Understanding $d^*(2380)$ in a chiral quark model

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Abstract. We review our recent progresses made in the study of the structure and decay properties of the newly observed $d^*(2380)$ within a chiral constituent quark model. It is found that the $d^*(2380)$ can be explained as a compact hexaquark-dominated exotic state with a fraction of hidden color components of about 2/3 in its configuration. Based on this scenario the single- and double-pionic partial decay widths are calculated and the corresponding numerical results are in good agreement with the experimental data.

1 Introduction

So far most of the observed hadrons can be categorized into mesons and baryons, which are composed of a pair of constituent quark-antiquark and three constituent quarks, respectively. However, the fundamental theory of strong interactions, QCD, does not exclude the existence of the so-called exotic states which are color-singlet but cannot be attributed to the traditional mesons or baryons, e.g. glueballs, hybrids, molecules, and multiquark states. In systems with six constituent quarks, deuteron is for a few decades the only two-baryon molecule confirmed by experiments. Searching for other possible baryon-baryon molecules or hexaquark sates is a challenging and inspiring task for physicists in the community of hadron physics.

Recently a resonance with isospin (spin-parity) $I(J^P) = 0(3^+)$, mass $M \approx 2380$ MeV and width $\Gamma \approx 70$ MeV has been reported by the WASA-at-COSY Collaboration in an exclusive and kinematically complete measurement of the double pionic fusion reaction $pn \to d\pi^0\pi^0$ [1]. Later the same resonance has also been observed in several other two-pion production reactions: $pn \to d\pi^+\pi^-$, $pn \to pn\pi^0\pi^0$, $pn \to pp\pi^-\pi^0$, $pd \to {}^3\mathrm{He}\,\pi^0\pi^0$, $pd \to {}^3\mathrm{He}\,\pi^+\pi^-$, $dd \to {}^4\mathrm{He}\,\pi^0\pi^0$ and $dd \to {}^4\mathrm{He}\,\pi^+\pi^-$ [2–7]. In a partial wave analysis of the neutron-proton (np) scattering data performed by the WASA-at-COSY Collaboration and SAID Data Analysis Group, a resonance pole at $(2380 \pm 10) - i\,(40 \pm 5)$ MeV in the ${}^3D_3$-${}^3G_3$ coupled-channel partial waves has been reported [8, 9] when the newly observed analyzing power data for the polarized $\vec{n}p$ scattering reaction has been incorporated into the old data base for np scattering.

Theoretically, the newly observed $d^*(2380)$ is of particular interest. One of the major reasons is that it has an unusual narrow width. It is true that the mass of $d^*(2380)$ is about 80 MeV lower than the threshold of $\Delta\Delta$, but it is still much higher than the thresholds of

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the $\Delta N\pi$, $NN\pi\pi$ and NN channels. Naively, a rather wide decay width is expected since the Δ is very broad and moreover, the $d^*(2380)$ can decay into $\Delta N\pi$, $NN\pi\pi$ and NN channels via strong interactions. However, the experimentally observed decay width is only about 70 MeV, which is even smaller than 1/3 of the width of two free Δs, implying that the $d^*(2380)$ may have an unconventional structure involving new physical mechanisms.

When explaining $d^*(2380)$ as a $\Delta\Delta$ bound state, it is found that the calculated decay width is too large compared with data, even the mass can be reproduced properly [10]. Instead, there are two other explanations for the structure of $d^*(2380)$ which can reproduce both the mass and width simultaneously. One is claimed by our group [11–16], later mentioned by Bashkanov, Brodsky and Clement in Ref. [17], as a hexaquark-dominated exotic state. The other is claimed by Gal in Ref. [18] as a mixture of $\Delta\Delta$ state and $\Delta N\pi$ resonance structure.

In this talk, we briefly review the scenario we proposed for the structure of $d^*(2380)$ and the calculation of the mass and decay of $d^*(2380)$ in this scenario. We refer the readers to our published works [12–16] for details.

2 Mass and structure of $d^*(2380)$

We use a chiral SU(3) quark model to study the $\Delta\Delta$-CC system. The total Hamiltonian for a 6-quark system can be written as

$$H = \sum_{i=1}^{6} T_i - T_G + \sum_{j>i=1}^{6} \left(V_{ij}^{\rm OGE} + V_{ij}^{\rm conf} + V_{ij}^{\rm ch} \right), \tag{1}$$

with T_i being the kinetic energy operator for the i-th quark, T_G the kinetic energy operator for the center of mass motion of the whole system, $V_{ij}^{\rm OGE}$, $V_{ij}^{\rm conf}$ and $V_{ij}^{\rm ch}$ the one-gluon-exchange (OGE) potential, the phenomenological confinement potential and the chiral fields induced effective interaction between the i-th and j-th quarks, respectively. In the chiral SU(3) quark model, $V_{ij}^{\rm ch}$ reads

$$V_{ij}^{\rm ch} = \sum_{a=0}^{8} V_{ij}^{\sigma_a} + \sum_{a=0}^{8} V_{ij}^{\pi_a}, \tag{2}$$

and in the extended chiral SU(3) quark model, $V_{ij}^{\rm ch}$ reads

$$V_{ij}^{\rm ch} = \sum_{a=0}^{8} V_{ij}^{\sigma_a} + \sum_{a=0}^{8} V_{ij}^{\pi_a} + \sum_{a=0}^{8} V_{ij}^{\rho_a}, \tag{3}$$

with σ_a, π_a and ρ_a ($a = 0, 1, \cdots, 8$) being the scalar, pseudo-scalar and vector nonet fields, respectively. The explicit expressions of those potentials can be found in Ref. [13]. All the model parameters are taken from our previous work [19, 20], and no additional parameters are introduced in the study of $\Delta\Delta$-CC system.

The resonating group method (RGM) is employed to investigate the interaction properties of the $\Delta\Delta$-CC system. The trial microscopic wave function of the whole 6-quark system can be written as

$$\Psi_{6q} = \mathcal{A}\left[\phi_\Delta(\boldsymbol{\xi}_1,\boldsymbol{\xi}_2)\,\phi_\Delta(\boldsymbol{\xi}_4,\boldsymbol{\xi}_5)\,\eta_{\Delta\Delta}(\boldsymbol{r}) + \phi_{\rm C}(\boldsymbol{\xi}_1,\boldsymbol{\xi}_2)\,\phi_{\rm C}(\boldsymbol{\xi}_4,\boldsymbol{\xi}_5)\,\eta_{\rm CC}(\boldsymbol{r})\right]_{S=3,I=0,C=(00)}. \tag{4}$$

Here $\mathcal{A}$ is the antisymmetrizer required by the Pauli exclusion principle, $\phi_{\Delta({\rm C})}$ the antisymmetrized internal wave functions of the (123) ((456)) 3-quark cluster with $\boldsymbol{\xi}_i$ ($i = 1, 2$ $(4, 5)$) being its internal Jacobi coordinates, and $\eta_{\Delta\Delta({\rm CC})}$ the coordinate wave function of the relative motion of two clusters ΔΔ (CC) which is determined completely by the interaction dynamics of the whole six-quark system. Solving the RGM equation for a bound state problem,

$$\langle \delta\Psi_{6q}|H - E|\Psi_{6q}\rangle = 0, \tag{5}$$

one gets the binding energy E and the corresponding RGM 6-quark wave function Ψ_{6q}.

Table 1. Binding energy, root-mean-square radius (RMS), and fraction of each channel in $d^*(2380)$.

	$\Delta\Delta - \mathrm{CC}$ ($L = 0, 2$)		
	SU(3)	Ext. SU(3) (f/g=0)	Ext. SU(3) (f/g=2/3)
Binding energy (MeV)	47.27	83.95	70.25
RMS of $6q$ (fm)	0.88	0.76	0.78
Fraction of $(\Delta\Delta)_{L=0}$ (%)	33.11	31.22	32.51
Fraction of $(\Delta\Delta)_{L=2}$ (%)	0.62	0.45	0.51
Fraction of $(\mathrm{CC})_{L=0}$ (%)	66.25	68.33	66.98
Fraction of $(\mathrm{CC})_{L=2}$ (%)	0.02	0.00	0.00

The calculated binding energies for ΔΔ-CC system with $I(J^P) = 0(3^+)$ are tabulated in Table 1, where f/g means the ratio of tensor and vector couplings for vector meson exchanges in the extended chiral SU(3) quark model. One sees that the mass of the ΔΔ-CC bound state is about 2.38 – 2.42 GeV and the RMS is about 0.76 – 0.88 fm in various models, indicating that d^* is a deeply bound and compact state. This distinctive feature can be easily understood if we notice that both the quark exchange effect and the short-range interaction of the ΔΔ with $I(J^P) = 0(3^+)$ are "attractive" [12, 13].

The microscopic RGM wave function in Eq. (4) for ΔΔ and CC are not orthogonal to each other due to the transition between these two channels, and thus it is not suitable to be used directly to clarify the components of ΔΔ and CC in $d^*(2380)$. Instead, the channel wave function in the quark cluster model is introduced for ΔΔ and CC,

$$\chi_{\Delta\Delta(\mathrm{CC})}(\boldsymbol{r}) \equiv \left\langle \hat{\phi}_{\Delta(\mathrm{C})}(\boldsymbol{\xi}_1, \boldsymbol{\xi}_2)\, \hat{\phi}_{\Delta(\mathrm{C})}(\boldsymbol{\xi}_4, \boldsymbol{\xi}_5) \,\middle|\, \Psi_{6q} \right\rangle, \tag{6}$$

with $\hat{\phi}_{\Delta(\mathrm{C})}$ being the antisymmetrized internal wave function for the cluster of Δ(C). Then the wave function of d^* can be simply abbreviated and expanded as

$$\Psi_{d^*} = |\Delta\Delta\rangle\, \chi_{\Delta\Delta}(\boldsymbol{r}) + |\mathrm{CC}\rangle\, \chi_{\mathrm{CC}}(\boldsymbol{r})\,. \tag{7}$$

It is obvious that the ΔΔ and CC components in d^* as depicted in Eq. (7) are orthogonal to each other. By an integral of the square of the normalized relative wave functions $\chi_{\Delta\Delta(\mathrm{CC})}$, the fractions of each individual channel in total wave functions can be extracted, and the results are listed in Table 1. One sees that the fraction of the CC channel in d^* is about 66% – 68%. Note that according to symmetry, a pure hexaquark state of the ΔΔ-CC system with isospin $I = 0$ and spin $S = 3$ reads

$$[6]_{\mathrm{orb}}[33]_{IS=03} = \sqrt{\frac{1}{5}}\, |\Delta\Delta\rangle_{IS=03} + \sqrt{\frac{4}{5}}\, |\mathrm{CC}\rangle_{IS=03}\,, \tag{8}$$

which indicates that the fraction of CC channel in a pure hexaquark state is 80%. It is thus fair to say that d^* is a hexaquark-dominated exotic state as it has a CC configuration of about 66% – 68%.

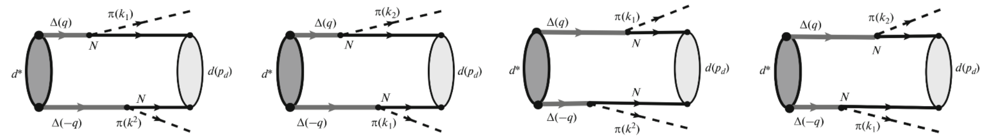

Figure 1. Illustration of $d^*(2380) \to d\pi\pi$ decay.

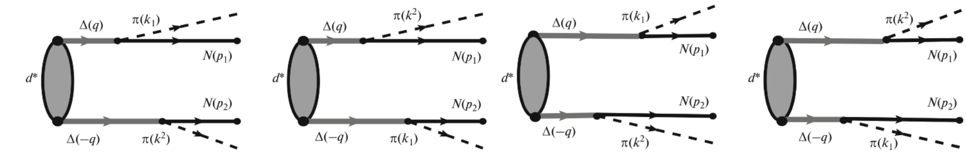

Figure 2. Illustration of $d^*(2380) \to NN\pi\pi$ decay.

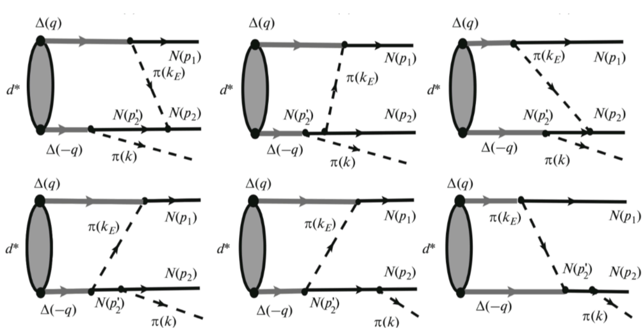

Figure 3. Illustration of $d^*(2380) \to NN\pi$ decay.

3 Decay width of $d^*(2380)$

As the CC component in $d^*(2380)$ cannot result in a direct break-up decay, in the lowest order, we only need to consider the contributions from the $\Delta\Delta$ components in $d^*(2380)$ for its decay. Figure 1 illustrates the possible decay mechanisms for $d^* \to d\pi\pi$ in time-ordered perturbation theory (TOPT). There the decay occurs in such a way that each of the two Δ's in d^* emits a pion and the remaining two nucleons form a deuteron [14]. Figure 2 illustrates the possible decay mechanisms for $d^* \to NN\pi\pi$ in TOPT. It differs from $d^* \to d\pi\pi$ in such a way that after the two Δ's in d^* emits two pions, the remaining two nucleons go out directly rather than form a deuteron [15]. Figure 3 illustrates the possible mechanisms for $d^* \to NN\pi$ in TOPT. There one pion is emitted from one of the two Δ's in d^*, and the other pion, emitted from another Δ in d^*, is absorbed by the system [16].

To calculate the transition matrix elements and further the partial decay width for the processes illustrated in Figs. 1-3, apart from the wave functions of Δ and N that are described by Gaussian wave functions in the model, one also needs the wave function of d^* which is given by Eq. (7), the wave function of deuteron which is obtained by study of the NN interaction, and the quark-quark-pion interaction that in the non-relativistic approximation can be written as

$$\mathcal{H}_{qq\pi} = \frac{g_{qq\pi}}{(2\pi)^{3/2}\sqrt{2\omega_\pi}} \boldsymbol{\sigma} \cdot \boldsymbol{k} \boldsymbol{\tau} \cdot \boldsymbol{\phi}_\pi, \tag{9}$$

with $g_{qq\pi}$ being the effective coupling constant to be fixed by the experimental decay width of $\Delta \to N\pi$, $\boldsymbol{\phi}_\pi$ the pion field, and $\boldsymbol{k}$ and $\omega_\pi = \sqrt{m_\pi^2 + \boldsymbol{k}^2}$ the three-momentum and energy of pion, respectively. With these quantities provided, one can then calculate the decay width explicitly [14–16], and the results are listed in Table 2. Note that the decay width for the last mode $d^* \to pn$ is estimated from the cross section ratio of the $\sigma_{d^*\to pn}/\sigma_{d^*\to d\pi^0\pi^0}$.

Table 2. Calculated decay widths of $d^*(2380)$ (in MeV).

Decay mode	Ours	Expt.
$d^* \to d\pi^+\pi^-$	16.8	16.7
$d^* \to d\pi^0\pi^0$	9.2	10.2
$d^* \to pn\pi^+\pi^-$	20.6	21.8
$d^* \to pn\pi^0\pi^0$	9.6	8.7
$d^* \to pp\pi^0\pi^-$	3.5	4.4
$d^* \to nn\pi^0\pi^+$	3.4	4.4
$d^* \to NN\pi$	0.7	—
$d^* \to pn$	8.7	8.7
Total	72.5	74.9

From Table 2 one sees that all of our calculated partial decay widths are in good agreement with the data, and so does the total width. This justifies the scenario we proposed for $d^*(2380)$, i.e. it has about 2/3 CC component and thus is a hexaquark-dominated exotic sate.

4 Summary

The structure and decay properties of $d^*(2380)$ have been detailedly investigated in both the chiral SU(3) quark model and the extended chiral SU(3) quark model. It is found that the $d^*(2380)$ has a mass of about $2.38 - 2.42$ GeV which is consistent with the experiment, a root-mean-square radius of about $0.76 - 0.88$ fm, and a CC configuration in its wave function of about $66\% - 68\%$. Based on this scenario, the partial decay widths of $d^* \to d\pi^+\pi^-$, $d^* \to d\pi^0\pi^0$, $d^* \to pn\pi^+\pi^-$, $d^* \to pn\pi^0\pi^0$, $d^* \to pp\pi^0\pi^-$, $d^* \to nn\pi^0\pi^+$ and $d^* \to NN\pi$ are further explicitly evaluated, and the numerical decay widths are in good agreement with the data. The consistency of our calculated mass and decay width compared with experiments supports the scenario we proposed for the structure of $d^*(2380)$, i.e. it is a hexaquark-dominated exotic state.

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References

[1] P. Adlarson *et al.* (WASA-at-COSY Collaboration), Phys. Rev. Lett. **106**, 242302 (2011)
[2] P. Adlarson *et al.* (WASA-at-COSY Collaboration), Phys. Rev. C **88**, 055208 (2013)
[3] P. Adlarson *et al.* (WASA-at-COSY Collaboration), Phys. Lett. B **743**, 325 (2015)
[4] P. Adlarson *et al.* (WASA-at-COSY Collaboration), Phys. Rev. C **91**, 015201 (2015)
[5] M. Bashkanov *et al.* (CELSIUS/WASA Collaboration), Phys. Lett. B **637**, 223 (2006)
[6] P. Adlarson *et al.* (WASA-at-COSY Collaboration), Phys. Rev. C **86**, 032201 (2012)

[7] S. Keleta *et al.* (WASA-at-COSY Collaboration), Nucl. Phys. A **825**, 71 (2009)
[8] P. Adlarson *et al.* (WASA-at-COSY Collaboration & SAID DAC), Phys. Rev. Lett. **112**, 202301 (2014)
[9] P. Adlarson *et al.* (WASA-at-COSY Collaboration & SAID DAC), Phys. Rev. C **90**, 035204 (2014)
[10] H. X. Huang, J. L. Ping, and F. Wang, Phys. Rev. C **89**, 034001 (2014)
[11] X. Q. Yuan, Z. Y. Zhang, Y. W. Yu, and P. N. Shen, Phys. Rev. C **60**, 045203 (1999)
[12] F. Huang, P. N. Shen, Z. Y. Zhang, and W. L. Wang, Chin. Phys. C **39**, 071001 (2015)
[13] F. Huang, P. N. Shen, Y. B. Dong, and Z. Y. Zhang, Sci. China-Phys. Mech. Astron. **59**, 622002 (2016)
[14] Y. B. Dong, P. N. Shen, F. Huang, and Z. Y. Zhang, Phys. Rev. C **91**, 064002 (2015)
[15] Y. B. Dong, F. Huang, P. N. Shen, and Z. Y. Zhang, Phys. Rev. C **94**, 014003 (2016)
[16] Y. B. Dong, F. Huang, P. N. Shen, and Z. Y. Zhang, Phys. Lett. B **769**, 223 (2017)
[17] M. Bashkanov, S. J. Brodsky, H. Clement, Phys. Lett. B **727**, 438 (2013)
[18] A. Gal, Phys. Lett. B **769**, 436 (2017)
[19] L. R. Dai, Z. Y. Zhang, Y. W. Yu, and P. Wang, Nucl. Phys. A **727**, 321 (2003)
[20] F. Huang, Z. Y. Zhang, and Y. W. Yu, Phys. Rev. C **73**, 025207 (2006)