Theoretical study of the $d^*(2380) \rightarrow d\pi\pi$ decay width

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The decay widths of the $d^* \rightarrow d\pi^0\pi^0$ and $d^* \rightarrow d\pi^+\pi^-$ processes are explicitly calculated in terms of our chiral quark model. By using the experimental ratios of cross sections between various decay channels, the partial widths of the $d^* \rightarrow pn\pi^0\pi^0$, $d^* \rightarrow pn\pi^+\pi^-$, $d^* \rightarrow pp\pi^0\pi^-$, and $d^* \rightarrow nn\pi^+\pi^0$ channels are also extracted. Further including the estimated partial width for the $d^* \rightarrow pn$ process, the total width of the d^* resonance is obtained. In the first step of the practical calculation, the effect of the dynamical structure on the width of d^* is studied in the single $\Delta\Delta$ channel approximation. It is found that the width is reduced by a few tens of MeV, in comparison with the one obtained by considering the effect of the kinematics only. This presents the importance of such an effect from the dynamical structure. However, the obtained width with the single $\Delta\Delta$ channel wave function is still too large to explain the data. It implies that the d^* resonance will not consist of the $\Delta\Delta$ structure only, and instead there should be enough room for other structures such as the hidden-color (CC) component. Thus, in the second step, the width of d^* is further evaluated by using a wave function obtained in the coupled $\Delta\Delta$ and CC channel calculation in the framework of the resonating group method (RGM). It is shown that the resultant total width for d^* is about 69 MeV, which is compatible with the experimental observation of about 75 MeV and justifies our assertion that the d^* resonance is a hexaquark-dominated exotic state.

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I. INTRODUCTION

In recent years, the CELSIUS/WASA and WASA@COSY Collaborations successively reported the observation of a resonancelike structure in the double pionic fusion channels $pn \rightarrow d\pi^0\pi^0$ and $pn \rightarrow d\pi^+\pi^-$ when they studied the ABC effect and in the polarized neutron-proton scattering [1–3]. They mentioned that because the width of the structure is rather narrow, which is three more times smaller than $2\Gamma_\Delta$ in the conventional $\Delta\Delta$ process, the observed data cannot be explained by the contribution from either the Roper excitation or the t-channel $\Delta\Delta$ process. Therefore, they proposed a d^* hypothesis, in which its quantum number, mass, and width are $I(J^P) = 0(3^+)$, $M \approx 2360$ MeV, and $\Gamma \approx 80$ MeV [1] (in their recent paper [4], they take averaged values over the results from elastic scattering and two-pion production, i.e., $M \approx 2375$ MeV and $\Gamma \approx 75$ MeV), respectively, to accommodate the data. Because "the structure, containing six valence quarks, constitutes a dibaryon, and could be either an exotic compact particle or a hadronic molecule" [5], this result draws physicists' special attention.

In fact, the existence of the nontrivial six-quark configuration with $I(J^P) = 0(3^+)$ (called d^* lately) has intensively been studied since Dyson's estimation [6]. A variety of methods or models, such as group theory [6], the bag quark model [7], the quark potential model [8–10], etc., has been employed to investigate the structure of d^*, among which some investigations have produced a mass close to the recent data; they either are not a dynamical calculation or are a calculation without the width prediction or with an incorrect width prediction. It should specially be noted that in one of those papers [10], one performed a coupled-channel dynamical calculation in 1999 where a $\Delta\Delta$ channel and a hidden-color channel (denoted by CC) are included and the predicted binding energy is about 40–80 MeV. This means that in this structure there might exist a six-quark configuration, which coincides with COSY's assertion. Nevertheless, in that paper, the width of the state has not been calculated.

After COSY reported their finding, many investigations have been devoted to this aspect. There are mainly three kinds of models on the structure of the d^* resonance. (a) It is a $\Delta\Delta$ resonance [11]. Huang *et al.* [11] performed a multichannel scattering calculation and obtained a binding energy of about 71 MeV with respect to the $\Delta\Delta$ threshold and a width of about 150 MeV where $\Gamma_{NN} = 14$ MeV and $\Gamma_{\text{inel}} = 136$ MeV. (b) It is dominated by a "hidden-color" six-quark configuration. Bashkanov *et al.* [12] argued in 2013 that this hidden-color structure is necessary for understanding the strong coupling of d^* to $\Delta\Delta$. Later, Huang and his collaborators made an explicit dynamic calculation in the framework of the resonating group method (RGM) [13] and showed a binding energy of about 84 MeV and almost 67% of "hidden-color" configuration in d^*. This implies that d^* is probably a six-quark dominated exotic state. (c) It is a result of the $\Delta N\pi$ three-body interaction [14]. To justify which one of these three is more reasonable, a detailed calculation, especially the decay width, should be performed and further experimental investigation should be carried out.

In this paper, we focus on d^* width study. We first examine the effect of the dynamical structures of the d^* and deuteron bound states on the decay width of d^* and consequently fetch the contribution from the $\Delta\Delta$ structure of d^* with $J^P = 3^+$. Then, we estimate the total width of d^* by including the contributions from other possible decay channels. At the beginning, we temporarily assume that d^* is composed of the $\Delta\Delta$ structure only. In the calculation, the extended chiral SU(3) quark model is employed, because this constituent quark potential model can successfully reproduce the spectra of baryon ground states, the binding energy of the deuteron, the nucleon-nucleon (NN), the Kaon-nucleon (KN) scattering phase shifts, and the hyperon-nucleon (YN) cross sections (for details see Refs. [15–17]). With the same set of model parameters fixed in explaining the abovementioned data, the bound state problem of the $\Delta\Delta$ system is solved and the realistic wave functions of d^* and deuterons are obtained via the dynamical RGM calculation. With these wave functions, the two-pion decay width of $d^*(2380)$ in the process of $d^* \to d\pi\pi$ is calculated on the quark level, where the chiral effective Lagrangian of the quark-quark-pion is employed. In terms of the experimental data of other observed decay channels such as $d^* \to np\pi^0\pi^0$, $d^* \to np\pi^+\pi^-$, $d^* \to nn\pi^+\pi^0$, $d^* \to pp\pi^0\pi^-$, etc., the total width of d^* is estimated, and the role of dynamical structures to the decay width is analyzed. The result with the single $\Delta\Delta$ channel assumption exhibits the importance of the dynamical structure effect, which reduces the decay width by about a few tens of MeV. However, the width is still larger than the experimentally observed value, so that the other structure in d^* should further be considered. Subsequently, we evaluate the width of d^* with the wave function obtained in the coupled $\Delta\Delta$ and CC channel RGM calculation [13]. The resultant total width of d^* is about 69 MeV, which is compatible with the experimental data. In the next section, the formalism is briefly given. The numerical results and discussion are presented in the final section.

II. BRIEF FORMALISM

Referring to Ref. [18], the phenomenological effective Hamiltonian for the quark-quark-pion interaction in the nonrelativistic approximation is

$$\mathcal{H}_{qq\pi} = g_{qq\pi}\vec{\sigma}\cdot\vec{k}_\pi \tau\cdot\phi \frac{1}{(2\pi)^{3/2}\sqrt{2\omega_\pi}}, \tag{1}$$

where $g_{qq\pi}$ is the coupling constant, ϕ stands for the π meson field, ω_π and $\vec{k}_\pi$ are the energy and three-momentum of the π meson, respectively, and $\sigma(\tau)$ represents the spin (isospin) operator of a single quark. In the conventional constituent quark model, the wave functions are

$$|N\rangle = \frac{1}{\sqrt{2}}[\chi_\rho\psi_\rho + \chi_\lambda\psi_\lambda]\Phi_N(\vec{\rho},\vec{\lambda}) \tag{2}$$

for the nucleon and

$$|\Delta\rangle = \chi_s\psi_s\Phi_\Delta(\vec{\rho},\vec{\lambda}) \tag{3}$$

for the $\Delta(1232)$ resonance. In Eqs. (2) and (3), χ and ψ stand for their spin and isospin wave functions, $\Phi_N(\vec{\rho},\vec{\lambda})$ and Φ_Δ are the spatial wave functions of the nucleon and the Δ resonance, respectively, and ρ and λ are the Jacobi coordinates for the internal motion. Then, the decay width for $\Delta \to \pi N$ reads

$$\Gamma_{\Delta\to\pi N} = \frac{4}{3\pi}k_\pi^3(g_{qq\pi}I_o)^2\frac{\omega_N}{M_\Delta}, \tag{4}$$

where $\omega_{\pi,N} = \sqrt{M_{\pi,N}^2 + \vec{k}_\pi^2}$ are the energies of the pion and the nucleon, respectively, $k_\pi \sim 0.229$ GeV, and I_o denotes the spatial overlap integral of the internal wave functions of the nucleon and the Δ resonance. By fitting the measured width of 117 MeV for $\Delta_{3/2^+}(1232)$ [19], one gets the value of the factor $G = g_{qq\pi}I_o \sim 5.41\ \text{GeV}^{-1}$, which is an effective coupling of Δ to the nucleon and π, and involves the coupling constant $g_{qq\pi}$ and the spatial integral I_0. With this G value and the employed conventional constituent quark model, the remaining calculation would be meaningful.

Now using the knowledge of $\mathcal{M}_{\Delta\to\pi N}$ obtained above, we can estimate the decay width in the $d^* \to d\pi\pi$ process. The transition matrix element between the initial state d^* and the final state $d\pi^0\pi^0$ can be written as

$$\begin{aligned}\mathcal{M}_{if}^{\pi^0\pi^0} = & \frac{1}{\sqrt{3}}\sum F_1F_2k_{1,\mu}k_{2,\nu}I_S^0I_I^0C_{1\nu,1\mu}^{jm_j}C_{3m_{d^*},jm_j}^{1m_d} \\ & \times\int d^3q\Bigg[\frac{\chi_d^*(\vec{q}-\frac{1}{2}\vec{k}_{12})}{E_\Delta(q)-E_N(q-k_1)-\omega_1} \\ & + \frac{\chi_d^*(\vec{q}+\frac{1}{2}\vec{k}_{12})}{E_\Delta(q)-E_N(q-k_2)-\omega_2} \\ & + \frac{\chi_d^*(\vec{q}+\frac{1}{2}\vec{k}_{12})}{E_\Delta(-q)-E_N(-q-k_1)-\omega_1} \\ & + \frac{\chi_d^*(\vec{q}-\frac{1}{2}\vec{k}_{12})}{E_\Delta(-q)-E_N(-q-k_2)-\omega_2}\Bigg]\chi_{d^*}(\vec{q}),\end{aligned} \tag{5}$$

where i and f stand for the initial d^* state with quantum numbers $[(Sm_S) = (3m_{d^*})]$ and the final deuteron state with $[(Sm_S) = (1m_d)]$, respectively, $I_{S(I)}^0$ is the spin (isospin) factor shown in the Appendix, $F_{1,2} = F(k_{1,2}^2) = \frac{4G}{(2\pi)^{3/2}\sqrt{\omega_{1,2}}}$, $\vec{k}_{12} = \vec{k}_1 - \vec{k}_2$, and $\omega_{1,2} = \sqrt{m_\pi^2 + \vec{k}_{1,2}^2}$. $\chi_d(\vec{q})$ and $\chi_{d^*}(\vec{q})$ are, respectively, the relative wave functions of the final deuteron (between the two nucleons) and the initial d^* (between the two Δs), where $\vec{q} = \frac{1}{2}(\vec{p}_1+\vec{p}_2+\vec{p}_3-\vec{p}_4-\vec{p}_5-\vec{p}_6)$ with $\vec{p}_i$ being the momentum of the ith quark. Four terms in the brackets of Eq. (5) are related to the propagators of four subdiagrams in Fig. 1. In our calculations, we only consider the process in which these two pions are emitted from two constituent Δs, respectively, due to the fact that the dominant decay mode of the Δ resonance is $N\pi$.

With the transition matrix element $\mathcal{M}_{if}^{\pi^0\pi^0}$, the decay width of d^* in the $d^* \to d\pi\pi$ channel can be evaluated by

$$\begin{aligned}\Gamma_{d^*\to d\pi^0\pi^0} = & \frac{1}{2!}\int d^3k_1d^3k_2d^3p_d(2\pi)\delta^3(\vec{k}_1+\vec{k}_2+\vec{p}_d) \\ & \times\delta\big(\omega_{k_1}+\omega_{k_2}+E_{p_d}-M_{d^*}\big)\big|\overline{\mathcal{M}_{if}^{\pi^0\pi^0}}\big|^2,\end{aligned} \tag{6}$$

where ω_{k_1} and ω_{k_2} are the energies of the two outgoing pions, E_{p_d} is the energy of the outgoing deuteron with momentum p_d, and the bar on the top of the transition matrix $\mathcal{M}_{if}^{\pi^0\pi^0}$ means that this matrix element is averaged over the initial states and summed over the final states. The factor of 2! is due to the two identical pions in the final states.

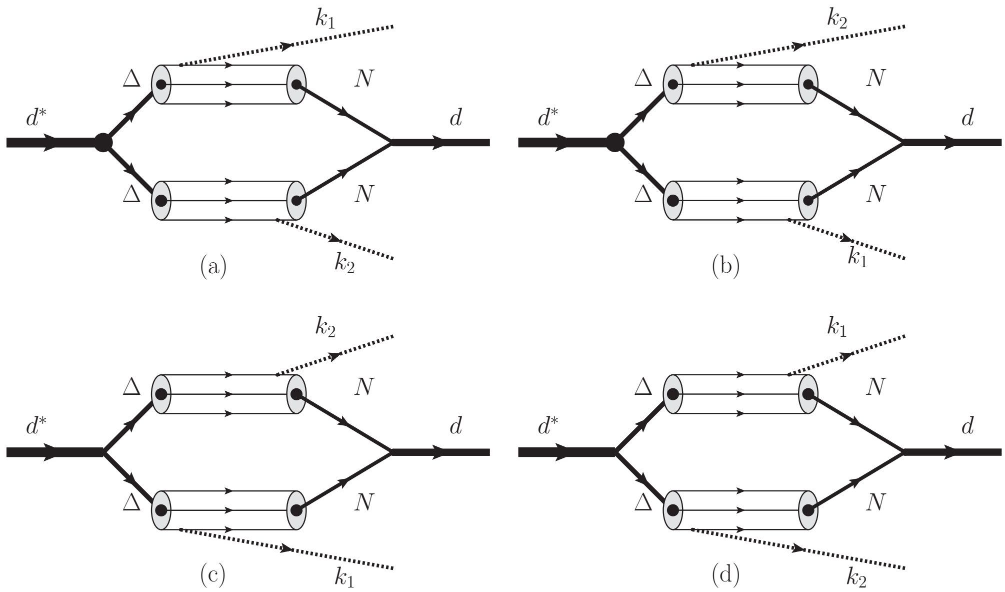

FIG. 1. Four possible emission paths in the decay of the d^* resonance composed of the $\Delta\Delta$ structure only. Two pions with momenta of $\vec{k}_1$ and $\vec{k}_2$ are emitted from one of the three quarks in two Δs, respectively.

In the practical decay width calculation, one needs the explicit relative wave functions of the deuteron and $d^*(2380)$ systems. These wave functions can usually be taken from the realistic solutions of the systems considered. In this work, we acquire these wave functions by dynamically solving the RGM equation in the extended chiral SU(3) quark model [13]. In this calculation, the resultant binding energy is $\epsilon = 2.2$ MeV for the deuteron and $\epsilon \approx 62$ MeV and $\epsilon \approx 84$ MeV for d^* in the single $\Delta\Delta$ channel approximation and in the coupled $\Delta\Delta + \mathrm{CC}$ channel case, respectively. Then, the definition of the d^* mass is $M_{d^*} = 2M_\Delta - \epsilon$. In the coordinate space, the wave functions of the deuteron and d^* systems can also be expressed, respectively, as

$$\begin{aligned}\Psi_d &= \big[\phi_N(\xi_1,\xi_2)\phi_N(\xi_4,\xi_5)\chi_d(R)\\&\quad+\phi_C^d(\xi_1,\xi_2)\phi_C^d(\xi_4,\xi_5)\chi_{CC}^d(R)\big]\zeta_{(SI)=(10)},\\\Psi_{d^*} &= \big[\phi_\Delta(\xi_1,\xi_2)\phi_\Delta(\xi_4,\xi_5)\chi_{\Delta\Delta}(R)\\&\quad+\phi_C^{d^*}(\xi_1,\xi_2)\phi_C^{d^*}(\xi_4,\xi_5)\chi_{CC}^{d^*}(R)\big]\zeta_{(SI)=(30)},\end{aligned} \tag{7}$$

where ϕ_N and ϕ_Δ denote the internal wave functions of N and Δ in the coordinate space, ϕ_C^{d,d^*} stands for the internal wave function of C (color-octet cluster in the deuteron and d^*, respectively, χ_d describes the relative wave functions of the deuteron between two nucleons, $\chi_{\Delta\Delta}$ and χ_{CC}^{d,d^*} represent the relative wave functions between Δs and between Cs for the deuteron and d^*, respectively, and $\zeta_{(SI)}$ stands for the spin-isospin wave function of the corresponding system. In the single $\Delta\Delta$ channel approximation, the CC component is not considered in both the deuteron and the d^* wave functions; however, in the coupled $\Delta\Delta + \mathrm{CC}$ case, it is omitted only in the deuteron wave function, because it is negligibly small. It should be specially noted that the wave function in Eq. (7) is normally called the channel wave function [13]. In the coupled-channel calculation, this wave function is obtained by projecting the totally antisymmetrized wave function, as the solution of the RGM equation, onto the physical basis, namely, the cluster internal wave function in each component, so that the effect of the total antisymmetrization of the wave function can be absorbed in the channel wave function. An important feature of such a wave function is that the channel wave functions are orthogonal to each other. The relevant channel wave functions of the concerned systems are plotted in Fig. 2.

Here we would like to mention that, in the RGM calculation, the trial wave function of the d^* system is assumed to have two major components, $\Delta\Delta$ and CC, which are totally antisymmetrized. Solving the RGM equation, one obtains the relative wave functions of the system. By projecting the resultant wave function onto the cluster internal wave function in each component, we get the intercluster relative wave function, namely, the channel wave function, for the corresponding channel. Now, the contribution from the CC channel via the quark exchange is included in the projected wave function (or the channel wave function) $\chi_{\Delta\Delta}(R)$ already [13]. We should specially emphasis that the channel wave functions obtained in Eq. (7) are orthogonal to each other. Therefore, in the lowest order, by using this channel wave function, there is no quark exchange between the two physical particles and thus the colored clusters (color octet) cannot turn into the uncolored clusters (color singlet).

For the sake of convenience, we expand the relative wave function in the following:

$$\chi(R) = \sum_{i=1}^{4} c_i \exp\left(-\frac{R^2}{2b_i^2}\right). \tag{8}$$

We would also mention that the D-wave contribution is omitted due to its relatively small contribution, although both the S- and D-wave functions exist in our resultant wave functions.

With these wave functions, two additional assumptions are employed in the estimation of the decay width in

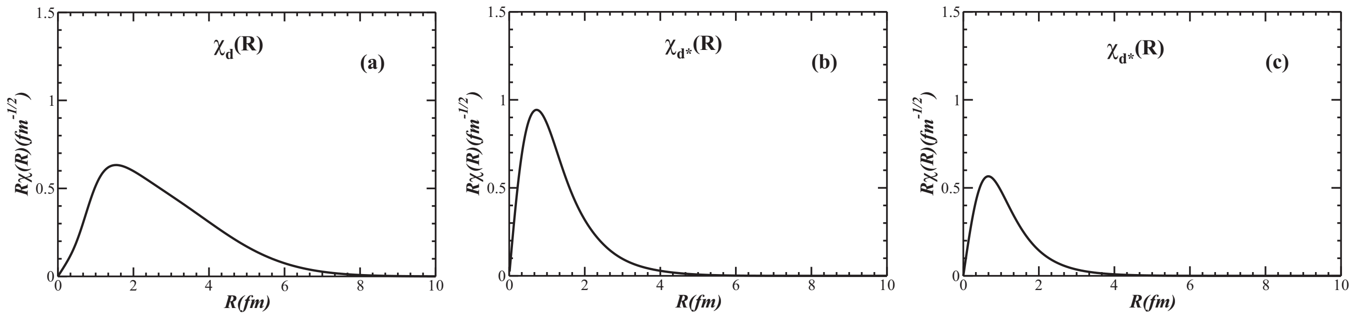

FIG. 2. Relative wave functions in the S wave in the extended chiral SU(3) quark model: (a) for deuteron, (b) for $\chi_{\Delta\Delta}$ in the single $\Delta\Delta$ channel case for $d^*(2380)$, and (c) for $\chi_{\Delta\Delta}$ in the coupled $\Delta\Delta$ and CC channel case for $d^*(2380)$.

$d^* \to d\pi\pi$. One is associated with the energy denominators in Eq. (5), where the pole position is simply taken, as is usually done in the K-matrix approximation approach. The other one is related to the directions of the two outgoing pions. Because the experimental data show that the angle between the two outgoing pions is almost zero, namely, the pions are propagating in the same direction, we can employ this experimental fact to constrain the directions of two emitted pions, namely, add the condition $\vec{k}_1 \parallel \vec{k}_2 \parallel \hat{z}$ to the directions of the momenta of emitted pions, so that the numerical calculation can be greatly simplified. It is clear that our approach, under this condition, would give an upper limit for the width.

III. NUMERICAL RESULTS AND DISCUSSION

In the calculation, the masses of deuterons, Δ, nucleons, and pions are taken from the Particle Data Group [19]. The mass of d^* is $M_{d^*} = 2M_\Delta - \epsilon$ with ϵ being 62 MeV for the single $\Delta\Delta$ channel case and ∼84 MeV for the coupled $\Delta\Delta$ and CC channel case, respectively. The value of G is already fixed by using the $\Delta \to \pi N$ decay data. The decay width in the $d^* \to d\pi\pi$ process with realistic wave functions from the RGM calculation can numerically be obtained by using Eq. (6).

Moreover, the experimental data [1,2,20,21] and one of theoretical calculations [22] have shown that, for the d^* resonance at $\sqrt{s} = 2370$ MeV, the decay cross section in the $d^* \to pn\pi^+\pi^-$ process is about 0.20 mb, which is comparable with that of 0.24 mb in the $d^* \to d\pi^0\pi^0$ process, and the decay cross section in the $d^* \to pp\pi^0\pi^-$ process (also its mirrored channel $d^* \to nn\pi^+\pi^0$) has a visible value of about 0.10 mb as well. Therefore, contributions in these processes should also be accounted for in the d^* width estimation. Using the Breit-Wigner formalism and those cross-section data, the branching ratios of various decay modes have been estimated [4,23]. For reference, we tabulate them in the second to the last column in Table I. It should be noted that if the isospin symmetry of pions is not broken, due to the multiplicity of pion, a simple count leads to a factor 2 for the cross section ratio of the $d^* \to d\pi^+\pi^-$ process to the $d^* \to d\pi^0\pi^0$ process. However, a small isospin symmetry breaking, namely, a small mass difference between $\pi^\pm$ and π^0, would reduce this factor to about 1.6 [2,4,23]. In our explicit calculation, this factor is about 1.81, which is again smaller than 2, but larger than the factor 1.6 found in Refs. [2,4,23]. Based on the resultant decay widths for $d^* \to d\pi^0\pi^0$ and $d^* \to d\pi^+\pi^-$ and the cross sections mentioned above, we get the branching ratios, and consequently the partial decay widths, for all possible decay modes. Finally, we achieve the total width of d^*.

To see the dynamical effect on the decay width, we should compare our estimated width with that noted by Bashkanov *et al.* [12] under the same mass condition (namely, with the same phase space factor) in the single $\Delta\Delta$ channel case. Because the binding energy of d^* in our single-channel case is 62 MeV ($M_{d^*} \approx 2402$ MeV), we have to readjust

TABLE I. Decay width.

M_{d^*}(MeV)	Ours			Expt.	
Mode	Single channel $\Delta\Delta$ 2374	Two channels $\Delta\Delta$ + CC 2380		[4,20,21,23] 2375	
	Γ(MeV)	$\mathcal{B}_r$	Γ(MeV)	$\mathcal{B}_r$	Γ(MeV)
$d^* \to d\pi^0\pi^0$	16.6	13.3%	9.2	14(1)%	10.2
$d^* \to d\pi^+\pi^-$	30.1	24.3%	16.8	23(2)%	16.7
$d^* \to pn\pi^0\pi^0$	14.1	11.3%	7.8	12(2)%	8.7
$d^* \to pn\pi^+\pi^-$	34.6	27.8%	19.2	30(4)%	21.8
$d^* \to pp\pi^0\pi^-$	7.06	5.65%	3.9	6(1)%	4.4
$d^* \to nn\pi^+\pi^0$	7.06	5.65%	3.9	6(1)%	4.4
$d^* \to pn$	8.24	12.0%	8.3	12(3)%	8.7
Total	117.7	99.9%	69.1	103(14)%	74.9

our model parameter to get a binding energy of about 90 MeV ($M_{d^*} \approx 2374$ MeV) to fit the condition in Ref. [12]. Fortunately, the resultant relative wave function of the $\Delta\Delta$ system, which represents the dynamical feature of the system in some sense, has a tiny deviation from that in the case of the binding energy of 62 MeV. Thus, the results with this wave function ($\epsilon \sim 90$ MeV) contain both the dynamical feature of the $\Delta\Delta$ system and the same phase space factor as in Ref. [12]. We tabulate these results in the second column in Table I.

From this table, one sees that in the single $\Delta\Delta$ channel calculation, the resultant total width of d^* justifies the fact that in a composite system, due to the binding behavior, namely, the attractive interaction between constituents, the decay width of the system is much smaller than the total decay widths of its constituents if they are assumed to be free particles. And even more, deeper binding would cause narrower width. This feature is reasonable, because the width is not only related to the phase space but also depends on the overlap of the wave functions of the bound states d^* and the deuteron. In comparison with the width of about 160 MeV estimated by Bashkanov *et al.* [12] with a binding energy of 90 MeV, where the effect of the phase space is considered only, we conclude that the contribution to the width from the dynamical effect is about a few tens of MeV. This conclusion tells us how important the effect of the dynamics on the width of an unstable composite system is, namely, the decay width is not only related to the phase space but also depends on the dynamical structure of the system. It also shows that the width of d^* in the single $\Delta\Delta$ channel case still exceeds the experimental value of 75 MeV. This means that the $\Delta\Delta$ structure alone cannot provide a reasonable width of d^*.

With the same scenario, we further exam the width contributed by the $\Delta\Delta$ component in d^* if d^* has the $\Delta\Delta$ + CC structure proposed in Refs. [10,13]. The results are also tabulated in Table I. It shows that with the wave function of the $\Delta\Delta$ component in Ref. [13], the decay widths for the $d^* \to d\pi^0\pi^0$ and $d^* \to d\pi^+\pi^-$ modes are about 9 and 17 MeV, respectively. If we further consider the $d^* \to pn\pi\pi$, $pp\pi^0\pi^-$, $nn\pi^+\pi^0$, and NN modes, the total width would be about 69.1 MeV. Of course, we should remember that there are uncertainties in our approach; small variations of our model parameter values in reasonable regions may produce about 10% uncertainties in our estimated decay widths.

Here we would like to emphasize again, in our RGM calculation, that the trial wave function of the d^* system is assumed to have two major components, $\Delta\Delta$ and CC, which are totally antisymmetrized. By using the projection technique mentioned above, we obtain corresponding channel wave functions, which are orthogonal to each other and include the required total antisymmetrization effect. Then, with these channel wave functions, there is no quark exchange between the two physical clusters in the lowest order and between the two bases as well, and thus the colored clusters (color octet) cannot turn into the uncolored clusters (color singlet). As a consequence, the width contributed by the projected CC component would almost be zero. Combining this point with the contribution from the $\Delta\Delta$ component, one sees that total width of d^* in our $\Delta\Delta$ + CC model is about 69.1 MeV, which is compatible with the experimental data of 75 MeV. Apparently, because the fraction of the wave function of the CC component in our $\Delta\Delta + \text{CC}$ model is about 67%, the resultant width of d^* justifies our assertion that the d^* resonance is a hexaquark-dominated exotic state.

Finally, it should also be mentioned that the existence of d^* should further be checked in other experimental processes. Now, except the $\gamma + d$ (or $e + d$) reaction and pp collision, the strong decay of the hidden heavy flavor meson, such as the $b\bar{b}$ meson and the $c\bar{c}$ meson, is also a place to hunt for d^*. In particular, searching for its antiparticle $\bar{d}^*$ in these processes is even plausible, because the antideuteron $\bar{d}$ and consequently $\bar{d}^*$ can only be created from quark-pair productions, so that the background would be very clean [24]. Now, at $\sqrt{s} \approx$ 10.6 GeV, the integrated luminosity is about 470 fb^{-1} at BaBar and about 3 fb^{-1} at CLEO. And both collaborations have observed $\bar{d}$ production at $\sqrt{s} \approx 10.6$ GeV [25,26]. Thus, one might search for $\bar{d}^*$ in the $\Upsilon(nS) \to \bar{d}^* + p + n$ process. Moreover, the Belle Collaboration has collected even more data of about 1000 fb^{-1} around $\sqrt{s} \approx 10.6$ GeV, and they might have the chance to observe the $\bar{d}$ and $\bar{d}^*$ productions in a similar process. Also, BEPCII/BESIII has reached an integrated luminosity of 1 fb^{-1} at $\sqrt{s} = 4.42$ GeV and 0.57 fb^{-1} at $\sqrt{s} = 4.6$ GeV. It might be possible to detect $\bar{d}^*$ in the $e^+ + e^- \to \bar{d}^* + p + n$ process as well. If one could observe d^* in the data set accumulated by BaBar, Belle, CLEO, and BEPCII/BESIII, it would definitely be helpful in confirming the existence of $d^*(2380)$ and its structure.

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APPENDIX: SPIN-ISOSPIN PART

The spin matrix element in the calculation is

$$\begin{aligned} I_S &= \sum C^{S_{AB}m_{AB}}_{S_Am_A,S_Bm_B} C^{S'_{AB}m'_{AB}}_{S'_Am'_A,S'_Bm'_B} C^{S'_Am'_A}_{S_Am_A,1\mu} C^{S'_Bm'_B}_{S_Bm_B,1\nu} \\ &= \sum (-)^{S'_{AB}-S_{AB}+S_A+S_B-S'_A-S'_B} \hat{S}'_A \hat{S}'_B \hat{S}_{AB} \hat{j}^2_{23} \hat{j} \\ &\quad \times \begin{Bmatrix} 1 & S_A & S'_A \\ S'_B & S'_{AB} & j_{23} \end{Bmatrix} \begin{Bmatrix} 1 & S_B & S'_B \\ S_A & j_{23} & S_{AB} \end{Bmatrix} \\ &\quad \times \begin{Bmatrix} S_{AB} & 1 & j_{23} \\ 1 & S'_{AB} & j \end{Bmatrix} C^{jm_j}_{1\nu,1\mu} C^{S'_{AB}m'_{AB}}_{S_{AB}m_{AB},jm_j} \\ &= I^0_S C^{jm_j}_{1\nu,1\mu} C^{S'_{AB}m'_{AB}}_{S_{AB}m_{AB},jm_j}, \end{aligned} \tag{A1}$$

where $\hat{a} = \sqrt{2a+1}$. For the present process, the initial d^* and the final deuteron have $S_{AB} = 3$ and $S'_{AB} = 1$, respectively. Moreover, Δ and the nucleon have $S_A = S_B = 3/2$ and $S'_A = S'_B = 1/2$, respectively. Therefore, in the present case $j_{23} = j = 2$ is restricted.

Moreover, one can deal with the isospin matrix element similarly. The isospins of Δ, the nucleon, d^*, and the deuteron are $3/2$, $1/2$, 0, and 0, respectively. Then $j = 0$ and $j_{23} = 1$ are constraints for the isospin part.

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