The two-body open charm decays of $Z^+(4430)$

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The two-body open charm decays $Z^+(4430) \to D^+\bar{D}^0$, $D^{*+}\bar{D}^0$, $D^{*+}\bar{D}^0$ occur through the rescattering mechanism and their branching ratios are strongly suppressed if $Z^+(4430)$ is a $D\bar{D}$ molecular state. In contrast, $Z^+(4430)$ falls apart into these modes easily with large phase space and they become the main decay modes if $Z^+(4430)$ is a tetraquark state. Experimental search of these two-body open charm modes and the hidden charm mode $\chi_{cJ}\rho$ will help distinguish different theoretical schemes.

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I. INTRODUCTION

Belle Collaboration observed a new resonance $Z^+(4430)$ in the invariant mass spectrum of $\psi'\pi^+$ of $B \to K\psi'\pi^+$\textsuperscript{1}. Its mass and width are $m = 4433 \pm 4 \text{(stat)} \pm 1 \text{(syst)}$ MeV and $\Gamma = 44^{+17}_{-15} \text{(stat)}^{+30}_{-11} \text{(syst)}$ MeV respectively. This charged state stimulated extensive studies of its nature\textsuperscript{2-7}. Theoretical explanations of $Z^+(4430)$ include the S-wave threshold effect\textsuperscript{2}, the $D_1(1235)\bar{D}^*$ molecular state\textsuperscript{8-10}, the tetraquark state\textsuperscript{11,12,13,14,15,16}, the cusp effect\textsuperscript{11} and the $\Lambda_c - \Sigma_c^0$ bound state\textsuperscript{13}.

Recently we studied whether $Z^+(4430)$ could be an S-wave $D^*_1D^*$ ($D_1D^*$) molecular state considering both the pion and sigma meson exchange potentials\textsuperscript{17}. Our numerical results show that there may exist an S-wave $D^*_1\bar{D}^*_1$ molecular state with $J^P = 0^-$. If one ignores the width of $D'_1$, there may also exist an S-wave $D^*_1\bar{D}^*_1$ molecular state with $J^P = 0^-$. However, $D'_1$ will rapidly decay into $D^+\pi$ before the formation of the $D'_1D^*$ bound state because of its large width around 384 MeV.

In this work we assume $Z^+(4430)$ is a $D^*_1\bar{D}^*_1$ molecular state with $J^P = 0^-$ and study its two-body open charm decay modes, which may be used to distinguish the tetraquark and molecule picture. This work is organized as follows. After introduction, we discuss the hidden vs open charm decays of $Z^+(4430)$. In Section \textbf{III} the decay amplitude of the two-body open charm decay of $Z^+(4430)$ is given. The last section is the numerical results and discussion.

II. THE HIDDEN VS OPEN CHARM DECAYS OF $Z^+(4430)$

Assuming $Z^+(4430)$ is an S-wave $D^*_1\bar{D}^*_1$ molecular state, we illustrate its strong decays allowed by Okubo-Zweig-Iizuka (OZI) rule in Fig. \textbf{1}. Here indices 1, 2, 3, and 4 are $c, \bar{u}, \bar{c}$ and $d$ quarks respectively. The dashed-line box denotes the S-wave $D^* - D_1$ molecular state.

A. Hidden charm decays

Fig. \textbf{1} (a) describes the hidden charm decay process $Z^+(4430) \to D^*\bar{D}_1 \to (c\bar{c})(d\bar{u})$ by exchanging one charmed meson between $D^*$ and $\bar{D}_1$. $Z^+(4430)$ was observed in the $\psi'\pi^+$ channel. If it’s the S-wave $D^*_1\bar{D}^*_1$ molecular state, its quantum number is $I^{G}(J^{P}) = 1^+ (0^- 1^- 2^-)$\textsuperscript{4}. Kinematically allowed hidden charm decays can be classified into (1) P-wave modes: $\psi\pi, \psi'\pi, \psi(3S)\pi, \psi(4S)\pi, \psi(1D)\pi, \psi(2D)\pi, \eta_c, \eta_c(2S)\rho$; (2) S-wave modes: $\chi_{cJ}\rho$. The neutral partner of $Z^+(4430)$ may also decay into $\psi\omega$ via P-wave and $\chi_{cJ}\eta$ via S-wave.

$Z^+(4430)$ was observed only in the $\psi'\pi^+$ channel up to now, which is very puzzling. One of the possible reasons is the mismatch of the Q-values of the initial and final states\textsuperscript{4}. If so, one should also expect a signal in the $\pi^+\psi(3S)$ channel since there is nearly no mismatch of the Q-value. Another potential reason is the specific nodal structure in the wave functions of the final states, which was discussed by Bugg recently\textsuperscript{12}. Meng and Chao adopted the re-scattering mechanism to explain the suppression of the $\pi^+J/\psi$ decay mode\textsuperscript{3}.

Besides the discovery mode $\psi'\pi^+$, we want to emphasize that the S-wave $\chi_{cJ}\rho^+$ mode is very important since there is no additional suppression factor ($\frac{k}{m_2}$\textsuperscript{2}) where $k$ is the decay momentum and $m_2$ is the mass of $Z^+(4430)$. Naively one may expect that the orbital excitation in the $D_1$ meson easily transfers to $\chi_{cJ}$. Moreover, the $\chi_{c0}\rho^+$...
mode may help distinguish the $J^P$ of $Z^+(4430)$ and test the $D^* D_1$ molecular state assignment. If the $\chi_{c0} \rho^+$ mode is observed, one can exclude the $J^P = 0^-$ possibility for the $D^* D_1$ system. We strongly urge experimental colleagues to search $Z^+(4430)$ in the $\chi_{cJ} \pi^+\pi^0$ channel.

### B. Open charm decays

Both $Z^+(4430)$ and $D_1$ mesons have finite widths. $Z^+(4430)$ can decay through the upper tail of its mass distribution into $D_1 D^*$, especially the lower part of the $D_1$ mass distribution. As pointed out in Ref. [3], the dominant decay mode of $Z^+(4430)$ is $Z^+(4430) \rightarrow D_1 D^* \rightarrow D^* D^* \pi$.

Besides the above dominant mode, there exists another class of open charm decay mode through the re-scattering mechanism [17, 18], which is shown in Fig. 1(b). One pion or $\rho$ ($\omega$) meson exchange occurs between the light quarks. These two-body decay modes include $D D^* + D^* D$ and $D^* D^*$. The $DD$ decay mode is forbidden for a pseudoscalar meson.

This kind of open charm decay is strongly suppressed if $Z(4430)$ is a molecular state, as will be shown in the following sections. However, $Z(4430)$ will fall apart into these two-body final states very easily with large phase space if $Z(4430)$ is a tetraquark state as proposed in Refs. [8, 9, 10]. Therefore, these two-body decay modes can be used to distinguish the molecular and tetraquark pictures. This is the key motivation of the present work.

### III. THE AMPLITUDE OF THE TWO-BODY OPEN CHARM DECAY

Assuming $Z^+(4430)$ is an $S$-wave $D^* - \bar{D}_1$ molecular state with $J^P = 0^-$ [2], we derive the two-body open charm decay amplitude using the optical theorem. From the unitarity of the S-matrix $S^* S = 1$, one obtains

$$-i(T - T^\dagger) = T^\dagger T$$

where $S = 1 + iT$. We sandwich the above equation between the one-particle state $|P\rangle$ and two-particle state $|k_1, k_2\rangle$. By inserting a complete set of intermediate states to the right-hand side, one gets

$$\langle k_1, k_2 | T^\dagger T | P \rangle = \sum_\alpha \prod_{i=1}^\alpha \left( \frac{d^3 p_i}{(2\pi)^3 2E_i} \right) \langle k_1, k_2 | T^\dagger | p_i \rangle \langle p_i | T | P \rangle.$$  \hspace{1cm} (2)

Now the absorptive part reads

$$\text{Abs} \mathcal{M}(A(P) \rightarrow B(k_1) C(k_2))$$

$$= \frac{1}{2} \sum_\alpha \prod_{i=1}^\alpha \left( \frac{d^3 p_i}{(2\pi)^3 2E_i} \right) (2\pi)^4 \delta(k_1 + k_2 - \sum_{i=1}^\alpha p_i) \times \mathcal{M}[k_1 k_2 \rightarrow \{p_i\}] \mathcal{M}^*[P \rightarrow \{p_i\}].$$

The optical theorem relates the absorptive part of the $A \rightarrow B + C$ decay amplitude to the sum of all possible $A \rightarrow \{p_i\}$ decays and the re-scattering process $\{p_i\} \rightarrow B + C$.

Thus, for the two-body charm decay $Z^+(4430) \rightarrow D_1 D^* \rightarrow D^{(*)} \bar{D}^{(*)}$, the absorptive part of the decay amplitude can be written as

$$\text{Abs}[Z^+(4430) \rightarrow \bar{D}_1 D^* \rightarrow D^{(*)} \bar{D}^{(*)}]$$

$$= \frac{|\mathbf{p}|}{32\pi^2 M_{Z}} \int d\Omega \mathcal{M}^{*}[Z^+ \rightarrow D^* \bar{D}_1] \times \mathcal{M}[D^* \bar{D}_1 \rightarrow D^{(*)} \bar{D}^{(*)}]$$

$$= \frac{1}{\pi} \int_{s_{\text{min}}}^{s_{\text{max}}} \frac{\text{Dis} \mathcal{M}(M_Z)}{s - M_Z^2} ds,$$  \hspace{1cm} (5)

with

$$\text{Dis} \mathcal{M}(s) = \text{Abs}[Z^+(4430) \rightarrow \bar{D}_1 D^* \rightarrow D^{(*)} \bar{D}^{(*)}] \times \exp(-\eta|\mathbf{k}|^2),$$

where $|\mathbf{k}| = [\lambda(M_Z^2, m_{D^*}^2, m_{\bar{D}_1}^2)]^{1/2}/2M_Z$ is the three momentum of the intermediate state in the rest frame of
\[ L_{Z+D^*} = g_{Z+D^*}Z(D^* \cdot D_1) + h.c. \]  

\[ L_1 = \frac{1}{2} \int g_{D^*D\rho} \epsilon_{\mu\nu\alpha\beta} D^\mu_{\mu} D^\nu_{\nu} D_{D^\beta} - i g_{D^\rho} D^\mu_{\mu} \partial_\mu (D^\beta_{D^\rho} - D^\beta_{D^*}) - i g_{D^\rho} D^\mu_{\mu} \partial_\mu (D^\beta_{D^\rho} - D^\beta_{D^*}) \]  

\[ L_{D_1D^*} = i g_{D_1D^*} \pi \left[-3D^\mu_{\rho} \partial_\mu \partial_\rho + (D^* \cdot D_1) \partial^2 \pi \right] - \frac{1}{m_{D^*} m_{D_1}} \partial_\mu D^\rho_\mu \partial_\rho D_{D^\mu} \partial^2 \pi + h.c. \]  

where \( D \) and \( D^* \) are pseudoscalar and vector heavy mesons respectively, i.e. \( D^* = ((D^0)^*), (D^-)^* \). \( P \) and \( V \) denote the octet pseudoscalar and the nonet vector meson matrices. The values of the coupling constants will be given in Section IV. The Lagrangian relevant to the interaction of \( D_1 \) with \( \rho(\omega) \) and \( D^*(s) \) mesons is given in Ref. 21.  

The flavor wave function of \( Z^+(4430) \) is \([4]\)

\[ |Z^+(4430)\rangle = \frac{1}{\sqrt{2}} \left( |D^+D_1^0\rangle + |D^0D_1^+\rangle \right). \]

Thus \( Z^+(4430) \) with \( J^P = 0^- \) can decay into \( D^+D^0 \), \( D^+D^0 \) and \( D^+D^0 \) via the intermediate states \( D^+D_1^0 \) and \( D^0D_1^+ \). If one ignores the mass difference between neutral and charged charmed mesons, the contribution from the intermediate state \( D^+D_1^0 \) is same as that from \( D^0D_1^+ \).

**A. \( Z^+(4430) \rightarrow D^{*+}D_1^0(D^{*0}D_1^+ \rightarrow D^{*0}D^+) \)**

Fig. 2(b) describes the open charm decay \( Z^+(4430) \rightarrow D^{*+}D_1^0 \rightarrow \bar{D}^{*0}D^+ \). The absorptive part of the decay amplitude of \( Z^+(4430) \rightarrow D^{*+}(p_1, \epsilon_1)D^{*+}(p_2, \epsilon_2) \rightarrow \)
where the index $i$ in $I^{(i)}_1$ and $m_i$ denotes the $\rho(\omega)$ meson.
$I^{(\rho)}_1 = -I^{(\omega)}_2 = -\frac{i}{\sqrt{2}}$ and $I^{(\rho)}_2 = I^{(\omega)}_2 = \frac{i}{\sqrt{2}}$. The same notations are also used in the following subsections.

**B. $Z^+(4430) \rightarrow D^{*+}\bar{D}^0(\bar{D}^{*0}D_1^+) \rightarrow D^0 D^{**}$**

The open charm decay $Z^+(4430) \rightarrow D^{*+}\bar{D}^0 \rightarrow \bar{D}^0 D^{**}$ is depicted in Fig. [2] (c). The absorptive part of the decay amplitude of $Z^+(4430) \rightarrow \bar{D}^0(p_1,\epsilon_1)D^{*+}(p_2,\epsilon_2) \rightarrow D^0(p_3)D^{**}(p_4,\epsilon_4)$ from the $\rho(\omega)$ meson exchange is

$$
\text{Abs}^{\rho(\omega)}[Z^+ \rightarrow D^{**}\bar{D}^1_0 \rightarrow D^{*+}\bar{D}^0] = \frac{|p|}{32\pi^2 M_Z} \int d\Omega \ i[i g_{Z^+D_1^+D^+}] 
\times I^{(i)}_1 \left[ -2 i g_{D^*D^\prime\bar{D}} p_2 \tau \epsilon^4_i - 4 i f_{D^*D^\prime\bar{D}} (q^\prime \epsilon_{4\bar{U}} - g^\prime \epsilon_q \epsilon_4) \right] 
\times I^{(i)}_2 \left[ i g_{2\bar{D}^0D^+} \Theta^{\epsilon_3} + i g_{1,0} (g^\rho - p^{\rho}_1 p^{\rho}_2)^2 \left[ -g^\rho + \frac{q \epsilon_2}{m^2_D} \right] \right] 
\times \left[ -g_{\sigma\mu} + \frac{p^{\rho}_1 p^{\rho}_2}{m^2_D} \right] \left[ -g_{\bar{D}^0 D^+} + \frac{p_{2\bar{D}^0 p_{2\bar{D}}}}{m^2_D} \right] \frac{F^2(q^2, m^2)}{q^2 - m^2_\pi}. 
(14)
$$

**C. $Z^+(4430) \rightarrow D^{*+}\bar{D}^1_0(\bar{D}^{*0}(\bar{D}^0,D_1^+) \rightarrow D^{*+}\bar{D}^{*0}$**

Fig. [2] (d) corresponds to the process $Z^+(4430) \rightarrow \bar{D}^1_0(p_1,\epsilon_1)D^{*+}(p_2,\epsilon_2) \rightarrow D^{*0}(p_3,\epsilon_3)D^{*+}(p_4,\epsilon_4)$. The absorptive part of the amplitude from the $\pi$ exchange is

$$
\text{Abs}^{\pi}[Z^+ \rightarrow D^{*+}\bar{D}^1_0 \rightarrow D^{*+}\bar{D}^{*0}] = \frac{|p|}{32\pi^2 M_Z} \int d\Omega \ i[i g_{Z^+D_1^+D^+}] 
\times [-i g_{D^*D^\prime\bar{D}} \epsilon_\mu \epsilon_\rho (i q^\prime) \left( i p^{\rho}_1 + i p^{\rho}_2 \right) \epsilon^\alpha_1] \left[ -\frac{g^{\rho \beta}}{m_D^2} \epsilon_\beta \epsilon_\alpha \epsilon_\mu \epsilon_\rho \right] 
\times \left[ -3 g^{\beta\gamma} q^\prime + g^{\rho\beta} q^2 - \frac{g^{\rho\beta}}{m_D^2 m_D^2} (p_3 \cdot q) (p_1 \cdot q) \right] 
\times \left[ -g_{\sigma\mu} + \frac{p^{\rho}_1 p^{\rho}_2}{m^2_D} \right] \left[ -g_{\bar{D}^0 D^+} + \frac{p_{2\bar{D}^0 p_{2\bar{D}}}}{m^2_D} \right] \frac{F^2(q^2, m^2)}{q^2 - m^2_\pi}. 
(15)
$$

For the $\rho$ meson exchange, the amplitude is

$$
\text{Abs}^{\rho(\omega)}[Z^+ \rightarrow D^{*+}\bar{D}^1_0 \rightarrow D^{*+}\bar{D}^{*0}] = \frac{|p|}{32\pi^2 M_Z} \int d\Omega \ i[i g_{Z^+D_1^+D^+}] 
\times I^{(i)}_1 \left[ -2 i g_{D^*D^\prime\bar{D}} p_2 \tau \epsilon^4_i - 4 i f_{D^*D^\prime\bar{D}} (q^\prime \epsilon_{4\bar{U}} - g^\prime \epsilon_q \epsilon_4) \right] 
\times I^{(i)}_2 \left[ i g_{2\bar{D}^0D^+} \Theta^{\epsilon_3} + i g_{1,0} (g^\rho - p^{\rho}_1 p^{\rho}_2)^2 \left[ -g^\rho + \frac{q \epsilon_2}{m^2_D} \right] \right] 
\times \left[ -g_{\sigma\mu} + \frac{p^{\rho}_1 p^{\rho}_2}{m^2_D} \right] \left[ -g_{\bar{D}^0 D^+} + \frac{p_{2\bar{D}^0 p_{2\bar{D}}}}{m^2_D} \right] \frac{F^2(q^2, m^2)}{q^2 - m^2_\pi}. 
(16)
$$

Throughout this section, $F(q^2, m^2)$ is the form factor to describe the structure effect in the vertex of the re-scattering process $\bar{D}^0 D^{*+}(D_1^+D^*) \rightarrow D^{*0}D^{*+}$. We use the monopole form [17,22]

$$
F(q^2, m^2) = \left( \frac{m^2 - \Lambda^2}{q^2 - \Lambda^2} \right)^2 
(17)
$$

where $\Lambda = m_i + \alpha \Lambda_{QCD}$ with $\Lambda_{QCD} = 220$ MeV and $\alpha = 1 \sim 3$.

**IV. RESULTS AND DISCUSSION**

We collect the values of these coupling constants below

$$
g_{D^*D^\prime\bar{D}} = \frac{g_{D^*D^\prime\bar{D}}}{\sqrt{m_D m_D}} = \frac{2g}{f_\pi}, 
$$

$$
f_{D^*D^\prime\bar{D}} = \frac{f_{D^*D^\prime\bar{D}}}{\sqrt{2}} = \frac{\lambda_{\bar{D}}}{\sqrt{2}}, 
$$

$$
g_{D_1^+D^\prime\bar{D}} = \frac{-\sqrt{m_D m_D}}{3f_\pi \Lambda_\chi h_1 + h_2}, \ g_{D} = \frac{m_\rho}{f_\pi}, 
$$

where $g = 0.59$, $\lambda = 0.56$ GeV$^{-1}$, $\beta = 0.9$ are the parameters in the effective Lagrangian [20,22,23,24]. Casalbuoni and his collaborators extracted $h' = (h_1 + h_2)/\Lambda_\chi = 0.55$ GeV$^{-1}$ with the available experimental data [20]. In Ref. [21], Zhu and Dai gave $g_{2,2} = \sqrt{6} g_4/6$, $g_{1,0} = -\sqrt{6} g_4/3, g_{2,2} = \sqrt{6} g_4/4,$ $g_{1,2} = \sqrt{6} g_4/12,$ $g_{1,0}' = \sqrt{6} g_4/6, g_4 = 2.1$ and $g_4 = 3.8$ GeV$^{-2}$ in the framework of QCD sum rule.

For the parameter $\eta$, we use $\eta = 0.4$ GeV$^{-2}$ [25].

The meson masses are from PDG: $m_{D\bar{D}} = 1864.5$ MeV, $m_{D^*} = 1869.3$ MeV, $m_{D_1^+} = 2422.3$ MeV, $m_{D^{*0}} = 2006.7$ MeV, $m_{D^{**}} = 2010.0$ MeV, $m_\tau = 135.0$ MeV, $m_\rho = 757.0$ MeV, $m_{\pi} = 782.7$ MeV [20].

With the above parameters, we plot the dependence of the branching ratio of the two-body open charm decays $Z^+(4430) \rightarrow D^+D^{*0}, D^{*+}\bar{D}^0, D^+D^{*0}$ on $\alpha$ in Fig. [3]. In Table [3] we also list the branching ratios of $D^+D^{*0}, D^{*+}\bar{D}^0, D^+D^{*0}$ modes with typical values of $\alpha$. 


In short summary, we have calculated the two-body open charm decay widths assuming $Z^+(4430)$ is a pseudoscalar molecular state. Our numerical results show that the branching ratios of the two-body decays $Z^+(4430) \to D^+D^{*0}, D^{*+}D^{*0}$ are around $10^{-5} \sim 10^{-3}$, which is strongly suppressed compared to the main decay modes $D^*\bar{D}^\pi$ if it’s a molecular state with $J^P = 0^-$. However, they are only moderately suppressed compared with the discovery mode $\psi/\pi^+$. 

As an excellent candidate of the exotic states, the observation of $Z^+(4430)$ has stimulated several speculations about its structure. The tetraquark scheme seems an interesting choice. However, there is no reliable dynamics forbidding the quarks and anti-quarks to regroup and fall apart. With plentiful phase space $Z^+(4430)$ will easily fall apart into final states such $\psi\pi, \psi'\pi, \psi(1D)\pi, \eta_\rho, \chi_{cJ}\rho, DD^*$ etc if $Z^+(4430)$ is a tetraquark. Especially the two-body open charm modes $D^*\bar{D}^{*0}, D^{*+}\bar{D}^0, D^{*+}\bar{D}^{*0}$ etc will become one of the main decay modes, in sharp contrast with the case of $Z^+(4430)$ being a molecular state. Thus these modes provide a smoking gun to distinguish the molecular and tetraquark schemes. We strongly urge experimentalists to look for these two-body open charm decay modes together with the hidden charm mode $\chi_{cJ}\rho^+$. 

![FIG. 3: The dependence of the branching ratios on $\alpha$. The solid, dashed and dotted lines correspond to the $D^+\bar{D}^0$, $D^{*+}D^0$ and $D^{*+}\bar{D}^{*0}$ modes respectively.](image)

| $\alpha$ | 1.0 | 1.4 | 1.8 | 2.2 | 2.6 | 3.0 |
|----------|-----|-----|-----|-----|-----|-----|
| $B[Z^+ \to D^+D^{*0}]$ | $1.6 \times 10^{-4}$ | $6.4 \times 10^{-5}$ | $1.9 \times 10^{-4}$ | $4.4 \times 10^{-4}$ | $8.9 \times 10^{-4}$ | $1.6 \times 10^{-3}$ |
| $B[Z^+ \to D^{*+}\bar{D}^0]$ | $8.9 \times 10^{-5}$ | $2.4 \times 10^{-4}$ | $4.7 \times 10^{-4}$ | $7.8 \times 10^{-4}$ | $1.2 \times 10^{-3}$ | $1.6 \times 10^{-3}$ |
| $B[Z^+ \to D^{*+}\bar{D}^{*0}]$ | $6.3 \times 10^{-6}$ | $2.4 \times 10^{-5}$ | $5.6 \times 10^{-5}$ | $1.3 \times 10^{-4}$ | $2.5 \times 10^{-4}$ | $4.3 \times 10^{-4}$ |

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