Newly observed $D(2550)$, $D(2610)$, and $D(2760)$ as $2S$ and $1D$ charmed mesons

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We study three newly observed $D(2550)$, $D(2610)$, and $D(2760)$ by the BaBar Collaboration utilizing the mass spectra and investigating the strong decays. Our calculation indicates that $D(2610)$ is an admixture of $2^3S_1$ and $1^3D_1$ with $J^P = 1^-$. $D(2760)$ can be explained as either the orthogonal partner of $D(2610)$ or $1^1D_1$. Our estimate of the decay width for $D(2550)$, assuming it as $2^3S_0$, is far below the experimental value. The decay behavior of the remaining two $1D$ charmed mesons, i.e., $3^2D_2$ and $3^1D_3$ ($J^P = 2^-$) states, is predicted, which will help future experimental search for these missing $D$-wave charmed mesons.

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Very recently the BaBar Collaboration has observed new charmed mesons, $D(2550)$, $D(2610)$, and $D(2760)$ [1]. The spectra of $D$ mesons are very poorly known because higher states have been hindered by poor statistics and their relatively large widths. The BaBar analysis on these particles is that $2S$ and $1D$ are the most likely candidates when relying on the mass values predicted by the conventional nonrelativistic potential model [2] and the relativistic potential models [3–5]. By reanalyzing their data, especially by studying their decay widths with successful $^3P_0$ model [6], we would like to see whether the quark model prediction fits with their data.

In the $D^+\pi^-$ invariant mass spectrum, two $D$ mesons, $D(2610)^0$ and $D(2760)^0$, with neutral charge, have been observed along with confirming two established charmed mesons, $D_s^0(2460)^0$ and $D_s^*(2460)^0$. BaBar has also found the isospin partners $D(2610)^+$ and $D(2760)^+$ in $D^0\pi^+$ channel. By analyzing the $D^+\pi^-$ invariant mass spectrum, three structures around 2553.0 MeV, 2619.0 MeV, and 2774.7 MeV have been released, which shows that BaBar collaboration has not only confirmed $D(2610)^0$ and $D(2760)^0$ in $D^+\pi^-$ channel but also has found a new charmed state $D(2550)^0$. The resonance parameters (in units of MeV) of $D(2550)$, $D(2610)$, and $D(2760)$ are summarized as [1]

\[
\begin{align*}
M_{D(2550)^0}/\Gamma_{D(2550)^0} & = 2539.4 \pm 4.5 \pm 6.8/130 \pm 12 \pm 13, \\
M_{D(2610)^0}/\Gamma_{D(2610)^0} & = 2608.7 \pm 2.4 \pm 2.5/93 \pm 6 \pm 13, \\
M_{D(2760)^0}/\Gamma_{D(2760)^0} & = 2763.3 \pm 2.3 \pm 2.3/60.9 \pm 5.1 \pm 3.6, \\
M_{D(2610)^+}/\Gamma_{D(2610)^+} & = 2621.3 \pm 3.7 \pm 4.2/93, \\
M_{D(2760)^+}/\Gamma_{D(2760)^+} & = 2769.7 \pm 3.8 \pm 1.5/60.9,
\end{align*}
\]

where the first error is statistical and the second is systematic.

As listed in the paper by the particle data group (PDG) [7], there are six charmed mesons $D$, $D^*$, $D_s^0(2400)$, $D_1(2430)$, $D_1(2420)$, and $D_s^*(2460)$ with the established spin-parity assignments (see Fig. [1] for details). The newly observed charmed resonances, $D(2550)$, $D(2610)$, and $D(2760)$, are not only making the spectroscopy of charmed mesons abundant, but also stimulating our interest in revealing the underlying properties of these particles, which, of course, provides a good opportunity to test the existing theory of heavy-light meson system and further enlarges our knowledge of non-perturbative QCD.

The BaBar analysis of angular distribution indicates that $D(2550)$ and $D(2610)$ may be identified as the first radial excitations of $S$-wave charmed mesons while $D(2760)$ can be a $D$-wave state [1]. The quantum number $J^P$ of $D(2550)$ and $D(2610)$ are assigned as $0^-$ and $1^-$, respectively, which explains why BaBar has found $D(2550)$ only in $D\pi$ channel and $D(2610)$ both in $D\pi$ and $D^*\pi$ channels. As a candidate of the $D$-wave charmed meson, the spin-parity content of $D(2760)$ can be either $1^-$ or $3^-$ because the observed decay process $D(2760) \to DK$ fully excludes $J^P = 2^-$. 

FIG. 1: (Color online.) The figure shows mass spectrum of six established charmed mesons in PDG [7] and three newly observed charmed mesons by the BaBar Collaboration [1] compared with the thresholds of $D^{*+}\pi$, $D^{*+}\eta$, $D_0\pi$, and $D_0^0 K$. Here, the experimental decay channels corresponding to these charmed mesons are also drawn as down arrows. The decay channel $D(2550) \to D_0^0(2400) + \pi$ is omitted from the figure.
where $s$ satisfies regarded as an admixture of $D_0^*$ served masses of charmed mesons for $D_2(2550)$, $D_2(2610)$, and $D_2(2760)$ can be respectively treated as admixtures, one of which is $D_0^*$ and the other of which is $D_2^*$. It is noted that the predicted mass spectra for charmed mesons are close to each other [1–5].

**TABLE I:** Theoretical calculations for charmless $D$ mesons and an admixture of $D_0^*$, which are presented. This table includes $D_0^*$ and $D_2^*$ as well as other states.

| $J^P(n^{2+1})$ | Expt[1, 2] | GIL[2] | MMS[3] | PE[4] | EFG[5] |
|-----------------|------------|--------|--------|-------|--------|
| $0^+(1S_0)$     | 1867      | 1880   | 1869   | 1868  | 1871   |
| $1^+(1S_1)$     | 2008      | 2004   | 2011   | 2005  | 2010   |
| $0^+(1P_0)$     | 2438      | 2400   | 2283   | 2377  | 2406   |
| $1^+(1P_1)$     | 2427      | 2490   | 2421   | 2417  | 2469   |
| $1^+(1P_2)$     | 2420      | 2440   | 2425   | 2460  | 2426   |
| $2^+(2S_0)$     | 2460      | 2600   | 2468   | 2490  | 2460   |
| $2^+(2S_1)$     | 2533      | 2580   | 2483   | 2589  | 2581   |
| $1^+(3D_1)$     | 2619      | 2640   | 2671   | 2692  | 2632   |
| $3^+(1D_1)$     | ?         | 2830   | -      | 2799  | 2863   |

From the above analysis and Table I, we conclude that $2S_0$ is a good candidate for pseudoscalar meson $D(2550)$. $D(2610)$ in the $2S_1$ state or an admixture of $2S_1$ and $1D_1$ states. $D(2760)$ can be a pure $1D_1$ or an admixture of $2S_1$ and $1D_1$ as the mass of the orthogonal meson.

**Decay width**: Further studies of the two-body strong decay will be helpful to distinguish the different structure assignment to $D(2550)$, $D(2610)$, and $D(2760)$ using the quark pair creation (QPC) model [6, 7, 10], which is a successful phenomenological model with the Okubo-Zweig-Iizuka (OZI) allowed strong decays of hadron. The relevant decay channels of these particles are listed in Table II applying the quantum number assignment to $D(2550)$, $D(2610)$, and $D(2760)$ discussed above. Defining the transition operator $T$ in the QPC model [6, 7, 10], the main task is to calculate the helicity amplitude $M_{\ell m}(M_p M_q K)$ corresponding to the strong decay processes $A\{1(\bar{q}q)(2)\} \rightarrow B\{1(\bar{q}q)(3)\} + C(\bar{q}q)(4)$ shown in Table II where the harmonic oscillator (HO) wave function $\Psi_{n_{\ell m}}(k) = R_{n_{\ell m}}(R, k)|Y_{n_{\ell m}}(k)$ is applied to calculate the spatial integral in the transition matrix element (See Ref. [11] for more details). The parameter $R$ in the HO wave function is adjusted so that it reproduces the realistic root mean square (RMS) radius. The RMS is obtained by solving the Schrödinger equation with the potential in Refs. [12, 13], which gives different $R$ values corresponding to $\pi/\eta, \rho/\omega, K, D, D^*, D_s, D_s^*, D_1(2430), D_1(2420), D_2(2460)$, $D(2420)$, and $D(2460)$, respectively. The remaining input parameters are the constituent quark masses of charm, up/down, and strange, i.e., 1.45 GeV, 0.33 GeV, and 0.55 GeV, respectively [12]. In addition, the strength of the QPC from the vacuum can be extracted by fitting the data. In this letter, we take $\gamma = 6.3$ [14]. The strength of $s \bar{s}$ creation satisfies $\gamma = \gamma/\sqrt{3}$ [9].

**TABLE II**: The allowed decay channels (\(\bullet\)) of $2S_0$ and $1D$ charmed mesons with the quantum number assignment to $D(2550)$, $D(2610)$, and $D(2760)$ discussed in this letter. For $D(2610)$, decays into $D_0, D_0^*$, $D_1$, and $D_2^*$ are forbidden due to the limit of phase space. Here, $D_1(2430)$ and $D_2(2420)$ are the $1^+$ states in the $S = (0^+, 1^+)$ and $T = (1^+, 2^+)$ doublets, respectively.

| Modes | Channel | $0^+(2S_0)$ | $1^+(2S_1)$ | $1^+(1D_1)/3^+(1D_3)$ |
|-------|---------|-------------|-------------|----------------------|
| $0^+ + 0^-$ | $Dn$ | $\bullet$ | $\bullet$ | $\bullet$ |
| $0^+ + 1^-$ | $D\rho$ | $\bullet$ | $\bullet$ | $\bullet$ |
| $1^+ + 0^-$ | $D^*\pi$ | $\bullet$ | $\bullet$ | $\bullet$ |
| $0^+ + 0^-$ | $D_0(2400)$ | $\bullet$ | $\bullet$ | $\bullet$ |
| $1^+(S) + 0^-$ | $D_1(2430)$ | $\bullet$ | $\bullet$ | $\bullet$ |
| $1^+(T) + 0^-$ | $D_1(2420)$ | $\bullet$ | $\bullet$ | $\bullet$ |
| $2^+ + 0^-$ | $D_2(2460)$ | $\bullet$ | $\bullet$ | $\bullet$ |

In Figs. 2 and 3 the decay behaviors of $D(2550)$, $D(2610)$, and $D(2760)$ with different quantum number assignments are presented.

$D(2550)$ : The total decay width of $D(2550)$ mainly comes from its $D^*\pi^0$ and $D^*\pi^+$ contributions just shown in Fig. 2 where the theoretical estimate of the width for $D(2550)$ is given by $\Gamma \approx 8$ MeV for the typical value $R = 3.6$ GeV$^{-1}$, which is far below the observed value of the decay width 127.6 MeV for $D(2550)$. In Fig. 2 we also show the $R$ dependence of the total decay width for $D(2550)$, whose shape is resulted from the node effects of the higher radial wave function. In the range $3.4 \leq R \leq 3.8$ GeV$^{-1}$, the upper limit of the the-
D(2550) and D(2610) : As shown in Fig. 3, assignment of D(2610) and D(2670) to pure $2^3S_1$ and $1^3D_1$ charmed mesons, respectively, can be fully excluded because their decay widths estimated by the QPC model cannot be fitted with the corresponding observed ones when setting the mixing angle $\phi = 0$. Instead, there exits unique, possible assignment to the structure of D(2610), i.e., an admixture of $2^1S_0$ and $1^3D_1$ charmed mesons just discussed in Eq. (1). One finds an overlap region (green band) between the theoretical and experimental results for D(2610) with the mixing angle $0.9 \leq \phi \leq 1.5$ radians, which strongly supports that D(2610) and D(2670) are the orthogonal cousins. This explains why D(2610) has been first observed in both $D\pi$ and $D\eta$ channels because the main decay modes of of D(2610) are $D_1(2430)\pi$, $D_0^*(2490)\pi$, and $D\eta$ as shown in Fig. 3. In addition, theoretical estimate for the several ratios $R_l = \Gamma(D^{*}\pi)/\Gamma(D\rho)$, $R_2 = \Gamma(D\pi)/\Gamma(D_1(2430)\pi)$, and $R_3 = \Gamma(D^*\eta)/\Gamma(D\eta)$ for the dominant decays of D(2610) is calculated in this mixing angle region $0.9 \leq \phi \leq 1.5$ which may provide to check the validity of the assumption that the structure assignment to D(2610) is given by Eq. (1). Measurement of the ratio $\Gamma(D^{*}\pi)/\Gamma(D\rho)$ for D(2610) may be easier to do because the final states $D^{*}\pi$ and $\pi$ can be easily detected.

D(2670) and D-waves : If explaining D(2670) as $1^3D_1$, the calculated total decay width for $D(1^3D_1)$ is about a half of the observed one when scanning the range $3.4 \leq R \leq 3.8$ GeV$^{-1}$, where the total widths are 33.2, 32.9, 32.5, 31.9, and 31.3 MeV corresponding to $R = 3.4, 3.5, 3.6, 3.7, 3.8$ GeV$^{-1}$, respectively, which indicates the total decay width is not sensitive to $R$. Owing to the uncertainties coming from the QPC model and the present experiment, $1^3D_1$ assignment to D(2670) cannot be excluded. We especially notice that $D^{*}\pi$ and $D\rho$ are the dominant decay modes for $D(1^3D_1)$ with the ratio $\Gamma(D^{*}\pi)/\Gamma(D\rho) = 1.1$ with the typical value $R = 3.6$ GeV$^{-1}$ (see Table III), which explains why $D^{*}\pi$ is first observed among many decay channels of D(2670). In addition to this, D(2670) can be the orthogonal partner of D(2610) because the total decay width for D(2670) calculated by the QPC model is close to the upper limit of the observed one with the same mixing angle range as D(2610). This is shown in Fig. 3 with the predicted partial decay behaviors of D(2670). One needs to have further precise measurements on the main decay channels of D(2670), especially on $D^{*}\pi$ and $D_1(2420)$ because the two-body strong decays of D(2670) for the above two different structure assignments display different behaviors as shown in Table III and illustrated in the right diagram of Fig. 3.

$D(2^-$) states : In the following, the decay behaviors of two $2^-$ states in 1D charmed mesons, which are still missing in experiment, are predicted. As described in Fig. 4, the total and partial decay widths for two $2^-$ states are given with the mass dependence because the spectra of two $2^-$ states are unknown. By increasing the mass of $2^-$ charmed meson, more decay channels are open. As a result, the widths of two $2^-$ charmed mesons become broad, where $1^3D_1$ and $2^3S_1$ channels (with the underline to mark the quantum number of charmed meson) are dominant decay modes of both $2^-$ charmed mesons for the whole mass region. Additionally, $2^1P_1$ is also the dominant decay of $2^- (1^3D_2^-)$ charmed meson once this channel
FIG. 3: (Color online.) The variation of the total and partial decay widths for two $^1D_3$ states discussed in this letter with the mixing angle range $-1.5 \leq \phi \leq 1.5$ radians. Here, dashed lines with error bands are the BaBar’s result of the widths for $D(2610)$ and $D(2760)$.

| Decay channel | Decay width (MeV) |
|---------------|-------------------|
| Total         | 32.47             |
| $D^*\pi$      | 12.78             |
| $D\rho$       | 3.49              |
| $D\omega$     | 1.07              |
| $D\eta$       | 0.55              |
| $D^*\eta$     | 0.30              |
| $D(2430)\pi$  | 0.12              |

In summary, three newly observed charmed resonances, $D(2550)$, $D(2610)$, and $D(2760)$, have been for the first time assigned as $2S$ and $1D$ charmed meson by the analysis of mass spectrum as well as the calculation of two-body strong decay. Concretely, $D(2610)$ should be the mixing of $D(2S_1^3)$ and $D(1D_1^1)$ charmed mesons with spin-parity $J^P = 1^-$, where pure $1^- (2S_1^3)$ state assignment to $D(2610)$ has been fully excluded in this letter. There exist two structure assignments to $D(2760)$, i.e., the orthogonal cousin of $D(2610)$ or $3^- (1^D_3)$, which can be distinguished by further study on the main decay channels of $D(2760)$ in future experiment. Although $D(2550)$ is seemingly explained as $21S_0$ state under the analysis of the mass spectra, we have found discrepancy between theory and the experiment on the width for $D(2550)$. Our theoretical calculation of its decay width is far less than the observed one by BaBar. This may be due to our quark model assumption or due to the assignment $21S_0$ to $D(2550)$. Moreover, the decay behavior of the remaining two $1D$ charmed mesons have also been predicted, which provides valuable information for future experiments to search for all $1D$ charmed states.

Just because of the similarity between charmed and charmed-strange mesons, this study will shed light on the underlying properties of the observed charmed-strange states $D_{1s}(2710)$ and $D_{1s}(2860)$ [17] due to two facts which may reflect the global flavor $SU(3)$ recovery [18]: the mass gap between $D(2760)$ and $D(2610)$ surprisingly agrees with that of $D_{1s}(2860)$ and $D_{1s}(2710)$, both of which are about 150 MeV; $D_{1s}(2860)/D_{1s}(2710)$ have almost the same mixing angle between $1S_1^3$ and $1D_1^1$ states as that of charmed cousins $D(2760)/D(2610)$ if considering the mixing of two $1^-$ states to explain $D(2760)/D(2610)$ and $D_{1s}(2860)/D_{1s}(2710)$ [12]. More abundant experimental phenomena together with further efforts on phenomenological study will contribute to our understanding of heavy-light meson system.

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[1] P. del Amo Sanchez et al. [The BABAR Collaboration], arXiv:1009.2076 [hep-ex].
[2] S. Godfrey and N. Isgur, Phys. Rev. D 32, 189 (1985).
[3] T. Matsuki, T. Morii, and K. Sudoh, Prog. Theor. Phys. 117, 1077 (2007).
[4] M. Di Pierro and E. Eichten, Phys. Rev. D 64, 114004 (2001).
[5] D. Ebert, V.O. Galkin, and R.N. Faustov, Eur. Phys. J. C66, 197 (2010).
[6] L. Micu, Nucl. Phys. B 10, 521 (1969).
[7] K. Nakamura et al. (Particle Data Group), J. Phys. G 37, 075021 (2010).
[8] J. L. Rosner, Phys. Rev. D 64, 094002 (2001).
[9] A. Le Yaouanc, L. Oliver, O. Pene, and J. C. Raynal, Phys. Lett. B 72, 57 (1977).
[10] A. Le Yaouanc, L. Oliver, O. Pene, and J. C. Raynal, Hadron Transition in the Quark Model, NEW YORK, USA: GORDON AND BREACH (1988) p.311.
[11] Z. G. Luo, X. L. Chen, and X. Liu, Phys. Rev. D 79, 074020 (2009); B. Zhang, X. Liu, W. Z. Deng, and S. L. Zhu, Eur. Phys. J. C 50, 617 (2007); Z. F. Sun and X. Liu, Phys. Rev. D 80, 074037 (2009); X. Liu, Z.G. Luo, and Z.F. Sun, Phys. Rev. Lett., 104, 122001 (2010).
[12] D. M. Li and B. Ma, Phys. Rev. D 81, 014021 (2010).
[13] F. E. Close and E. S. Swanson, Phys. Rev. D 72, 094004 (2005).
[14] S. Godfrey and R. Kokoski, Phys. Rev. D 43, 1679 (1991).
[15] H. G. Blundell, arXiv:hep-ph/9608473.
[16] T. Matsuki, T. Morii, and K. Seo, Prog. Theor. Phys. 124, 285 (2010).
[17] B. Aubert et al. [The BABAR Collaboration], Phys. Rev. D 80, 092003 (2009) [arXiv:0908.0806 [hep-ex]].
[18] T. Matsuki, T. Morii, and K. Sudoh, Phys.Lett. B659, 593 (2008) [arXiv:0712.1288 [hep-ph]].