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

Xian-Hui Zhong *
Department of Physics, Hunan Normal University, and Key Laboratory of Low-Dimensional Quantum Structures and Quantum Control of Ministry of Education, Changsha 410081, P.R. China

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 $D(2600)$ 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 $|D^*_2⟩_H$ ($J^P = 2^-$) via the $1^3D_2$-$1^3D_2$ mixing. The $D(2600)$ favors the low-mass mixed state $(|SD⟩_L)(J^P = 1^-)$ via the $1^3D_1$-$2^1S_0$ mixing. The $D(2550)$ as the $2^1S_0$ assignment bears controversies for its too broad width given in experiments.

PACS numbers: 12.39.Fe, 12.39.Jh, 13.20.Fc, 14.40.Lb

I. INTRODUCTION

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

\[
\frac{D(2600)^0 → D^+π^-}{D(2600)^0 → D^{∗+}π^-} = 0.32 ± 0.02_{stat} ± 0.09_{syst}, \quad (1)
\]

\[
\frac{D(2760)^0 → D^+π^-}{D(2760)^0 → D^{∗+}π^-} = 0.42 ± 0.05_{stat} ± 0.11_{syst}. \quad (2)
\]

The other observed results are summarized in Tab. 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 PDG book [2], it is seen that only six low-lying states, $D$, $D^*$, $D_0(2400)$, $D_1(2430)$, $D_1(2420)$ and $D_2(2460)$, have been established. The higher excitations, $2S$ and $1D$ waves, are still absent. Thus, the finding of $D(2550)$, $D(2600)$, $D(2750)$ and $D(2760)$ provides us a good opportunity to establish the missing $2S$ and $1D$ states. The BaBar analysis of helicity distribution ($x sin^2 θ_H$) [1] also indicates that the $D(2600)$ may be $1^-$ or $3^-$ assignments [3]. The typical quark model predicted mass of $1^3D_3$ is $<2.83$ GeV [3, 4], which is much larger than that of $D(2600)$. 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 $D^{∗+}π^−$ channel, its possible $J^P$ are $1^−$, $2^−$ and $3^−$. The helicity distribution of the $J^P = 1^−$ and $3^−$ assignments is a simple $sin^2 θ_H$ 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 $D(2760)$ is very close to that of $D(2750)$, they may be two different states for their mass and width values differ by 2.6σ and 1.5σ, respectively [1]. The observation of $D(2760)$ in $Dπ$ channel indicates it may be a candidate of $1^3D_1$ 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, 7]. Very recently, the strong decays of the $D(2550)$, $D(2600)$ and $D(2760)$ were studied by Liu et al. in a $3^P_0$ model [8]. For the $D(2550)$ and $D(2600)$, the main $3^P_0$ model predictions are compatible with our quark model predictions. In [8], two candidates are suggested for the $D(2760)$. They are the mixed state via $2^1S_1$-$1^3D_1$ mixing and $1^3D_3$, respectively. In our predictions, only the $1^3D_3$ is the favored assignment to $D(2760)$.

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.
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 \[11\] \[12\]

$$\mathcal{L}_{Vqq} = \sum_j \bar{\psi}_j \left( a \gamma_{\mu}^j + \frac{ib}{2m_j} \sigma_{\mu\nu} q^\nu \right) V^\mu \psi_j,$$  \hspace{1cm} (3)

where $\psi_j$ represents the $j$-th quark field in the hadron, $\phi_m$ 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 \[14\] \[16\]

$$\mathcal{L}_{Vq\bar{q}} = \sum_j \bar{\psi}_j (a\gamma_\mu^j + \frac{ib}{2m_j} \sigma_{\mu\nu} q^\nu) V^\mu \psi_j,$$ \hspace{1cm} (4)

where $V^\mu$ represents the vector meson field with four-vector momentum $q$. Parameters $a$ and $b$ denote the vector and tensor coupling strength, respectively.

To match the non-relativistic harmonic oscillator wave function of the heavy-light meson $\psi_m^\nu = R_m Y_{lm}$ adopted in the calculation of the strong decay amplitudes, we should provide the quark-pseudoscalar and quark-vector-meson coupling operators in a non-relativistic form. Considering light meson emission in a heavy-light meson strong decays, the effective quark-pseudoscalar-meson coupling operator in the center-of-mass system of the initial meson is \[6\] \[7\] \[11\] \[12\]

$$H_m = \sum_j \left[ A \sigma_j \cdot q + \frac{\omega_m}{2m_q} \sigma_j \cdot p_j \right] I_j \varphi_m,$$ \hspace{1cm} (5)

where $A \equiv - (1 + \frac{\omega_m}{E_j + M_f})$. 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 \[14\] \[16\]:

$$H_m^T = \sum_j \left\{ \frac{b'}{2m_q} \sigma_j \cdot (q \times \epsilon) + \frac{a}{2m_q} (p_j \cdot \epsilon) \right\} I_j \varphi_m,$$ \hspace{1cm} (6)

and

$$H_m^L = \sum_j \frac{a M_j}{|q|} I_j \varphi_m.$$ \hspace{1cm} (7)

In the above three equations, $q$ and $\omega_m$ are the three-vector momentum and energy of the final-state light meson, respectively. $p_j$ is the internal momentum operator of the $j$-th quark in the heavy-light meson rest frame. $\sigma_j$ is the spin operator on the $j$-th quark of the heavy-light system, and $\mu_q$ 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 $j$-th quark in the initial and final mesons, respectively. Here, the $j$-th 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 $\varphi_m = e^{-i q \cdot r}$, 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. (4) is defined as $b' \equiv b - a$.

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

$$\Gamma = \left( \frac{\delta}{f_m} \right)^2 \frac{(E_f + M_f) |q|}{4\pi M_i (2J_i + 1)} \sum_{J_{is},f_s} |M_{J_i,J_s}|^2,$$ \hspace{1cm} (8)

where $M_{J_i,J_s}$ is the transition amplitude, $J_{is}$ and $J_{fs}$ stand for the third components of the total angular momenta of the initial and final heavy-light mesons, respectively. $\delta$ 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 constituent quark system is an approximation. This will bring uncertainties to coupling vertices and form factors. The parameter $\delta$ 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 $\beta$ in the wave function $\psi_m^\nu = R_m Y_{lm}$ is taken as $\beta = 0.40$ GeV. The decay constants for $\pi$, $K$ and $\eta$ mesons are taken as $f_\pi = 132$ MeV, $f_K = f_\eta = 160$ 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. $a \approx -3$ and $b' \approx 5$ \[14\] \[16\]. The masses of the mesons used in the calculations are adopted from the PDG \[2\].

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 non-relativistic quark model,
where the non-relativistic 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. \( D(2550) \)

TABLE II: The partial decay widths and total width (MeV) for the \( D(2550) \) as the \( 2^3S_0 \) candidate, where the mass of \( D_0(2400) \) is set with 2338 MeV [1].

| \( D^\ast \pi \) | \( D_0(2400)\pi \) | total | \( \Gamma(D_0(2400)\pi)/\Gamma(D^\ast \pi) \) |
|---|---|---|---|
| \( 2^3S_0 \) | 7.2 | 14.9 | 22.1 |
| \( 1^3D_1 \) | 1.8 | 2.4 | 2.7 |

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

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

| \( D\pi \) | \( D_\pi \) | \( D_\pi \) | \( D^\ast\pi \) | \( D^\ast\pi \) | \( D^\ast\pi \) | \( D^\ast\pi \) | \( D^\ast\pi \) | \( D^\ast\pi \) | total |
|---|---|---|---|---|---|---|---|---|---|
| \( 2^3S_1 \) | 1.9 | 2.4 | 2.7 | 9.9 | 1.3 | 0.02 | 23.3 | 0.01 | 0.002 |
| \( 1^3D_1 \) | 119.9 | 17.9 | 23.1 | 39.0 | 1.8 | 0.03 | 7.9 | 43.6 | 0.00 |

B. \( D(2600) \)

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

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

\[
\Gamma \approx 42 \text{ MeV}, \quad \frac{\Gamma(D\pi)}{\Gamma(D^\ast\pi)} \approx 0.2.
\]

(9)

It shows that the predicted width \( \Gamma \approx 42 \text{ MeV} \) is too narrow to compare with the data although the ratio \( \Gamma(D\pi)/\Gamma(D^\ast\pi) \) is compatible with that of measurement. Thus, with the pure \( 2^3S_1 \) we can not well explain observations of \( D(2600) \). Our conclusion is consistent with that of \( 3P_0 \) model [9]. Furthermore, the relativistic quark model calculations also indicate that the \( 2^3S_1 \) is a narrow width state (with the determined value \( g_A^s = 0.53 \sim 0.82 \), the predicted decay width is \( \Gamma \approx (23 \sim 57) \text{ MeV} \) [4]. The strong decay properties of \( 2^3S_1 \) in \( D \) mesons were studied by Colangelo et al. as well with the heavy quark effective theory [13]. In their framework, when the \( D(2600) \) is considered as the \( 2^3S_1 \) assignment its decay width, \( \Gamma \approx (128 \pm 61) \text{ MeV} \), is compatible with that of measurement, while the predicted ratio, \( \Gamma(D\pi)/\Gamma(D^\ast\pi) \approx 0.82 \), is obviously larger than the measured value \( \Gamma(D\pi)/\Gamma(D^\ast\pi) = 0.32 \pm 0.02 \pm 0.09 \).

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

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

\[
\begin{align*}
&|\langle SD \rangle^L \rangle_L = + \cos(\phi)|2^3S_1 \rangle + \sin(\phi)|1^3D_1 \rangle, \quad (10) \\
&|\langle SD \rangle^H \rangle_H = - \sin(\phi)|2^3S_1 \rangle + \cos(\phi)|1^3D_1 \rangle, \quad (11)
\end{align*}
\]

where the physical partner in the mixing is included. Assuming that the low-mass state \( |\langle SD \rangle^L \rangle_L \) corresponds to \( D(2600) \), we plot the decay width of \( |\langle SD \rangle^L \rangle_L \) as a function of the mixing angle \( \phi \approx -(36 \pm 6)^\circ \), the measured
has also been suggested by Liu et al. In their predicted mixing angle, $\phi$, the mixing width of $D,sK$ is roughly comparable with our prediction obtained in \[20, 21\]. This mixing angle is close to that obtained in \[20, 21\]. However, we have noted that the ratio $\Gamma(D,sK)/\Gamma(D^*\pi)$ is $\sim 13$, which just corresponds to the limit of zero mixing of $[(SD)_{1}]_L$. A combined study of $D(2600)$ and $D_s(2710)$ may be helpful to clarify these controversies.

Following this mixing scheme, one can examine the high-mass partner $[(SD)_{1}]_H$. Supposing that the mass of $[(SD)_{1}]_H$ 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 $D(2600)$. It is shown that the $[(SD)_{1}]_H$ should be a broad state with a width of $\Gamma = (300 \sim 550)$ MeV. Its decay modes are dominated by $D\pi$ and $D^*\pi$, with the increasing mass, the $D_1(2420)\pi$ and $D_1(2430)\pi$ decay channels become dominant as well.

decl width
\[
\Gamma \simeq (93 \pm 6 \pm 13) \text{ MeV}
\]
can be well explained. The predicted partial width ratio is
\[
\frac{\Gamma(D\pi)}{\Gamma(D^*\pi)} \simeq 0.63 \pm 0.21,
\]
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 $[(SD)_{1}]_L$. Its main strong decay channels are $D^*\pi$, $D\pi$, $D_1(2420)\pi$ and $D_1(2430)\pi$.

Recently, $D(2600)$ as an admixture of $2^3S_1$ and $1^3D_1$ has also been suggested by Liu et al. \[8\]. They adopted different mixing scheme from ours. In our mixing scheme their predicted mixing angle, $-86^\circ \leq \phi \leq -51^\circ$, is roughly comparable with our prediction $\phi \simeq -(36 \pm 6)^\circ$. However, we have noted that the ratio $\Gamma(D\pi)/\Gamma(D^*\pi)$ is $2.13 \sim 2.86$ predicted by Liu et al. \[8\] 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 \[8\], 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 $[(SD)_{1}]_L$ with a mixing angle $\phi \simeq -(54 \pm 7)^\circ$, similar prediction also were obtained in \[20, 21\]. This mixing angle is close to that of $D(2600)$. If both $D(2600)$ and $D_s(2710)$ correspond to the the mixed state $[(SD)_{1}]_L$, indeed, the $2^3S_1-1^3D_1$ mixing might be a common character in the heavy-light mesons. The future search for $[(SD)_{1}]_L$ in $B$ and $B_s$ spectroscopies will clarify this assumption. Finally, we should point out that there still exist controversies in $D_s(2710)$ about the extent of the mixing. The $D_s(2710)$ is also interpreted as the first radial excitation of $D^*_s$ (i.e. $2^3S_1$) \[19\], which just corresponds to the limit of zero mixing of $[(SD)_{1}]_L$. A combined study of $D(2600)$ and $D_s(2710)$ may be helpful to clarify these controversies.

![FIG. 1: (Color online) The partial decay widths and total decay width of $[(SD)_{1}]_L$ with a mass of 2609 MeV as a function of mixing angle $\phi$. For the tiny contributions of the $D_2(2460)\pi$ and $D_1^*K$, they are not shown in the figure.](image1)

![FIG. 2: (Color online) The partial decay widths and total width of $[(SD)_{1}]_H$ 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.](image2)

C. $D(2760)$

The $D(2760)$ is a good candidate of $D$ waves \[11\], in which the $J^P = 2^-$ states [i.e. $1D_2(2^-)$ 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 $D(2760)$. Assuming the $D(2760)$ as a candidate of $1^3D_1(1^-)$ or $1^3D_3(3^-)$, it can decay into $D\pi$, $D\rho$, $D\eta$, $D^{*}\pi$, $D^{*}\eta$, $D^{*}K$, $D_1(2430)\pi$, $D_1(2420)\pi$, $D_2(2640)\pi$, $D_\omega$ and $D_\rho$. We calculate these partial decay widths and list the results in Tab. IV.

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

|        | $D\pi$ | $D\rho$ | $D\eta$ | $D^{*}\pi$ | $D^{*}\eta$ | $D^{*}K$ | $D_1(2430)\pi$ | $D_1(2420)\pi$ | $D_2(2640)\pi$ | $D_\omega$ | $D_\rho$ | Total |
|--------|--------|---------|---------|-----------|-----------|--------|-------------|-------------|-------------|---------|-------|-------|
| $1^3D_3$ | 32.5   | 2.1     | 0.2     | 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 $1^3D_1(1^-)$, from the table it is seen that the strong decays of $D(2760)$ are dominated by $D\pi$ and $D_1(2420)\pi$. The dominant roles of the $D\pi$ and $D_1(2420)\pi$ decay modes in the strong decays of $1^3D_1(1^-)$ were also predicted in Ref. [22]. It is found that the total decay width, $\Gamma \approx 550$ MeV, is too broad to compare with the data. Thus, $D(2760)$ as the $1^3D_1(1^-)$ assignment should be excluded.

As the assignment of $1^3D_3(3^-)$, the $D(2760)$ has two dominant decay channels $D\pi$ and $D^{*}\pi$, which is compatible with the predictions in Ref. [22]. The other decay modes, such as $D_1(2430)\pi$, $D_2 K$ and $D\eta$ have sizeable contributions. The decay width and partial decay width ratio are

$$\Gamma \approx 68 \text{ MeV}, \quad \frac{\Gamma(D\pi)}{\Gamma(D^{*}\pi)} \approx 1.58.$$ (14)

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

Finally, it should be mentioned that in Ref. [9] two possible assignments to $D(2760)$ are suggested, which are $1^3D_3(3^-)$ and the high-mass partner $|SD\rangle_H^1$ via the $2^3S_1-1^3D_1$ mixing, respectively. Our calculations exclude $D(2760)$ as the $|SD\rangle_H^1$ assignment. It is shown in fig. 2 that as the assignment of $|SD\rangle_H^1$, the $D(2760)$ should be a broad resonance with a width of $\Gamma \approx 500$ 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 $|SD\rangle_H^1$ between our model and that in Ref. [9] mainly come from the different predictions of the strong decay properties of $1^3D_1$. In our model, the decays of the $|SD\rangle_H^1$ are dominated by both the $D\pi$ and $D_1(2420)\pi$ channels. We find that the main contributor to the partial widths of $D\pi$ and $D_1(2420)\pi$ is the $1^3D_1$, whose decay modes are dominated by $D\pi$ and $D_1(2420)\pi$. However, in Ref. [9] the strong decays of $1^3D_1$ are predicted to be dominated by $D_1(2430)\pi$. It should be pointed out that with the $^3P_0$ model, Close and Swanson predicted that the dominant decay modes of $1^3D_1$ are $D_1(2420)\pi$ 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.

![FIG. 3: (Color online) The partial decay widths and total width of $|1D_{24}\rangle_H$ with a mass of 2750 MeV as a function of mixing angle $\phi$. The tiny contributions of the $D\rho$ and $D_\omega$ are not shown in the figure.](image-url)
The $D(2750)^0$ is observed in $D^{*+}\pi^-$. Although its mass is very close to that of $D(2760)$, 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 the Sec. III C they should be the $1^3D_3$ assignment. However, the simple helicity distribution of $1^3D_3$, $\sin^2\theta_H^H$ [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) The measured mass and width values differ by 2.6$\sigma$ and 1.5$\sigma$, respectively [1].

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

$$|1D_2\rangle_{L} = \cos(\phi)|1D_2\rangle + \sin(\phi)|1D_2\rangle,$$
$$|1D_2\rangle_{H} = -\sin(\phi)|1D_2\rangle + \cos(\phi)|1D_2\rangle,$$

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 $|1D_2\rangle_{H}$ as a function of the mixing angle $\phi$ 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 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 interestingly found that the mixing angle is consistent with that ($\phi \simeq 50^{\circ}$) obtained in the heavy quark effective theory [5, 22, 24, 25]. Considering the $D(2760)$ as the $1^3D_3$, we predicted the ratio

$$\frac{D(2760)^0 \to D\pi}{D(2750)^0 \to D^{*}\pi} \simeq 0.37 \sim 0.57,$$

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 $\phi \simeq -(50 \pm 15)^{\circ}$. The $D(2750)$ might be observed in $D_1(2420)\pi$, $D_0(2400)\pi$, $D^*\eta$ and $D_1(2430)\pi$ channels for their sizeable partial widths. The $D(2750)$ can not be interpreted as either a pure $1^3D_2$ state or a pure $1^3D_2'$ state for their too broad widths to compare with the data. It is shown in Fig. 3 the decay widths of the $1^3D_2$ and $1^3D_2'$ are $\Gamma \simeq 220$ MeV (taking $\phi = 90^{\circ}$) and $\Gamma \simeq 330$ MeV (taking $\phi = 0^{\circ}$), 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 low-mass partner $|1D_2\rangle_{L}$ is about 50 MeV lighter than that of $|1D_2\rangle_{H}$ [3]. Thus, the mass of $|1D_2\rangle_{L}$ is likely to be $\sim 2.7$ GeV. To know about the decay properties of $|1D_2\rangle_{L}$, 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 $\phi = -50^{\circ}$ fixed by $D(2750)$. 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 $D^{*}\pi$ and $D_2(2460)\pi$. Furthermore, the $D^*\eta$ and $D^*K$ also have sizeable contributions to the strong decays of $|1D_2\rangle_{L}$. The $|1D_2\rangle_{L}$ may be too broad to be observed in experiments.

**E. Sensitivity to $\beta$**

The harmonic oscillator parameter $\beta$ 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 $\beta$ may aect our conclusions. The typical quark model value of $\beta$ is $\sim 0.4$ GeV. To examine the sensitivity of the calculation to $\beta$, we plot the decay widths, partial decay widths and partial decay width ratios of $2^1S_0$, $1^3D_3$, mixed state $|(SD)\rangle_{L}$ of $2^1S_0$-$1^3D_1$ and mixed state $|(SD)\rangle_{H}$ of $1^3D_2$ as a function of $\beta$ in Fig. 5.

It shows that the decay widths of these excited charmed mesons exhibit some sensitivities to the parameter $\beta$. The uncertainties of the width of $1^3D_3$ mainly come from the $D\pi$ and $D^{*}\pi$ channels, while for the $2^1S_0$, the $|(SD)\rangle_{L}$ and the $|1D_2\rangle_{H}$, the uncertainties of their
The mixing angle of $2S_0$ is set with $\phi = -36^\circ$, while the mixing angle of $|D_2\rangle_H$ is set with $\phi = -50^\circ$. The masses of $2S_0$, $|(SD)\rangle_L$, $|D_2\rangle_H$ and $1^3D_3$ are set with 2539 MeV, 2609 MeV, 2750 MeV and 2760 MeV, respectively.

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 [4]. 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 $\Gamma(D(2400)\pi)/\Gamma(D\pi)$ of $2S_0$ and $\Gamma(D\pi)/\Gamma(D^*\pi)$ of the mixed state of $|(SD)\rangle_L$ are sensitive to $\beta$. In contrast, the ratios of the $D$ waves, $1^3D_3$ and $|D_2\rangle_H$, are insensitive to $\beta$.

In brief, although the harmonic oscillator parameter $\beta$ 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 $D\rho$ and $D\omega$ channels. From the Tab.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 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 Tab. For comparison, the $D_s$ meson spectroscopy is also included.

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

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

The $D(2760)$ is most likely to be the $1^3D_3(3^-)$. Its decays are governed by $D\pi$ and $D^*\pi$, which can naturally explain why $D(2760)$ is first observed in $D\pi$ channel. The

| $n^{2S+1}L_J(J^p)$ | $D_J$ state | $D_{LJ}$ state |
|-------------------|-------------|---------------|
| $1^3S_0(0^-)$     | $D(1865)$   | $D_s(1968)$   |
| $1^3S_1(1^-)$     | $D^*(2007)$ | $D_s(2112)$   |
| $1^3P_0(0^+)$     | $D_1(2430)$ | $D_{s1}(2460)$|
| $1^3P_1(1^-)$     | $D_2(2420)$ | $D_{s2}(2536)$|
| $1^3P_2(2^-)$     | $D_3(2460)$ | $D_{s3}(2573)$|
| $2^1S_0(0^-)$     | $D(2550)$   | $D_s(2710)$   |
| $|(SD)\rangle_L(1^-)$ | $D(2600)$   | $D_{s1}(2860)$|
| $|(SD)\rangle_H(1^-)$ | ?             | ?             |
| $|D_2\rangle_H(2^-)$ | $D(2750)$   | $D_{s2}(2860)$|
| $1^3D_3(3^-)$     | $D(2760)$   | $D_{s3}(2860)$|

FIG: 5. (Color online) The partial decay widths, total widths and partial decay width ratios of different configuration assignments as a function of $\beta$, 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 $2^3S_0-1^3D_1$ stand for the mixed states $|(SD)\rangle_L$ and $|D_2\rangle_H$, respectively. The mixing angle of $|(SD)\rangle_L$ is fixed with $\phi = -36^\circ$, while the mixing angle of $|D_2\rangle_H$ is set with $\phi = -50^\circ$. The masses of $2S_0$, $|(SD)\rangle_L$, $|D_2\rangle_H$ and $1^3D_3$ are set with 2539 MeV, 2609 MeV, 2750 MeV and 2760 MeV, respectively.
likely to be the two largely overlapping resonances, one resonance is interpreted as the high mass mixed state 1\(D_{sJ}^+\)/\(D_s^+\) (2\(^-\)) via the 1\(D_2\)-1\(D_2^\prime\) mixing. Its low-mass partner 1\(D_2\) may be too broad to be observed in experiments. To confirm the 1\(D_2\), the decay channels \(D_1\) and 1\(D_2\) are suggested to be observed in future experiments.

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

Acknowledgements

The author would like to thank Professor Xiang Liu for drawing his attention to the BaBar Collaboration’s new data. This work is supported by the National Natural Science Foundation of China (Grant Nos. 10775145 and 11075051).

References

[1] J. Benitez et al., in ICHEP2010, Paris, July 23, 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. B 234, 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) [Erratum-ibid. C 76, 039905 (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 [hep-ph].
[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).