$d^*(2380)$ Resonance in a Chiral SU(3) Constituent Quark Model

Yubing Dong^{*,†,‡}, Pengnian Shen^{*,†}, Fei Huang^{*,‡} and Zongye Zhang^{*,†,‡}

^{*}*Institute of High Energy Physics, Chinese Academy of Sciences,
 Beijing 100049, China*

[†]*Theoretical Physics Center for Science Facilities, CAS, Beijing 100049, China*

[‡]*School of Physical Sciences, University of Chinese Academy of Sciences,
 Beijing 101408, China*

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Recent studies on the newly observed resonance $d^*(2380)$ ($I(J^P) = 0(3^+)$) with a compact structure in a chiral SU(3) constituent quark model are briefly reported. The overall properties, including the mass, the partial decay widths in various decay modes, and the total width, comparing with the experimental data, show that a compact hexaquark dominated structure might be a reasonable interpretation for this state. Moreover, the charge distribution of d^* is also discussed.

1. Introduction

The d^* state has intensively been studied by various models from the hadronic degrees of freedom to the quark degrees of freedom more than fifty years. The predicted mass was ranged from a few MeV to several hundred MeV. Although it had also been searched in several experimental projects, no confidential results were released until 2009. Since then, a series of experimental studies for such a state, including various double- and single-pion decays in the pn interactions, the analyzing power of the neutron-proton scattering and etc., have carefully been carried out by CELSIUS/WASA and WASA@COSY Collaborations.^{1–4} As their finding, they announced that a new resonance with a mass of about 2380 MeV, an averaged narrow width of about 75 MeV, and the quantum numbers of $I = 0$ and $J^P = 3^+$ has been observed in the above mentioned nuclear processes, and such a state is just the d^* state which has been hunted for several decades.

Following their report, many theoretical models for the structure of d^* have been developed or proposed. Up to now, there are mainly two structure schemes

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which attract considerable attention of physicists. One of them (Scenario A) assumes that the d^* state has a compact structure, and may be an exotic hexaquark dominated state.^{5–11} Another one proposes (Scenario B) that the d^* state is basically a molecular-like hadronic state with a $\Delta\Delta - D_{12}\pi$ mixing,¹² which originates from a three-body $\Delta N\pi$ resonance assumption^{13,14} and a $D_{12}\pi$ molecular-like model.¹⁵ Which structure is more reasonable should be judged by the experimental data.

In this talk, we will concentrate our attention on the first scheme by discussing the properties of the $d^*(2380)$ state with an exotic hexaquark dominated structure. We will also cite some results in the second scheme from relevant article for comparison.

2. Nature of $d^*(2380)$ in chiral SU(3) constituent quark model

To reveal the properties of the $d^*(2380)$ state with a compact structure, a study in the quark degrees of freedom is necessary. For this aim, we employ the chiral SU(3) constituent quark model^{5–7} which has been proven successful in the study of the strong interaction. The wave function of a 6-quark system is usually solved by using a well-known Resonant Group Method (RGM). In order to gain a clear knowledge of the inner structure of the $d^*(2380)$ ($I(J^P) = 0(3^+)$) state, we assume that the $d^*(2380)$ state has a single $\Delta\Delta$ or a coupled $\Delta\Delta + CC$ structure, where Δ and C denote the isobar state with $(I, S, C) = (\frac{3}{2}, \frac{3}{2}, (00))$ and the color octet state with $(I, S, C) = (\frac{1}{2}, \frac{3}{2}, (11))$.⁶ The total wave function of a 6-quark system in the coupled $\Delta\Delta + CC$ case can be explicitly written as

$$\Psi_{6q} = \mathcal{A} \left[\phi_{\Delta}(\vec{\xi}_1, \vec{\xi}_2) \phi_{\Delta}(\vec{\xi}_4, \vec{\xi}_5) \eta_{\Delta\Delta}(\vec{r}) + \phi_C(\vec{\xi}_1, \vec{\xi}_2) \phi_C(\vec{\xi}_4, \vec{\xi}_5) \eta_{CC}(\vec{r}) \right]_{S=3, I=0}^{C=(00)}, \quad (1)$$

where $\mathcal{A} = 1 - 9P_{36}$ is the antisymmetrizer in the orbital (o), spin (s), flavor (f), and color (c) spaces, respectively, due to the Pauli exclusion principle, $\phi_{\Delta(C)}$ are the internal wave functions of the 3-quark cluster $\Delta(C)$, and $\eta_{\Delta(C)}$ stand for the relative wave functions between the two $\Delta(C)$ clusters. Then, $\eta_{\Delta(C)}$ can be obtained by solving the RGM equation. However, due to the effect of the quark exchange, these two components in eq. (1) are not orthogonal to each other. To see the role of each component in $d^*(2380)$, an orthogonalization procedure for these two components should be taken. It can be done by making projections $\chi_{\Delta\Delta}(\vec{r}) = \langle \phi_{\Delta}(\vec{\xi}_1, \vec{\xi}_2) \phi_{\Delta}(\vec{\xi}_4, \vec{\xi}_5) | \Psi_{6q} \rangle$ and $\chi_{CC}(\vec{r}) = \langle \phi_C(\vec{\xi}_1, \vec{\xi}_2) \phi_C(\vec{\xi}_4, \vec{\xi}_5) | \Psi_{6q} \rangle$, respectively. Clearly, the newly achieved functions, called channel wave functions, are orthogonal to each other and contain all the quark-exchange effects. Then, the wave function of the system could be expressed as

$$\Psi_{d^*} = \Psi_{d^*; \Delta\Delta} + \Psi_{d^*; CC} = |\Delta\Delta\rangle \chi_{\Delta\Delta} + |CC\rangle \chi_{CC}. \quad (2)$$

Based on the obtained channel wave functions, we can examine the decay properties of the $d^*(2380)$ state by calculating decay widths of $d^*(2380) \rightarrow d\pi\pi$ and $d^*(2380) \rightarrow pn\pi\pi$ which have been observed in WASA@COSY experiments. It should be mentioned that in the leading order approximation, the $\Delta\Delta$ component

of the $d^*(2380)$ wave function contributes only, but not the CC component. In order to make a solid base for the calculated widths of $d^*(2380)$, we have employed a vertex of the $qq\pi$ interaction by fitting the data of the $\Delta \rightarrow N\pi$ decay.

The schematic diagrams for the double-pion three-body (four-body) decays of $d^*(2380)$ in the time-ordered perturbation theory are shown in Fig.1. The detailed

Fig. 1. Schematic diagrams for $d^*(2380) \rightarrow d\pi\pi$ ($pn\pi\pi$) decays.

formalism for the transition matrix elements, and consequently the decay widths, of these two types of processes can be found in Refs. [8,9]. It should specially be emphasized that the final state interaction (FSI) between two outgoing nucleons in four-body decays should be taken into account. This can simply be realized by using the Jost function in the scattering theory (see Ref. [9] for detail.)

The single-pion decay mode, $d^* \rightarrow \pi NN$, becomes a crucial process to judge the rationality of different structural assumptions for $d^*(2380)$, recently. In this decay process, two pions are emitted from Δ s, respectively, but only one of them can fly away and the other one is absorbed by the system. Fig. 2 exhibits the schematic diagrams of the single-pion decay in the possible lowest order, and the outgoing pion is emitted from the second Δ cluster. The explicit forms of the transition matrix elements and the decay widths can be found in Ref.[10].

3. Numerical results and discussions

The mass of $d^*(2380)$ with $I(J^P) = 0(3^+)$ in the single $\Delta\Delta$ channel and the coupled $\Delta\Delta + CC$ channel are calculated with our chiral $SU(3)$ constituent quark model. The obtained mass in the extended chiral $SU(3)$ constituent quark model is about 2380 MeV in the $\Delta\Delta + CC$ case and about 2402 MeV in the single $\Delta\Delta$ case, which is compatible with the data. It is found that inclusion of the CC component reduces the mass of $d^*(2380)$ about 20 MeV. It is also shown that the S - wave dominates in both cases, and the probability of the CC component in the d^* wave function in eq. (2) is about 2 times larger than the one of the $\Delta\Delta$ component.

Fig. 2. Schematic diagrams of $d^*(2380) \rightarrow pn\pi$ decay in the possible lowest order. The outgoing pion is emitted from the second Δ cluster.

In terms of the obtained channel wave functions of $d^*(2380)$, the pionic-decay width of d^* can be calculated. They are tabulated in Tab. 1. It should be mentioned

Table 1. Decay widths (in MeV) of $d^*(2380)$ in the coupled-channel case.

Mode	Ours	Expt.	Mode	Ours	Expt.
$d^* \rightarrow d\pi^+\pi^-$	16.8	16.7	$d^* \rightarrow d\pi^0\pi^0$	9.2	10.2
$d^* \rightarrow pn\pi^+\pi^-$	20.6	21.8	$d^* \rightarrow pn\pi^0\pi^0$	9.6	8.7
$d^* \rightarrow pp\pi^0\pi^-$	3.5	4.4	$d^* \rightarrow nn\pi^0\pi^+$	3.5	4.4
$d^* \rightarrow pn$	8.7	8.7	Total	71.9	74.9

that all theoretical partial widths in the table are calculated, except the width of $d^* \rightarrow pn$ which is estimated from the ratio of the cross sections, $\sigma_{d^* \rightarrow pn} / \sigma_{d^* \rightarrow d\pi^0\pi^0}$. It is shown from Tab.1 that the obtained partial widths of all observed decay modes are consistent with the data, in particular, the resultant total width of about 72 MeV agrees with observed value quite well. If one only considers the single $\Delta\Delta$ structure, the obtained widths for the $d^* \rightarrow d\pi^0\pi^0$ and $d^* \rightarrow d\pi^+\pi^-$ modes would have an increment of about 17 MeV and 30.8 MeV, respectively, which are about two times larger than the observed data. This discrepancy exhibits a considerable effect from the CC component. This is because that in this leading order approximation which can be inferred as the dominant one, a much larger component CC would not contribute, and consequently, the contribution from the relatively smaller component $\Delta\Delta$ is suppressed.

Using the same method, the partial decay width of the single-pion decay of d^* can also be calculated. The resultant partial width is about 0.7 MeV corresponding to a branching ratio of less than 1%. This result is compatible with the upper limit of $< 9\%$ determined in the recent experiment.¹⁶ However, as a comparison, the branching ratio for a pure $D_{12}\pi$ (or $\Delta N\pi$ if one assumes that D_{12} is a ΔN resonance) structure is about 15% which is much larger than the deduced upper

limit from the experiment, and consequently, such a structure is excluded by the data. To solve this discrepancy, one proposed a structure with a $\Delta\Delta - D_{12}\pi$ mixing, where the mixing parameter is determined by fitting the experimental upper limit and is sensitive to the phenomenologically selected width of the $\Delta\Delta$ component.¹²

To further examine the structure of d^* , an additional physical quantity, the charge distribution of d^* , is calculated in terms of the channel wave functions.¹⁷ It should be mentioned that both $\Delta\Delta$ and CC components contribute in the calculation. The charge distribution curve is plotted in Fig. 3. This figure shows that the

Fig. 3. Charge distribution of $d^*(2380)$.

charge distribution of the CC component is wider than that of the $\Delta\Delta$ component and such a distribution in the $\Delta\Delta + CC$ case is wider than that in the $\Delta\Delta$ case, which is consistent with the calculated root-mean-square radius (RMS) of 0.72 fm (1.1 fm) for the d^* state with a $\Delta\Delta + CC$ ($\Delta\Delta$) structure.⁶ In particular, it is shown that the charge distribution of a compact hexaquark dominated structure is much wider than that of a $D_{12}\pi$ structure,¹⁷ which will be another quantity for judging the structure of d^* . Further link of this distribution to the experiment test is underway.

To summarize, a well-established chiral $SU(3)$ constituent quark model is applied to study the structure of d^* , in particular, its pionic decays. It is shown that not only its mass of about 2384 MeV, but also the partial widths of all observed decay modes, and consequently, the total width of about 72 MeV are in consistent with the data. Especially, the calculated branching ratio for the crucial single pion decay process is less than 1%, which again consists with the upper limit found in the experiment, but is quite different from the width for a pure $D_{12}\pi$ (or $\Delta\pi N$) structure. In addition, we calculate an additional testable quantity, charge distributions, of d^* with a compact hexaquark dominated structure, which is quite different with that with a molecular-like $D_{12}\pi$ structure. We hope future experiments at MAINZ, Jefferson Lab., and Belle II could provide more information for the nature of d^* .

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