Can we understand the decay width of the $T_{cc}^+$ state?

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Inspired by the recent discovery of a doubly charmed tetraquark state $T_{cc}^+$ by the LHCb Collaboration, we employ the effective Lagrangian approach to investigate the decay width of $T_{cc}^+ \to D^+D^0\pi^0/D^0D^0\pi^+ + T_{cc}^+ \to D^0D^+\gamma$ with the assumption that $T_{cc}^+$ is an isoscalar $DD^*$ molecule. We show that both the $T_{cc} \to DD\pi$ and $T_{cc} \to DD\gamma$ modes contribute to the decay width of $T_{cc}$, with the former being dominant. The resulting total decay width of about $\Gamma \approx 63$ keV is smaller than the experimental decay width obtained from the Breit-Wigner fit of the LHCb data, $\Gamma = 410 \pm 165 \pm 18 \pm 43$ keV, while close to the number obtained from the alternative unitary analysis, $\Gamma = 48 \pm 2^{+10}_{-14}$ keV, which supports the molecular nature of $T_{cc}$.

I. INTRODUCTION

Mesons made of a pair of quark and anti-quark and baryons made of three quarks can be well understood in the conventional quark model [1]. Although Quantum ChromoDynamics (QCD) allows for other quark configurations, such as tetraquark, pentaquark, and hexaquark states, their existence were not experimentally confirmed until the charged tetraquark state $Z_c(4430)$, with the minimum quark content $c\bar{c}u\bar{d}$, was discovered in 2007 by the Belle Collaboration [2]. In 2015, the LHCb Collaboration reported the first
pentaquark states $P_c(4380)$ and $P_c(4450)$ \[3\], while the latter was shown to be a superposition of two states, $P_c(4440)$ and $P_c(4457)$ \[4\]. In 2020, the LHCb Collaboration discovered the first fully heavy tetraquark state $X(6900)$ \[5\]. It should be noted that all of these exotic states carry hidden charm number. The first open charm tetraquark states, $X_0(2866)$ and $X_1(2904)$, were only discovered in 2020 by the LHCb Collaboration \[6\].

Since forty years ago, a series of pioneer works have already investigated the likely existence of $QQ\bar{q}\bar{q}$ tetraquark states in the quark model, which showed that the stability of a $QQ\bar{q}\bar{q}$ tetraquark depends on the mass ratio of $m_Q/m_{\bar{q}}$ \[7–13\]. As the ratio is larger, such a multiquark state is more stable. However, due to the uncertainty of $m_c/m_{\bar{q}}$, whether the mass of the $cc\bar{q}\bar{q}$ tetraquark state is above or below the $DD^*$ mass threshold is unsettled. Later, meson exchange potentials were employed to study the likely existence of $DD^*$ molecules \[14, 15\], where due to the unknown parameters the existence of $DD^*$ bound states is also uncertain. In 2002, a doubly charmed baryon was discovered by the SELEX Collaboration \[16\], which motivated further theoretical studies on $cc\bar{q}\bar{q}$ tetraquark states \[17, 18\]. In 2003, $X(3872)$ was discovered by the Belle Collaboration \[19\], which opened a new era in hadron physics. One of the most promising interpretations of $X(3872)$ is a $D\bar{D}^*$ bound state. This has further stimulated theoretical studies on $D^{(*)}D^{(*)}$ molecules, i.e., $T_{cc}$ \[20–32\]. In 2017, the LHCb collaboration reported the doubly charmed baryon $\Xi_{cc}$ \[33\], which allows the $cc$-diquark mass precisely extracted by the mass of $\Xi_{cc}$ and predicts a doubly charmed compact tetraquark state above the $DD^*$ mass threshold by 8 MeV \[34\]. Taking into account the heavy quark symmetry between $\Xi_{cc}$ and $T_{cc}$, in Refs. \[35, 36\] a doubly charmed compact tetraquark state above the $DD^*$ mass threshold was also predicted.

Very recently, the LHCb Collaboration reported the discovery of a doubly charmed tetraquark state $T_{cc}^+$ with $I(J^P) = 0(1^+)$, which is found in the $D^0\bar{D}^0\pi^+$ invariant mass spectrum \[37\]. Its binding energy with respect to the $D^{(*)}\bar{D}^{(*)}$ mass threshold is found to be $\delta = 273 \pm 61 \pm 5^{+11}_{-14}$ keV and decay width is $\Gamma = 410 \pm 165 \pm 43^{+18}_{-38}$ keV. In the unitarized Breit-Wigner profile that takes into account the effect of mass threshold, the binding energy and decay width change to $\delta = 360 \pm 40^{+4}_{-0}$ keV and $\Gamma = 48 \pm 2^{+0}_{-14}$ keV, respectively \[38\]. The $T_{cc}$ state could be either a compact tetraquark state or a hadronic molecule of $DD^*$. Since the $T_{cc}$ mass is below the mass threshold of $D^{(*)}\bar{D}^{(*)}$ by 273 keV, the molecular picture seems more appealing.

In the present work, we revisit the molecular picture for the $T_{cc}^+$ state. In particular, we study its hadronic and radiative decays to check whether one can obtain a decay width in reasonable agreement with the LHCb measurement. This can serve as a highly nontrivial check on its nature.
In this work, we assume that $T_{cc}$ is generated by couple channels $D^{*+}D^{0}$ and $D^{0}D^{*+}$, and it then can decay into $D^{+}D^{0}\pi^{0}/D^{0}D^{0}\pi^{+}$ and $D^{+}D^{0}\gamma$ via the tree-level diagrams, as shown in Fig. 1. In the following, we employ the effective Lagrangian approach to calculate the partial decay widths of $T_{cc} \rightarrow D^{+}D^{0}\pi^{0}/D^{0}D^{0}\pi^{+}$ and $D^{+}D^{0}\gamma$.

The interaction between the $T_{cc}$ state and the $DD^{*}$ pair is described by the following effective Lagrangian [40]

$$
\mathcal{L}_{T_{cc}}(x) = ig_{T_{cc}} T_{cc}^{\mu}(x) \int dy \Phi(y^{2}) D(x + \omega_{D^{*}} y) D^{\mu}_{p}(x - \omega_{D^{*}} y),
$$

where $\omega_{D^{*}} = \frac{m_{D^{*}}}{m_{p} + m_{D}}$ and $\omega_{D} = \frac{m_{D}}{m_{p} + m_{D}}$ are the kinematic parameters with $m_{D^{*}}$ and $m_{D}$ the masses of $D$ and $D^{*}$, and $g_{T_{cc}}$ is the coupling between $T_{cc}$ and the $D^{*}D$ component. The correlation function $\Phi(y^{2})$ is introduced to reflect the distribution of the two constituent hadrons in a molecule, which also renders the

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{Fig1.png}
\caption{Tree-level diagrams for strong decays of $T_{cc}^{+} \rightarrow D^{+}\pi^{0}(D^{*+})D^{0}$ (a), $T_{cc}^{+} \rightarrow D^{0}\pi^{+}(D^{*+})D^{0}$ (b) and $T_{cc}^{+} \rightarrow D^{0}\pi^{0}(D^{*0})D^{+}$ (c) as well as radiative decays of $T_{cc}^{+} \rightarrow D^{+}\gamma(D^{*+})D^{0}$ (d) and $T_{cc}^{+} \rightarrow D^{0}\gamma(D^{*0})D^{+}$ (e).}
\end{figure}
Feynman diagrams ultraviolet finite. Here we choose the Fourier transformation of the correlation function in form of a Gaussian function

$$\Phi(p^2) = e^{-p^2/\Lambda^2},$$

where $\Lambda$ is a size parameter, which is expected to be around 1 GeV \cite{41,42}, and $P_E$ is the Euclidean momentum. The coupling of $g_{T\cc}$ can be estimated by reproducing the binding energy of the $T_{cc}$ state via the compositeness condition \cite{43,44,45}. The condition indicates that the coupling constant can be determined from the fact that the renormalization constant of the wave function of a composite particle should be zero.

For a spin-1 meson, the self energy can be divided into a transverse part and a longitudinal part, i.e.,

$$\Sigma^{\mu\nu} = g_+^{\mu\nu} \Sigma_{T_{cc}}(k_0^2) + \frac{p^\mu p^\nu}{p^2} \Sigma_{L}(k_0^2),$$

with $g_+^{\mu\nu} = g^{\mu\nu} - \frac{p^\mu p^\nu}{p^2}$. The compositeness condition can then be estimated from the transverse part of the self energy

$$Z_{T_{cc}} = 1 - \frac{d\Sigma_{T_{cc}}(k_0^2)}{dk_0^2}
|_{k_0=m_{T_{cc}}} = 0.$$  \hspace{1cm} (4)

The $T_{cc}$ mass is below the $D^{*+}D^0$ mass threshold by 273 keV with an uncertainty of 66 keV. We note that the threshold of $D^{*0}D^+$ is above that of $D^{*+}D^0$ by only about 1.4 MeV, and therefore we assume that the couplings of $g_{T_{cc}D^{*0}D^+}$ and $g_{T_{cc}D^{*+}D^0}$ are the same, from SU(2)-isospin symmetry. Therefore, we take the average mass of $D^{*0}$ and $D^{*+}$ ($D^0$ and $D^+$) to calculate the coupling of $T_{cc}$ to its component $g_{T_{cc}D^+D^-}$ (as a result, the binding energy is 0.978 MeV), then obtain $g_{T_{cc}D^{*0}D^+}$ and $g_{T_{cc}D^{*+}D^0}$ using isospin symmetry. In the isospin symmetric limit, the $T_{cc}$ couplings to $D^{*+}D^0$ and $D^{*0}D^+$ satisfy the following relationship

$$g_{T_{cc}D^+D^0} = \frac{1}{\sqrt{2}} g_{T_{cc}D^0D^+}.$$  \hspace{1cm} (5)

Substituting the coupling $g_{T_{cc}D^0D^+}$ estimated by the compositeness condition, the couplings $g_{T_{cc}D^{*0}D^+}$ and $g_{T_{cc}D^{*+}D^0}$ are determined, which turn out to be consistent with the result of the chiral unitary approach \cite{48}. 

**Table I.** Masses, quantum numbers and partial decay widths of relevant mesons used in this work \cite{46}.

| Meson | $I(J^P)$ | M (MeV) | Meson | $I(J^P)$ | M (MeV) |
|-------|----------|---------|-------|----------|---------|
| $D^0$ | $\frac{1}{2}(0^-)$ | 1864.84 ± 0.05 | $D^+$ | $\frac{1}{2}(0^-)$ | 1869.66 ± 0.05 |
| $D^{*0}$ | $\frac{1}{2}(1^-)$ | 2006.85 ± 0.05 | $D^{*+}$ | $\frac{1}{2}(1^-)$ | 2010.26 ± 0.05 |
| $\pi^+$ | $1(0^-)$ | 139.57039 ± 0.00018 | $\pi^0$ | $1(0^-)$ | 134.9768 ± 0.0005 |

| Decay mode | Width (keV) | Decay mode | Width (keV) |
|-------------|-------------|-------------|-------------|
| $D^{*+} \rightarrow D^0\pi^+(D^+\pi^0)$ | 56.5 ± 1.2(25.6 ± 0.6) | $D^{*+} \rightarrow D^+\gamma$ | 1.33 ± 0.03 |
| $D^{*0} \rightarrow D^0\pi^0$ | 34.658 \cite{47} | $D^{*0} \rightarrow D^0\gamma$ | 21.242 \cite{47} |
In Fig. 2 we present the dependence of the $T_{cc}$ coupling to $DD^*$ on the $T_{cc}$ mass with the size parameter $\Lambda$ fixed at 1 and 2 GeV. The masses of the involved particles are given in Table I. One can see that the coupling gradually decreases as the $T_{cc}$ mass increases. Note that the coupling is only weakly dependent on the size parameter $\Lambda$.

![Graph showing the dependence of $g_{T_{cc}}$ on $m_{T_{cc}}$.](image)

**FIG. 2.** Coupling of $T_{cc}$ to $DD^*$ as a function of the $T_{cc}$ mass with $\Lambda = 1$ and $\Lambda = 2$ GeV. The vertical dashed line indicates the experimental central value for the $T_{cc}$ mass.

The Lagrangian describing the $D^*$ decay into $D\pi$ and $D\gamma$ are

\[
L_{DD^*\pi} = -ig_{DD^*\pi}(D\bar{\partial}\mu\pi D^\mu - D^\mu\bar{\partial}\mu\pi D^\dagger),
\]

\[
L_{DD^*\gamma} = eg_{DD^*\gamma}\varepsilon^{\mu\nu\alpha\beta}\partial_\mu A_\nu D^\beta D^\dagger, \tag{6}
\]

where the fine structure constant $\frac{e^2}{4\pi} = \frac{1}{137}$, and relevant couplings are determined as $g_{D^+D^0\pi^0} = 16.818$ and $g_{D^+D^0\gamma} = 0.468$ GeV$^{-1}$ by reproducing the decay widths of $D^{*+} \rightarrow D^0\pi^+$ and $D^{*+} \rightarrow D^+\gamma$ [46], respectively. Experimentally, there exists only an upper limit $\Gamma < 2.1$ MeV for the $D^{*0}$ width. Thus we turn to the quark model [47], where the strong and radiative decay widths of $D^{*0}$ were estimated to be $\Gamma_{D^{*0} \rightarrow D^0\pi^0} = 34.658$ keV and $\Gamma_{D^{*0} \rightarrow D^0\gamma} = 21.242$ keV. With these numbers, we obtain the couplings $g_{D^{*0}D^0\pi^0} = 11.688$ and $g_{D^{*0}D^0\gamma} = 1.843$ GeV$^{-1}$. It is clear that the strong couplings satisfy approximately isospin symmetry while the electromagnetic couplings do not.

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1 We note that the lattice QCD simulation [49] gave relatively larger values, i.e., $\Gamma_{D^{*0} \rightarrow D^0\pi^0} = 53 \pm 9$ keV and $\Gamma_{D^{*0} \rightarrow D^0\gamma} = 33 \pm 6$ keV. From isospin symmetry, we expect that the $D^{*0}$ strong decay width be smaller than the $D^{*+}$ strong decay width because the $D^{*0} \rightarrow D^*\pi^-$ decay mode is kinematically forbidden. As a result, we do not use these lattice QCD results.
With the above Lagrangians the decay amplitudes of $T_{cc} \rightarrow DD\pi$ and $T_{cc} \rightarrow DD\gamma$ are

$$M_{T_{cc} \rightarrow DD\pi} = ig_{T_{cc}}g_{DD\pi}p_2\mu\frac{\mu^\nu - k_1^\nu k_1^\mu/m_D^2}{k_1 - m_D^2 + im_D\Gamma_{m_D^2}}\epsilon_\nu(p_0),$$

$$M_{T_{cc} \rightarrow DD\gamma} = ig_{T_{cc}}g_{DD\gamma}\epsilon^{\mu\nu}\alpha\beta p_2\mu\epsilon_\nu(p_0)\frac{k_1^\mu k_1^\nu/m_D^2}{k_1^2 - m_D^2 + im_D\Gamma_{m_D^2}}\epsilon^{\alpha\beta}(p_0),$$

where $p_2$, $k_1$, and $p_0$ are the momentum of $\pi(\gamma)$, $D^\ast$, and $T_{cc}$, respectively. The partial decay widths of $T_{cc} \rightarrow DD\pi$ and $T_{cc} \rightarrow DD\gamma$ as a function of $m_{12}^2$ and $m_{23}^2$ read:

$$d\Gamma = \frac{1}{(2\pi)^3} \frac{1}{2J + 1} \frac{|M|^2}{32m_{T_{cc}}^3} dm_{12}^2 dm_{23}^2,$$

with $m_{12}$ the invariant mass of $DD$ and $m_{23}$ the invariant mass of $D\pi$ or $D\gamma$ for the $T_{cc} \rightarrow DD\pi$ or $T_{cc} \rightarrow DD\gamma$ decay, respectively.

In principle, there exist three possible decay channels, $T_{cc} \rightarrow D^0D^0\pi^\ast$, $T_{cc} \rightarrow D^0D^+\pi^0$, and $T_{cc} \rightarrow D^+D^+\pi^-$. In Fig. 3(a)(b), we show the decay width of $T_{cc} \rightarrow DD\pi/\gamma$ as a function of the $T_{cc}$ mass, where we take the size parameter $\Lambda = 1$ and 2 GeV. With the $T_{cc}$ mass varying from 3874.751 to 3874.883 MeV, the decay width of $T_{cc} \rightarrow DD\pi$ is found to be about 46 to 62 keV with the size parameter $\Lambda = 1$ GeV, which is smaller than the Breit-Wigner width by one order of magnitude [37], but close to the result yielded from the unitary analysis [38]. One should note that the decay $T_{cc}(D^0D^+) \rightarrow D^+\pi^-D^+$ is kinematically forbidden. The $T_{cc}(D^+D^0) \rightarrow D^0\pi^+D^0$ contribution accounts for 50% of the total decay width, and the remaining is from $T_{cc}(D^+D^0) \rightarrow D^+\pi^0D^0$ and $T_{cc}(D^0D^+) \rightarrow D^0\pi^0D^+$.

![Graph](image-url)

**FIG. 3.** Total decay width and partial decay widths of $T_{cc} \rightarrow DD\pi(a)$ and $T_{cc} \rightarrow DD\gamma(b)$ as a function of the $T_{cc}$ mass. The solid and dashed lines represent the results obtained with a cutoff $\Lambda = 1$ GeV and $\Lambda = 2$ GeV, respectively.

The radiative decay width of $T_{cc} \rightarrow DD\gamma$ is about 10 keV, which mainly originates from the $D^0D^+$ component of the $DD^*$ molecule because the radiative decay width of $D^0$ is about 16 times that of
Considering isospin breaking due to the mass difference of the $D^+D^0$ and $D^{*0}D^+$ channels, the radiative decay width will decrease. As a result, what we obtained should be viewed as an upper limit. The ratio of the decay widths of $T_{cc} \rightarrow DD\gamma$ and $T_{cc} \rightarrow DD\pi$ is in agreement with the ratio of the decay widths of $D^* \rightarrow D\gamma$ and $D^* \rightarrow D\pi$, reflecting the fact that the decay width of $T_{cc}$ is mainly from the decay of $D^*$. Since the decay width of a free $D^{*+}$ is 83.4 keV \cite{46}, the decay width of a weakly bound $DD^*$ molecule is not expected to be larger than 83.4 keV.

### III. SUMMARY AND OUTLOOK

We studied the decay width of the $T_{cc}^+$ state in the effective Lagrangian approach. Assuming that the $T_{cc}^+$ state is a hadronic molecule of $DD^*$, we obtained a partial decay width of $T_{cc} \rightarrow DD\pi$ of about 53 keV and a radiative decay width of about 10 keV. Their sum is much smaller than the central experimental value of the Breit-Wigner fit, but agrees with that of the unitary fit. We argued that although the experimental binding energy favors a molecular interpretation for the $T_{cc}$ state, a complete understanding of its decay width is still missing.

The discovery of the doubly charmed tetraquark state $T_{cc}^+$ may open up another new era for hadron physics, in the same way that the discovery of $X(3872)$ did \cite{19}. For open charm exotic baryons, it is very reasonable to expect a complete multiplet of doubly charmed $D^{(*)}\Sigma_c^*$ hadronic molecules, which are more bound than their hidden charm $\bar B^{(*)}\Sigma_c$ counterparts \cite{39}, consistent with Refs. \cite{50–52}. From SU(3) symmetry, one may expect the existence of $D^*D_s$ or $D^*D_s$ molecules. However, these two systems are found difficult to bind, at least from the perspective of OBE models \cite{26}. In a series of recent works \cite{53–56}, we predicted one $DD\pi$ bound state with isospin $1/2$, spin-parity $0^-$, and a minimum quark content of $cc\bar s\bar q$, which can be regraded as the strangeness partner of $T_{cc}$. All these remain to be further studied in more detail both theoretically and experimentally.

Note added: After the $T_{cc}^+$ state was discovered by the LHCb Collaboration, a series of works have been performed to investigate the property of $T_{cc}$ \cite{48, 50, 57–66}. In Refs. \cite{57, 58}, in addition to the tree level contribution, the final $DD$ rescattering effect was also taken into account. However, it only contributes several keV, which obeys the power counting of effective field theory. In Refs. \cite{59, 60}, the authors argued that in the molecular picture of $T_{cc}^+$ the explicit breaking of isospin should be considered and it may lead to another molecular state mainly coupling to the $D^{*0}D^+$ channel. However, the authors of Ref. \cite{48} did not find another $T_{cc}$ denominated by the $D^{*0}D^+$ channel in the chiral unitary model. In Ref. \cite{61}, Dai et al. have considered the interaction of $D^{*+}D^0$ and $D^0D^0\pi^+$ coupled channels by fitting to the LHCb data, and interpreted the $T_{cc}^+$ state as a virtual state. Moreover, several theoretical works investigated the production
of $T_{cc} [62, 63]$. In Ref. [64], M. Albaladco predicted several $D^*D^*$ bound states based on heavy quark spin symmetry and the molecular picture where the $T_{cc}$ state is a $DD^*$ molecule.

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