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The Properties of $d^*(2380)$ in a Hexaquark Scenario

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The properties of the newly observed dibaryon resonance $d^*(2380)$ ($IJ^p = 03^+$), calculated in a constituent chiral quark model, are briefly reported. Comparing to the available experimental data for its decays, we conclude that the resonance $d^*(2380)$ can be reasonably interpreted as a compact heaxquark dominant state.

KEYWORDS: $d^*(2380)$, dibaryon, chiral constituent quark model, hexaquark

1. Introduction

The history of the studies of dibaryon systems, like d^*, d' and H particles, can be traced back to about half century ago (see the review article of Clement [1]). The clear experimental evidence for the d^* was not observed until 2009. They were the CELSIUS/WASA and WASA@COSY collaborations, who carried out the study of ABC effect [2–5], and found that their measurements cannot be simply explained by the contribution either from the intermediate Roper excitation or from the t-channel $\Delta\Delta$ contribution, except introducing an intermediate new resonance. Then, the discovery of this new resonance with the quantum numbers of $I(J^P) = 0(3^+)$, the mass of $2370 \sim 2380$ MeV and the width of $70 \sim 80$ MeV was released. Very recently, this dibaryon resonance, called $d^*(2380)$, was also confirmed by Researcher Center of Electron Photon Sciences (ELPH) experiment from the $\gamma + d$ scattering process [6, 7]. It should be mentioned that the mass of this dibaryon resonant state is about 80 MeV below the $\Delta\Delta$ threshold and about 70 MeV above the $\Delta\pi N$ threshold [8–10]. This feature is different from the well-known XYZ particles which usually locate very near to a threshold. In addition, XYZ particles contains heavy flavor, whereas $d^*(2380)$ does not.

Currently, two scenarios were proposed for the structure of $d^*(2380)$. One assumes that it has a compact structure, and may be an exotic hexaquark dominated state [11–20]. Another basically regards it as a $D_{12}\pi$ molecular-like hadronic state, which originates from a three-body $\Delta N\pi$ resonance assumption [21–23]. Although some of the experimental data, like the $d^*(2380)$ mass and its double pionic decays, can be well-reproduced by using either scheme, the described structures of $d^*(2380)$ are quite different. In this talk, the results for $d^*(2380)$ in the hexaquark scenario will be briefly reported.

2. Description of $d^*(2380)$ in quarks degree of freedom

We know that nucleon-nucleon interaction has been studied for a long time in the quark degrees of freedom by considering various QCD inspired quark-quark interactions and using Resonant Group Method (RGM) for a dynamical calculation. Among various quark models, chiral constituent quark model has been proved to be a successful one since it can well-reproduce the lowlying baryon spectrum, nucleon-nucleon scattering phase-shifts, deuteron static properties as well as the nucleon-hyperon scattering. The details of the phenomenological effective model can be referred to [11]. Recently, this phenomenological model was also applied to the dibaryon systems, like $d^*(2380)$. It was found that the resonance might be a $\Delta\Delta + C_8C_8$ system. The quantum numbers of spin (S), isospin (I) and color (C) for Δ and C_8 clusters are $[S, I, C]_\Delta = [3/2, 3/2, (00)]$ and $[S, I, C]_{C_8} = [3/2, 1/2, (11)]$, respectively. Now an RGM calculation for the 3^+ system is done and the obtained wave function in the quark degrees of freedom is projected to the channel wave function in the hadronic picture. Then, the obtained channel wave function is written as

$$\left|d^*(2380)(S_{d^*(2380)} = 3, M_{d^*(2380)})\right\rangle = \sum_{ch=\Delta\Delta, C_8C_8} \sum_{pw=S,D} \left[|ch>_{S_{ch}, M_S} \chi_{ch}^{pw,m_l}(\vec{r})\right]_{S_{d^*(2380)}=3, M_{d^*(2380)}}, \quad (1)$$

with $ch = \Delta\Delta$ or C_8C_8 denoting the constituents of the configuration, $M_{d^*(2380)}$ representing the magnetic quantum number of spin $S_{d^*(2380)}$, $pw = l = 0$ and 2 depicting the S and D partial waves (pw) between the two clusters, respectively, and m_l being its magnetic quantum number. It should be mentioned that the Fourier transformation of the relative wave functions $\chi_{ch}^{pw,m_l}(\vec{r})$ stands for the relative momentum distributions of the two-clusters of "ch" inside the $d^*(2380)$ system.

Our numerical wave function of $d^*(2380)$ tells that the probability of the hidden-color C_8C_8 channel is about 69%, which is dominant comparing to the channel of $\Delta\Delta$ (around 31%). This phenomenon is due to the strong quark exchange effect between the two clusters and the special quantum number of 3^+. As a result, inclusion of the hidden-color channel suppresses the binding energy about 20 MeV, namely, the obtained mass of $d^*(2380)$ ($IJ^p = 03^+$) is about 2380 – 2414 MeV. Our channel wave function shows that $d^*(2380)$ is a compact system, and the C_8C_8 wave function is very similar to a typical single Gauss-type function with a width parameter of 0.45 fm. In addition, the $D-$wave components of the two channels are negligible small.

3. Decays of $d^*(2380)$ in our approach

We carry out numerical calculations for the double-pionic decays of $d^*(2380)$ (see the illustrations in Fig. 1). The above numerical $d^*(2380)$ wave function, which stimulates the relative momentum distribution of the two clusters (C_8C_8 or $\Delta\Delta$) inside $d^*(2380)$, as well as the deuteron wave function are employed in the calculation based on a non-relativistic framework. According to our analyses, the component of C_8C_8 cluster does not contribute to the strong decays, at least, in the leading order approximation, since the process of emitting a pion is color blind. In our calculations, the $N-N$ final state interaction of Fig. 1 (right) and the effect of isospin symmetry breaking, due to the mass difference of charge and neutral pions, are taken into account. Our model results for the partial widths of the double-pionic decay mode are listed in Table I. An excellent agreement can been seen. Here, we emphasize that the hidden-color component plays important role to reduce the partial widths as well as the total width. This is because that it remarkably suppresses the probability of $\Delta\Delta$ component. If only the single-channel $\Delta\Delta$ component is taken into account, the results of the partial and total decay widths are all overestimated.

Table I. Calculated double-pion decay widths of $d^*(2380)$ (MeV).

Mode	$d^* \to d\pi^+\pi^-$	$d^* \to d\pi^0\pi^0$	$d^* \to pn\pi^+\pi^-$	$d^* \to pn\pi^0\pi^0$	$d^* \to pp\pi^0\pi^-$	$d^* \to nn\pi^0\pi^+$	$d^* \to pn$	Total
$\Gamma_{\Delta\Delta+C_8C_8}$	16.8	9.2	20.6	9.6	3.5	3.5	8.7	71.9
$\Gamma^{Expt.}$	16.7	10.2	21.8	8.7	4.4	4.4	8.7	74.9

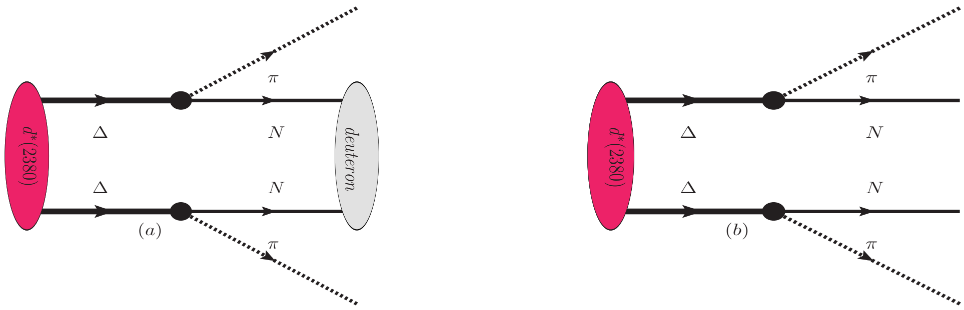

Fig. 1. $d^*(2380)$ double-pionic decays, (a) $d^*(2380) \to 2\pi + d$ and (b) $d^*(2380) \to 2\pi + pn$.

The single-pionic decay mode of $d^*(2380)$ in our scenario is also calculated (see Fig. 2(a) for example), and the details can be found in Ref. [17]). Here, we ignore the contribution of C_8C_8 as well and consider the next-leading effect, where the pion emitted from one Δ cluster is absorbed by another Δ. Our numerical branching ratio for $d^*(2380) \to pn\pi$ is about 1%, which is compatible to the upper limit (< 9%) of experimental measurement [24], but is much smaller than the calculated result from a pure $\Delta N\pi$ scenario, which is about 18% [25].

Clearly, the strong decays of $d^*(2380)$ in our scenario is contributed only by the $\Delta\Delta$ component, and the dominant component in our wave function, C_8C_8, does not play a directly role in the leading order approximation. In order to manifest the C_8C_8 effect, we apply the electromagnetic (EM) probes to $d^*(2380)$. Since it is a spin-3 particle, it has all together 7 form factors [18, 19]. We calculate its EM form factors (see Fig. 2(b)), where both the C_8C_8 and $\Delta\Delta$ contribute to the charge radius of $d^*(2380)$. We also find that the two scenarios, one with a 6-quark compact structure and another with a $\Delta N\pi$ picture, show quite different Q^2-dependence of the charge distributions of $d^*(2380)$ and show the remarkable difference on its charge radius. These quantities may be an additional criterion for discriminating d^*'s structures.

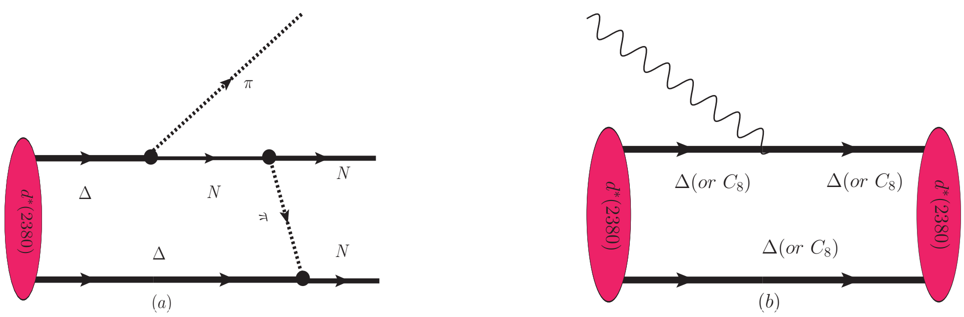

Fig. 2. (a), Typical example for single-pionic decay $d^*(2380) \to \pi + pn$ (total 24 figures shown in Ref. [17]) and (b) Electromagnetic form factors of $d^*(2380)$.

4. Summary

We report our current studies of the dibaryon resonance $d^*(2380)$ ($IJ^P = 03^+$). Our dynamical calculation, based on a chiral constituent quark model, tells that it might be a compact 6-quark system with a dominant hidden-color component of C_8C_8. This unusual structure is due to the strong quark exchange effect and the short-ranged attractive interaction in this channel. Thus, the $d^*(2380)$ wave function is localized in a compact space. In the $d^*(2380)$ strong decays, we expect that the dominant component of C_8C_8 does not directly contribute, at least, in leading order, since the interaction of quark-quark-pion or hadron-hadron-pion is color blind. Thus, only the suppressed $\Delta\Delta$ component contributes and makes the total width suppressed.

We also analyze other observables in the two scenarios of $d^*(2380)$. We find that although the two pictures can well-reproduce the $d^*(2380)$'s mass and the widths of the double-pionic strong decays simultaneously, the predicted width of the single-pionic decay, the Q^2-dependence of the EM form factors, and the charge radius might appear remarkable differences. Of course, the real world must be much more complicated than our imagination. Taking a nucleon as an example, it is now commonly believed that it is a three-quark core (in quark degrees of freedom) surrounded by a meson cloudy (hadronic degrees of freedom). For the $d^*(2380)$ case, as a consequence, one can also incorporate our 6-quark compact picture with the $\Delta N\pi$ scenario, and thus believe that this admixture picture should fairly describe the $d^*(2380)$ properties [25].

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