2750, 2760)$, their partial decay widths predicted in our model are so tiny that we can neglect their contributions. In fact, when we use large values for the quark-vector-meson couplings, a and b', the partial widths of $D\rho$ and $D\omega$ are still small. Thus, here we do not consider the effects of their uncertainties on the results.

IV. SUMMARY

In this work, we have studied the strong decay properties of the newly observed $D(2550)$, $D(2600)$, $D(2750)$, and $D(2760)$ by the *BABAR* Collaboration in a constituent chiral quark model. These newly observed charmed mesons provide us a chance to establish a more completed D-meson spectroscopy, which has been shown in Table V. For comparison, the D_s-meson spectroscopy is also included.

TABLE V. D- and D_s-meson spectroscopies. The $1P_1(1^+)$ and $1P_1'(1^+)$ stand for the mixed states via the 1^1P_1-1^3P_1 mixing defined in Ref. [22]. The $|(SD)_1\rangle_L(1^-)$ and $|(SD)_1'\rangle_H(1^-)$ are the mixed states via the 2^3S_1-1^3D_1 mixing defined in Eqs. (10) and (11), respectively, while the $|1D_2\rangle_L(2^-)$ and $|1D_2{}'\rangle_H(2^-)$ are the mixed states via the 1^3D_2-1^1D_2 mixing defined in Eqs. (15) and (16), respectively.

$n^{2S+1}L_J(J^P)$	D_J state	D_{sJ} state
$1^1S_0(0^-)$	$D(1865)$	$D_s(1968)$
$1^3S_1(1^-)$	$D^*(2007)$	$D_s(2112)$
$1^3P_0(0^+)$	$D_0(2400)$	$D_{s0}(2317)$
$1P_1(1^+)$	$D_1(2430)$	$D_{s1}(2460)$
$1P_1'(1^+)$	$D_1(2420)$	$D_{s1}(2536)$
$1^3P_2(2^+)$	$D_2(2460)$	$D_{s2}(2573)$
$2^1S_0(0^-)$	$D(2550)$?	...
$\vert(SD)_1\rangle_L(1^-)$	$D(\mathbf{2600})$	$D_s(\mathbf{2710})$
$\vert(SD)_1'\rangle_H(1^-)$	...	...
$\vert1D_2\rangle_L(2^-)$	...	...
$\vert1D_2{}'\rangle_H(2^-)$	$D(\mathbf{2750})$	$D_{sJ_2}(\mathbf{2860})$
$1^3D_3(3^-)$	$D(\mathbf{2760})$	$D_{sJ_1}(\mathbf{2860})$

We have found that the $D(2550)^0$ as the 2^1S_0 is still questionable. The predicted narrow width of the 2^1S_0 is inconsistent with the observation, although its decay modes, helicity distributions, and theoretical predicted mass satisfy this classification. Given the poor statistics of the $D(2550)^0$, its decay width may be overestimated by experimentalists. We expect them to observe it in both the $D^*\pi$ and $D_0(2400)\pi$ channels.

The $D(2600)$ can be identified as the low-mass mixed state $|(SD)_1\rangle_L(1^-)$ via the 2^3S_1-1^3D_1 mixing. This mixed state is also predicted in the D_s-meson spectroscopy, which corresponds to the $D_s(2710)$ [6]. In our mixing scheme, the high-mass partner $|(SD)_1\rangle_H(1^-)$ may be too broad to be observed in D-meson spectroscopy, while it might be found in D_s spectroscopy [6]. To understand the nature of the $D(2600)$ further, we suggest to observe it in the $D_1(2420)\pi$, $D_1(2430)\pi$, $D\eta$, and D_sK channels.

The $D(2760)$ is most likely to be the $1^3D_3(3^-)$. Its decays are governed by the $D\pi$ and $D^*\pi$, which can naturally explain why the $D(2760)$ is first observed in the $D\pi$ channel. The predicted ratio is $\Gamma(D\pi)/\Gamma(D^*\pi) \simeq 1.58$. The $D(2760)$ as a high-mass partner of the $D(2600)$ via the 2^3S_1-1^3D_1 mixing was also suggested in [9], where the predicted partial decay width of the $D\pi$ is tiny. Further experimental measurement of the ratios $\Gamma(D^*\pi)/\Gamma(D\pi)$, $\Gamma(D_sK)/\Gamma(D\pi)$, and $\Gamma(D\eta)/\Gamma(D\pi)$ should be able to disentangle its properties.

The $D(2750)$ and $D(2760)$ might be two different charmed meson states. The $D(2750)$ is favorably interpreted as the high-mass mixed state $|1D_2{}'\rangle_H(2^-)$ via the 1^1D_2-1^3D_2 mixing. Its low-mass partner $|1D_2\rangle_L$ may be too broad to be observed in experiments. To confirm the $D(2750)$, the decay channels $D_1(2420)\pi$, $D_0(2400)\pi$, $D^*\eta$, and $D_1(2430)\pi$ are suggested to be observed in future experiments.

Finally, we should mention that in our previous work [6], we predicted that the $D_s(2860)$ might correspond to two largely overlapping resonances: one resonance is likely to be the 1^3D_3 [denoted by $D_{sJ_1}(2860)$], and the other resonance seems to be the mixed state between the 1^3D_2 and 1^1D_2 [denoted by $D_{sJ_2}(2860)$]. Combining the study of the $D(2750)$ and $D(2760)$ in the present work, we easily conclude that both the $D(2760)$ and $D_{sJ_1}(2860)$ are most likely to be the 1^3D_3, while both the $D(2750)$ and $D_{sJ_2}(2860)$ might be classified as the mixed state $|1D_2{}'\rangle_H$, with almost the same mixing angle. To test our predictions and clarify the controversial situation of the $D_s(2860)$ [21,26–28], we suggest to analyze the helicity distribution of $D_s(2860) \to D^*K$ in experiments. If the helicity distribution is in proportion to $(1 + h\cos^2\theta_H)$, the $D_s(2860)$ should be two largely overlapping resonances.

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[1] J. Benitez *et al.*, in ICHEP2010, Paris, 2010; P. del Amo Sanchez *et al.* (The *BABAR* Collaboration), Phys. Rev. D **82**, 111101 (2010).
[2] C. Amsler *et al.* (Particle Data Group), Phys. Lett. B **667**, 1 (2008).
[3] S. Godfrey and N. Isgur, Phys. Rev. D **32**, 189 (1985).
[4] M. Di Pierro and E. Eichten, Phys. Rev. D **64**, 114004 (2001).
[5] D. Ebert, R. N. Faustov, and V. O. Galkin, Eur. Phys. J. C **66**, 197 (2010).
[6] X. H. Zhong and Q. Zhao, Phys. Rev. D **81**, 014031 (2010).
[7] X. H. Zhong and Q. Zhao, Phys. Rev. D **78**, 014029 (2008).
[8] X. H. Zhong and Q. Zhao, Phys. Rev. D **77**, 074008 (2008).
[9] Z. F. Sun, J. S. Yu, X. Liu, and T. Matsuki, Phys. Rev. D **82**, 111501 (2010).
[10] A. Manohar and H. Georgi, Nucl. Phys. **B234**, 189 (1984).
[11] Z. P. Li, Phys. Rev. D **50**, 5639 (1994).
[12] Z. P. Li, H. X. Ye, and M. H. Lu, Phys. Rev. C **56**, 1099 (1997).
[13] Q. Zhao, J. S. Al-Khalili, Z. P. Li, and R. L. Workman, Phys. Rev. C **65**, 065204 (2002).
[14] Q. Zhao, Z. P. Li, and C. Bennhold, Phys. Rev. C **58**, 2393 (1998); Phys. Lett. B **436**, 42 (1998).
[15] Q. Zhao, Phys. Rev. C **63**, 025203 (2001).
[16] Q. Zhao, J. S. Al-Khalili, and C. Bennhold, Phys. Rev. C **64**, 052201 (2001).
[17] I. Hleiqawi *et al.* (CLAS Collaboration), Phys. Rev. C **75**, 042201 (2007); **76**, 039905(E) (2007)].
[18] M. Nanova *et al.* (CBELSA/TAPS Collaboration), Eur. Phys. J. A **35**, 333 (2008).
[19] P. Colangelo, F. De Fazio, S. Nicotri, and M. Rizzi, Phys. Rev. D **77**, 014012 (2008).
[20] F. E. Close, C. E. Thomas, O. Lakhina, and E. S. Swanson, Phys. Lett. B **647**, 159 (2007).
[21] D. M. Li and B. Ma, Phys. Rev. D **81**, 014021 (2010).
[22] F. E. Close and E. S. Swanson, Phys. Rev. D **72**, 094004 (2005).
[23] Zhi-Gang Wang, arXiv:1009.3605.
[24] S. Godfrey and R. Kokoski, Phys. Rev. D **43**, 1679 (1991).
[25] E. S. Swanson, Phys. Rep. **429**, 243 (2006).
[26] P. Colangelo, F. De Fazio, and S. Nicotri, Phys. Lett. B **642**, 48 (2006).
[27] B. Chen, D. X. Wang, and A. Zhang, Phys. Rev. D **80**, 071502 (2009).
[28] E. van Beveren and G. Rupp, Phys. Rev. D **81**, 118101 (2010); Phys. Rev. Lett. **97**, 202001 (2006).