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Is d* a candidate for a hexaquark-dominated exotic state? *

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Abstract: We confirm our previous prediction of a d* state with $I(J^P)=0(3^+)$ [Phys. Rev. C 60, 045203 (1999)] and report for the first time based on a microscopic calculation that d* has about 2/3 hidden color (CC) configurations and thus is a hexaquark-dominated exotic state. By performing a more elaborate dynamical coupled-channels investigation of the ΔΔ-CC system within the framework of the resonating group method (RGM) in a chiral quark model, we find that the d* state has a mass of about 2.38–2.42 GeV, a root-mean-square radius (RMS) of 0.76–0.88 fm, and a CC fraction of 66%–68%. The last may cause a rather narrow width for the d* which, together with the quantum numbers and our calculated mass, is consistent with the newly observed resonance-like structure ($M\approx2380$ MeV, $\Gamma\approx70$ MeV) in double-pionic fusion reactions reported by the WASA-at-COSY Collaboration.

Key words: quark model, hexaquark states, hidden-color channel

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1 Introduction

The ABC effect has drawn a great deal of attention from physicists since its observation in the pd reaction in 1961 [1]. In recent years, much experimental progress in exploring the nature of the ABC effect has been made. In 2009, the CELSIUS/WASA Collaboration measured the most basic double-pionic fusion reaction $\mathrm{pn}\rightarrow \mathrm{d}\pi^0\pi^0$ with an incident proton energy of 1.03 GeV and 1.35 GeV [2], and found significant enhancements in the ππ invariant mass spectrum at ππ invariant mass below 0.32 GeV^2 and also in the dπ invariant mass spectrum at the Δ resonance region. To accommodate these data as well as the energy dependence of the total cross section at $\sqrt{s}<2.5$ GeV, the conventional t-channel ΔΔ intermediate state is found to be insufficient, and a new structure, namely an s-channel resonance with mass of about 2.36 GeV and width of about 80 MeV, is expected. In 2011, the WASA-at-COSY Collaboration further measured the $\mathrm{pn}\rightarrow \mathrm{d}\pi^0\pi^0$ reaction with beam energies of 1.0–1.4 GeV, covering the transition region of the conventional t-channel ΔΔ process [3]. They found that neither the t-channel ΔΔ process nor the Roper resonance process can explain the data, and an s-channel resonance with quantum numbers of $I(J^P)=0(3^+)$, a mass of about 2.37 GeV and a width of about 70 MeV are indeed needed to describe the data. Recently, the WASA-at-COSY Collaboration measured polarized $\vec{\mathrm{n}}\mathrm{p}$ scattering through the quasi-free process $\vec{\mathrm{d}}p\rightarrow p_{\mathrm{spectator}}\mathrm{np}$ [4, 5]. By incorporating the newly measured $\mathrm{A_y}$ data into the SAID analysis, they obtained a pole in the $^3\mathrm{D}_3$-$^3\mathrm{G}_3$ waves at (2380±10)+i(40±5) MeV, which again supports the existence of a resonance, called d*, as mentioned in Ref. [3]. Further evidence of this resonance has also been reported in the quasi-free $\mathrm{np}\rightarrow\mathrm{np}\pi^0\pi^0$ reaction [6]. Since its mass is above the threshold of the ΔNπ channel, while its width is much smaller than the decay width of the Δ, this resonance must be a very interesting state involving new physical mechanisms and is obviously worth investigating.

Theoretically, the possibility of the existence of dibaryon states was first proposed in 1964 by Dyson and Xuong, based on SU(6) symmetry [7]. Since then, extensive efforts have been made in exploring the possible existence of a ΔΔ dibaryon with hadronic degrees of freedom. However, no convincing results have ever been released. Since the birth of the quark model, dramatic progress has been made on this aspect. In 1980, by ana-

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lyzing the characteristics of the one-gluon-exchange (OGE) interaction between quarks, Oka and Yazaki pointed out that in all non-strange baryon-baryon (BB) systems, the ΔΔ system with $I(J^P)=0(3^+)$ is the only one in which the effective BB interaction induced by OGE shows an attractive feature [8]. In the following years, by including the interaction between the quark field and chiral field into the constituent quark model, one successfully reproduced the data of the nucleon-nucleon (NN) interaction and the binding energy of the deuteron [9], which would provide a much more reliable platform to predict the structures of dibaryons in the quark degrees of freedom. In 1999, we carefully performed a dynamical study of the ΔΔ system in the quark degrees of freedom within the framework of the Resonating Group Method (RGM), with the hidden color (CC) channel being properly taken into account [10]. By employing the chiral SU(3) quark model with a set of reasonable model parameters which can reproduce the NN scattering phase shifts at relatively lower energies and the binding energy of the deuteron, we found that the quark-exchange effect in the ΔΔ system with quantum number $I(J^P)=0(3^+)$ is so important (see also Ref. [11]) that the system should be bound in nature with a binding energy of about 20–50 MeV in a single ΔΔ channel calculation. The coupling to the CC channel was also intensively studied and found to play an important role in the binding behavior of the system. It offers an additional binding energy of over 20 MeV to the system, and thus the binding energy of d*, relative to the threshold of the ΔΔ channel, would run up to 40–80 MeV. Unexpectedly, our predicted mass and quantum numbers are quite close to the new observation released recently by the WASA-at-COSY Collaboration [4].

In this work, we perform a further detailed investigation of the ΔΔ-CC system within the RGM framework in a chiral quark model. Besides the binding energy, we concentrate on a detailed study of the relative wave function of the ΔΔ-CC system, which is crucial to the understanding of the structure and decay properties of the d*. We find for the first time based on a microscopic calculation that the d* has a CC component of about 2/3, which indicates that d* is a hexaquark-dominated exotic state. The large CC configuration is quite helpful for us to understand that d*, although located above the thresholds of the ΔNπ and NNππ channels, has a relatively narrow width, as will be discussed later in more detail. In the most recent experimental papers by the WASA-at-COSY Collaboration and the SAID Data Analysis Center [5, 6], our scenario for d* presented here has been cited as a plausible explanation of the resonance observed in the double-pionic fusion reaction, as both our calculated binding energy and the expected width from our picture of d* are in agreement with the experimental findings.

2 Analysis

The interaction between the i-th quark and j-th quark in our chiral quark model reads

$$V_{ij}=V_{ij}^{\mathrm{OGE}}+V_{ij}^{\mathrm{conf}}+V_{ij}^{\mathrm{ch}}, \tag{1}$$

where V_{ij}^{OGE} is the OGE interaction which describes the short-range perturbative QCD behavior, and V_{ij}^{conf} the confinement potential describing the long-range non-perturbative QCD effects. V_{ij}^{ch} is the chiral field induced quark-quark interaction which provides the medium-range non-perturbative QCD effects; to test the model dependence of our results, we employ two different models for this interaction. In the chiral SU(3) quark model, V_{ij}^{ch} reads

$$V_{ij}^{\mathrm{ch}}=\sum_{a=0}^{8}\left(V_{ij}^{\sigma_a}+V_{ij}^{\pi_a}\right), \tag{2}$$

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

$$V_{ij}^{\mathrm{ch}}=\sum_{a=0}^{8}\left(V_{ij}^{\sigma_a}+V_{ij}^{\pi_a}+V_{ij}^{\rho_a}\right), \tag{3}$$

with σ_a, π_a and ρ_a (a=0, 1, ⋯, 8) being the scalar, pseudo-scalar and vector nonet fields, respectively. Note that the OGE will be largely reduced when vector-meson exchanges are included, i.e. the short-range interaction mechanisms are quite different in these two models. We refer readers to Refs. [9, 12] for further details.

The parameters of both models are fixed by fitting the energies of the octet and decuplet baryon ground states, the NN scattering phase shifts in the low energy region ($\sqrt{s}\leqslant 2m_N+200$ MeV) and the binding energy of the deuteron [9, 12]. See Table 1 for the binding energy, root-mean-square radius (RMS) of six quarks, and the fraction of each partial wave for the deuteron obtained from our models. They are all quite reasonable.

Table 1. Binding energy, root-mean-square radius (RMS) of six quarks, and fraction of channel wave function for deuterons in the chiral SU(3) quark model and extended chiral SU(3) quark model with ratios of tensor coupling to vector coupling f/g=0 and f/g=2/3 for vector meson fields.

	SU(3)	ext. SU(3)	
		(f/g=0)	(f/g=2/3)
binding energy/MeV	2.09	2.24	2.20
RMS of 6q/fm	1.38	1.34	1.35
fraction of $(\mathrm{NN})_{\mathrm{L=0}}$ (%)	93.68	94.66	94.71
fraction of $(\mathrm{NN})_{\mathrm{L=2}}$ (%)	6.32	5.34	5.29

With all the parameters being properly fixed, we investigate the properties of the ΔΔ-CC system without introducing any new adjustable parameters. Here the hidden color channel CC with isospin $I=0$ and spin $S=3$ is built as

$$|\mathrm{CC}\rangle_{IS=03}\equiv-\frac{1}{2}|\Delta\Delta\rangle_{IS=03}+\frac{\sqrt{5}}{2}\mathcal{A}^{\mathrm{sfc}}|\Delta\Delta\rangle_{IS=03}, \tag{4}$$

with $\mathcal{A}^{\mathrm{sfc}}$ being the antisymmetrizer in spin-flavor-color space. We dynamically calculate the binding energy of this system by solving the RGM equation for a bound state problem, and then discuss the structure of this bound state via a systematic analysis of fractions of each channel in the resultant relative wave function. The results obtained in the chiral SU(3) quark model and the extended chiral SU(3) quark model with the ratios of the tensor coupling to vector coupling f/g=0 and f/g=2/3 for vector meson fields are listed in Table 2, where the RMS values of six quarks are also shown.

One sees from Table 2 that the ΔΔ state with $I(J^P)=0(3^+)$ has a binding energy of about 30–60 MeV and RMS of about 0.80–0.96 fm in a ΔΔ (L=0, 2) double-channel calculation. The coupling to the CC channel will further result in an increment of about 20 MeV to the binding energy and a considerable decrement of the RMS, and finally, the mass of this bound state will reach 2.38–2.42 GeV and the RMS will shrink to 0.76–0.88 fm. This clearly shows that d* is a ΔΔ-CC strongly bound and compact state where the coupling to the CC channel plays a significant role.

Apart from the RMS, more information about the "size" of d* can be acquired from its spatial distribution feature as shown in Fig. 1, where the partial-wave projected relative wave function in the physical basis as a function of the distance between two physical states in the extended chiral SU(3) quark model with f/g=0 is plotted. The results for the other two models are similar. For comparison, the results for the deuteron are also plotted. Here the relative wave function in the physical basis, namely the channel wave function in the quark cluster model, is defined in the usual way as [13–15]

$$\psi_{\mathrm{BB}}(\boldsymbol{r})\equiv\langle\phi_{\mathrm{B}}(\boldsymbol{\xi}_1,\boldsymbol{\xi}_2)\phi_{\mathrm{B}}(\boldsymbol{\xi}_4,\boldsymbol{\xi}_5)|\Psi_{6\mathrm{q}}\rangle, \tag{5}$$

Table 2. Binding energy, root-mean-square radius (RMS) of six quarks, and fraction of channel wave function for d* in the chiral SU(3) quark model and extended chiral SU(3) quark model with ratios of tensor coupling to vector coupling f/g=0 and f/g=2/3 for vector meson fields.

	ΔΔ (L=0,2)			ΔΔ-CC (L=0,2)		
	SU(3)	Ext. SU(3) (f/g=0)	Ext. SU(3) (f/g=2/3)	SU(3)	Ext. SU(3) (f/g=0)	Ext. SU(3) (f/g=2/3)
binding energy/MeV	28.96	62.28	47.90	47.27	83.95	70.25
RMS of 6q/fm	0.96	0.80	0.84	0.88	0.76	0.78
fraction of $(\Delta\Delta)_{L=0}$ (%)	97.18	98.01	97.71	33.11	31.22	32.51
fraction of $(\Delta\Delta)_{L=2}$ (%)	2.82	1.99	2.29	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

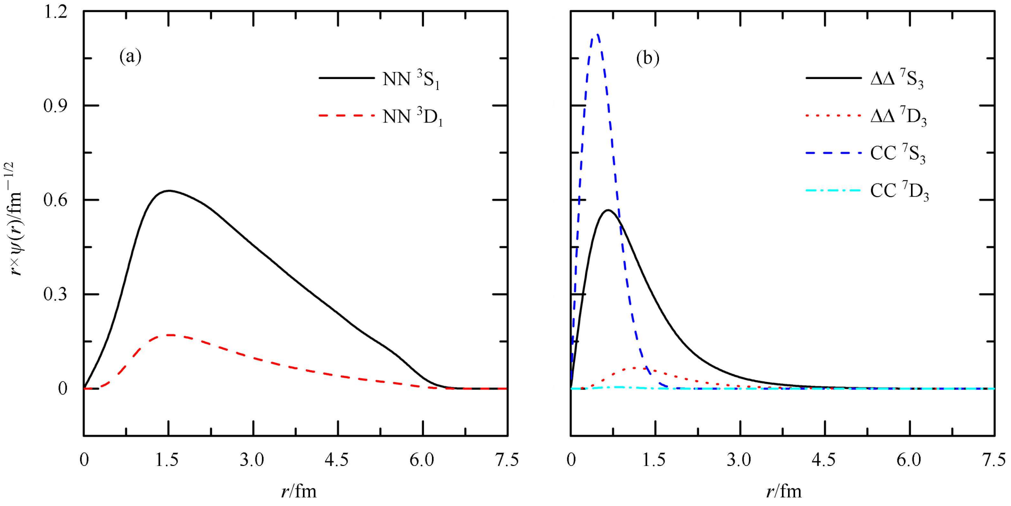

Fig. 1. (color online) Relative wave functions in the extended chiral SU(3) quark model with f/g=0 for the deuteron (a) and d* (b).

with B standing for Δ or C and $\Psi_{6\mathrm{q}}$ being the six-quark wave function from the RGM calculation,

$$\Psi_{6\mathrm{q}}=\sum_{\mathrm{B}=\Delta,\mathrm{C}}\mathcal{A}[\phi_{\mathrm{B}}(\boldsymbol{\xi}_1,\boldsymbol{\xi}_2)\phi_{\mathrm{B}}(\boldsymbol{\xi}_4,\boldsymbol{\xi}_5)\eta_{\mathrm{BB}}(\boldsymbol{r})]. \tag{6}$$

In Eqs. (5) and (6), ϕ_{B} is the antisymmetrized internal wave function for cluster B, with $\boldsymbol{\xi}_i$ (i=1, 2, 4, 5) being the internal Jacobi coordinates for the corresponding cluster; $\mathcal{A}$ is the antisymmetrizer for quarks from different clusters required by the Pauli exclusion principle; and $\eta_{\mathrm{BB}}(\boldsymbol{r})$ is the relative wave function between two clusters of B, which in the present investigation is completely determined by the interacting dynamics of the whole six-quark system. From Fig. 1 one sees that d* is rather narrowly distributed and it has a maximal distribution located around 0.7 fm for ΔΔ (L=0) and 0.4 fm for CC (L=0), respectively. The deuteron, on the other hand, is widely distributed with a maximal distribution located around 1.4 fm.

An even more interesting part of this investigation is to study the fractions of relative wave functions for each individual channel, which will help us get a further understanding of the structure of d*. Our extracted fractions of relative wave functions for ΔΔ and CC channels are tabulated in Table 2. Most interesting is 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

$$[6]_{\mathrm{orb}}[33]_{IS=03}=\sqrt{\frac{1}{5}}|\Delta\Delta\rangle_{IS=03}+\sqrt{\frac{4}{5}}|\mathrm{CC}\rangle_{IS=03}, \tag{7}$$

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 state as it has a CC configuration of 66%–68%. This finding is of great interest. It helps us to understand that d*, although located above the thresholds of the ΔNπ and NNππ channels, has a relatively narrow width since the CC component cannot be subject to a direct break-up decay. Actually, it can only decay to colorless hadrons via the re-combination processes of six color quarks together with quark-antiquark pair creation processes, which are highly suppressed and have much lower probability than those direct break-up decay processes. A conjecture that d* should have an unconventional origin and that the CC configuration will suppress its decay width has also been proposed by Bashkanov, Brodsky and Clement in Ref. [16]. Our microscopic calculation presented here supports their argument and our dynamical results show that d* has about 2/3 hidden-color configurations. However, a detailed calculation of the decay width of d* needs to take into account both the kinematic effects and the effects from the dynamical structure of d*. In the literature the former has been considered by using a simple momentum dependent prescription for the d* decay width [17]. Now an investigation of the latter also becomes possible, because the relative wave functions of d* are available in the present paper. Our work along this line is in progress.

It should particularly be stressed that the above-mentioned features of d* are due to both the quark exchange effect and the short-range interaction being attractive in the ΔΔ-CC system. As we have pointed out in Ref. [11], the quark exchange effect is highly dependent on the quantum numbers of the system. Opportunely, the ΔΔ system with $I(J^P)=0(3^+)$ is one of the few systems which have a strong quark exchange effect that drags two baryons together to form a compact state. As for the interaction property, Oka and Yazaki claimed in 1980 that in all the non-strange two-baryon systems, the ΔΔ system with $I(J^P)=0(3^+)$ is the only one in which the OGE provides strong attraction at short range [8]. In our chiral SU(3) quark model, the OGE indeed provides strong short-range attraction. In the extended chiral SU(3) quark model, although the OGE is largely reduced, the short-range interaction is still attractive and the attraction is even much stronger, as the vector meson exchanges (VMEs) are also strongly attractive at short range. Considering both above-mentioned facts, the ΔΔ system with $I(J^P)=0(3^+)$ is certainly strongly bound and it should couple to the CC channel strongly as the two interacting Δs are dragged close enough by strong attraction. For comparison, the NN $^3S_1$ partial wave has rather different features. In this partial wave, the quark exchange effect is very weak (almost negligible), and moreover, the short-range interactions stemming from OGE and VMEs are all repulsive. Therefore, the NN $^3S_1$ partial wave can only get attraction in the medium- and long-range through σ and π meson exchanges, and as a result, the deuteron is loosely bound and hardly couples to the CC channel. We emphasize that the ΔΔ system with $I(J^P)=0(3^+)$ is a highly unusual system where both the quark exchange effect and the short-range interaction are attractive, which makes this system strongly bound and promotes a strong coupling to the CC channel.

3 Summary

In summary, this is the first time it has been found, based on a microscopic calculation with no additional parameters besides those already fixed in the study of NN scattering phase shifts, that d* has about 2/3 hidden-color configurations and thus tends to be a hexaquark-dominated exotic state. It has a mass of about 2.38–2.42 GeV, a root-mean-square radius of 0.76–0.88 fm, and a CC fraction of 66%–68%, which may cause a relatively narrow width for the d*. Our findings are consistent with the newly observed resonance-like structure

($M\approx2380$ MeV, $\Gamma\approx70$ MeV) in double-pionic fusion reactions reported by the WASA-at-COSY Collaboration. If its character can be further verified, the d* will be the first hexaquark-dominated exotic state ever found, and may open a door to new physical phenomena.

In the literature there are several other interpretations of the recent WASA-at-COSY experiment. Gal et al. carried out a πNΔ three-body-calculation [18] and found the $\mathcal{D}_{03}$ state as a dynamically generated pole at the right mass and with a slightly larger width (see Ref. [5] for a comment on the width). Huang et al. performed a coupled-channel quark model calculation and obtained an energy close to the observed value, but their calculated width is still too large [17].

The πNΔ three-body resonance scenario proposed by Gal et al. [18] might have a relatively larger RMS than that from our picture. While measuring the “size” of d* is rather involved, future experiments might reach the d* by electromagnetic transitions, which will give information about d* form factor and further tell us the real structure of the observed resonance1). We look forward to experimental progress along this line.

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References

1 Booth N E et al. Phys. Rev. Lett., 1961, **7**: 35
2 Bashkanov M et al. Phys. Rev. Lett., 2009, **102**: 052301
3 Adlarson P et al. (WASA-at-COSY collaboration). Phys. Rev. Lett., 2011, **106**: 242302
4 Adlarson P et al. (WASA-at-COSY collaboration & SAID DAC). Phys. Rev. Lett., 2014, **112**: 202301
5 Adlarson P et al. (WASA-at-COSY collaboration & SAID DAC). Phys. Rev. C, 2014, **90**: 035204
6 Adlarson P et al. (WASA-at-COSY collaboration). arXiv:1409.2659 [nucl-ex]
7 Dyson F J, Xuong N H. Phys. Rev. Lett., 1964, **13**: 815
8 Oka M, Yazaki K. Phys. Lett. B, 1980, **90**: 41
9 ZHANG Z Y et al. Nucl. Phys. A, 1997, **625**: 59
10 YUAN X Q et al. Phys. Rev. C, 1999, **60**: 045203
11 LI Q B et al. Nucl. Phys. A, 2001, **683**: 487
12 DAI L R et al. Nucl. Phys. A, 2003, **727**: 321
13 Kusainov A M et al. Phys. Rev. C, 1991, **44**: 2343
14 Glozman L Y, Neudatchin V G, Obukhovsky I T. Phys. Rev. C, 1993, **48**: 389
15 Stancu F, Pepin S, Glozman L Y. Phys. Rev. C, 1997, **56**: 2779
16 Bashkanov M, Brodsky S J, Clement H. Phys. Lett. B, 2013, **727**: 438
17 HUANG H X et al. Phys. Rev. C, 2014, **89**: 034001
18 Gal A et al. Phys. Rev. Lett., 2013, **111**: 172301

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1) H. Clement, private communication.