The quasi-fission phenomenon of double charm $T_{cc}^+$ induced by nucleon

Jun He$^{1,2,*}$ and Xiang Liu$^{2,3,4,5,\dagger}$

1Department of Physics and Institute of Theoretical Physics, Nanjing Normal University, Nanjing 210097, China
2Lanzhou Center for Theoretical Physics, Lanzhou University, Lanzhou 730000, China
3School of Physical Science and Technology, Lanzhou University, Lanzhou 730000, China
4Key Laboratory of Theoretical Physics of Gansu Province, and Frontiers Science Center for Rare Isotopes, Lanzhou University, Lanzhou 730000, China
5Research Center for Hadron and CSR Physics, Lanzhou University and Institute of Modern Physics of CAS, Lanzhou 730000, China

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In this work, we study the reaction of a nucleon and a doubly charmed state $T_{cc}$. Under the assumption of the $T_{cc}$ as a molecular state of $D^0D^*$, the reaction of the nucleon and $T_{cc}$ is mediated by exchanges of $\pi$, $\eta$, $p$, and $\omega$ meson, which results in split of $T_{cc}$ state with two $D$ mesons in final state. With the help of the effective Lagrangians, the cross section of $p + T_{cc}^{*0} \rightarrow p + D^0 + D^*$ process is calculated, and a very large cross section can be obtained with very small incoming momentum of proton. It decrease rapidly with the increase of the momentum to about 10 mb at momenta of order of GeV. Such large cross section suggests that induced by a proton the $T_{cc}^{*0}$ state is very easy to decay and transit to two $D$ mesons. In the rest frame of the $T_{cc}^{*0}$ state, an obvious accumulation of final $D$ meson at small momentum region can be observed in predicted Dalitz plot, which is due to the molecular state interpretation of $T_{cc}^{*0}$ state. This novel quasi-fission phenomenon of double charm molecular $T_{cc}^{*0}$ state induced by a proton can be accessible at the forthcoming PANDA experiment.

I. INTRODUCTION

Recently, the $T_{cc}^{*+}$ state was discovered by the LHCb Collaboration [1, 2]. As a very narrow resonance structure, the $T_{cc}^{*0}$ with the significance over 10$\sigma$ exists in the $D^0\bar{D}^0\pi^+$ invariant mass spectrum, which shows that the $T_{cc}^{*+}$ has the minimal quark content $cc\bar{u}\bar{d}$. The LHCb measurement indicates that the $T_{cc}^{*+}$ has mass difference and width

$$\delta = m_{T_{cc}^{*0}} - (m_{D^0} + m_{D^*}) = -273 \pm 61 \pm 5.1^{+11}_{-14} \text{ keV},$$

$$\Gamma = 410 \pm 165 \pm 43^{+18}_{-38} \text{ keV},$$

respectively. The observation of the $T_{cc}^{*+}$ confirmed the existence of double charm tetraquark [3–34], and inspired further discussions of its properties [35–56]. The main reason why double charm tetraquark attracts the attention from both theorist and experimentalist is that double charm tetraquark is a manifestly exotic state, which can be distinguished from the conventional hadron. The zoo of exotic hadronic state becomes more abundant with adding the reported $T_{cc}^{*+}$.

When facing this novel phenomenon, different proposals to the inner structure of the the $T_{cc}^{*+}$ were proposed. At present, the molecular state [35–46] and compact tetraquark [47, 48] are two typical assignments to the $T_{cc}^{*+}$, which are competing with each other. The present experimental data cannot be applied to distinguish them. Under different assignment to the the $T_{cc}^{*+}$, the investigations of the mass spectrum [35–48], decay behavior [49–52], and production mechanism [53–56] can provide some important aspect of the spectroscopy behavior of the $T_{cc}^{*+}$. However, it is not the whole aspect of exploring hadronic spectroscopy.

In fact, the reaction of the $T_{cc}^{*+}$ with other hadrons can provide useful information to decode the property of the $T_{cc}^{*+}$. In this work, we find a novel quasi-fission phenomenon of the molecular $T_{cc}^{*+}$ induced by nucleon, which can be as a unique approach to test the molecular structure of the $T_{cc}^{*+}$. If the $T_{cc}^{*+}$ is the $DD^*$ molecular state [17], the $T_{cc}^{*+}$ cannot decay into its hadronic components $D$ and $D^*$ which is kinematically forbidden. However, when a proton interacts with the molecular $T_{cc}^{*+}$, the quasi-fission phenomenon can be happened. In this work, we investigate the quasi-fission phenomenon of the molecular $T_{cc}^{*+}$ induced by a proton.

In realistic calculation, we select a simple but typical reaction $p + T_{cc}^{*+} \rightarrow p + D^0 + D^*$ to illustrate how this reaction occurs, by which future experimental exploration of such a reaction is suggested. Among the running and forthcoming experiments, the PANDA experiment at the Facility for Antiproton and Ion Research (FAIR), which is under construction, has a potential to find out the reaction of $p + T_{cc}^{*+} \rightarrow p + D^* + D^0$. As peculiar phenomenon of the $T_{cc}^{*+}$ molecular state, its quasi-fission reaction behavior can be applied to test the molecular state assignment to the $T_{cc}^{*+}$.

II. REACTION OF THE $T_{cc}^{*+}$ WITH A PROTON

Under the molecular state picture, the $T_{cc}^{*+}$ state can be expressed as

$$|T_{cc}^{*+}\rangle = \frac{1}{\sqrt{2}}(|D^0D^*\rangle - |D^*D^0\rangle).$$

(1)

Attacked by an incoming proton, the $T_{cc}^{*+}$ molecular state can be split into its constituents. The reaction mechanism for the process $p + T_{cc}^{*+} \rightarrow p + D^* + D^0$ is illustrated in Fig. 1. Here, only the first term of the $T_{cc}^{*+}$ molecular state in the above expression is presented, and the second term can be obtained analogously. The exchanged light mesons are assumed to attack on the vector meson $D^*$, which leads to a transition to a scalar $D^0$ meson.
T describes the possibility of the reaction of a proton and a
the reaction. b) the Feynman diagram of the reaction, the denotations
coming proton or
FIG. 1: The reaction of A(1), as shown in Fig. 1 the amplitude of total reaction can be
by a split of the
In the current work, the most important physical quantity
First, we need to deduce the amplitude
σ
1
= 4(κ
Tcc), the amplitude can be determined by the scattering length a
as [58],
\begin{equation}
\mathcal{A}_{T_{cc}^{p}, \lambda_{p}^{a}} = \frac{16\pi m_{T_{cc}^{p}, \lambda_{p}^{a}D_{c}} m_{D} m_{D^{+}}}{\mu^{2} a^{2}} e_{T_{cc}^{p}} \cdot e_{\lambda_{p}^{a}D_{c}},
\end{equation}
where \(m_{T_{cc}^{p}, D_{c}}\) is the mass of the \(T_{cc}^{p}\) and the constituent
\(D^{+}\) or \(D^{0}\). The \(e_{T_{cc}^{p}}\) and \(e_{\lambda_{p}^{a}D_{c}}\) are the polarized vectors for
\(T_{cc}^{p}\) and \(D^{\pm}\), respectively. Scattering length \(a = 1 / \sqrt{2\mu E_{B}}\)
with the reduced mass \(\mu = m_{D} m_{D}/(m_{D} + m_{D^{+}})\) and the \(E_{B}\)
being the binding energy. As given in Ref. [59], the amplitudes for the \(T_{cc}\) splitting with the propagator of \(D^{*}\) meson can be expressed with wave function of the \(T_{cc}\), i.e., \(\psi(k) = \sqrt{8\pi a/(k^{2} + 1/a^{2})}\) with normalization \(\int d^{3}k/(2\pi)^{3}|\psi(k)|^{2} = 1\) [60], as
\begin{equation}
\mathcal{A}_{T_{cc}^{p}, \lambda_{p}^{a}D^{*}_{c}} = - \frac{8\pi m_{T_{cc}^{p}, \lambda_{p}^{a}D_{c}} m_{D} m_{D^{+}}}{\mu^{2} a^{2}} \psi(k) e_{T_{cc}^{p}} \cdot e_{\lambda_{p}^{a}D_{c}}.
\end{equation}
Besides the split of the \(T_{cc}\), we need describe the scattering \(pD^{*+} \rightarrow pD^{+}\) as shown in Fig. 1. To depict the scattering, the following Lagrangians under the heavy quark and chirality symmetries are adopted to construct the vertex of \(D^{+}, D^{0}\), and light meson [61],
\begin{equation}
\mathcal{L}_{p-p\pi} = \frac{-2g}{f_{\pi}} (\mathcal{P}_{B}^{a} \mathcal{P}_{A}^{a} + \mathcal{P}_{B}^{a} \mathcal{P}_{A}^{a}) \partial_{0} \mathcal{P}_{B},
\end{equation}
\begin{equation}
\mathcal{L}_{p-p\pi} = -2 \sqrt{2} g_{\pi} \gamma^{5} \epsilon_{\lambda_{p}^{a}D_{c}} (\mathcal{P}_{B}^{a} \mathcal{P}_{A}^{a} + \mathcal{P}_{B}^{a} \mathcal{P}_{A}^{a}) \partial_{0} \mathcal{P}_{B},
\end{equation}
where \(\mathcal{P}_{B}^{a} = (D^{(\pi)}, D^{(\rho)} (9)\) is the fields for \(D^{(\pi)}\) meson. And \(\mathcal{P}^{a}\) and \(\mathcal{V}^{a}\) are two by two pseudoscalars and vector matrices
\begin{equation}
\mathcal{P}^{a} = \begin{pmatrix} \pi^{+} / \sqrt{6} & 0 \\ -\sqrt{2} \pi^{0} / \sqrt{6} & \rho^{0} \end{pmatrix}, \quad \mathcal{V}^{a} = \begin{pmatrix} \rho^{0} / \sqrt{2} & \rho^{+} \\ 0 & -\rho^{+} / \sqrt{2} \end{pmatrix}.
\end{equation}
The parameters involved here were determined in the literature as \(g = 0.59, \beta = 0.9, \lambda = 0.56\) GeV\(^{-1}\), \(g_{\pi} = 5.9\), and \(f_{\pi} = 132\) MeV [61, 62].
The Lagrangians for the vertex of nucleon and light meson are
\begin{equation}
\mathcal{L}_{pNN} = - \frac{g_{pNN} N^{a}_{p} \gamma_{5} N^{a}_{p} \mu_{p} \bar{N}_{a}}{2m_{N}},
\end{equation}
\begin{equation}
\mathcal{L}_{NNNN} = - \sqrt{2} g_{\pi NN} \bar{N}_{a} \left( \gamma_{\mu} + \frac{k}{2m_{NN}} \sigma_{\mu\nu} \partial^{\nu} \right) \mu_{a} N_{a},
\end{equation}
where \(N^{T} = (p, n)\) is field for nucleon. The coupling constants
\(g_{pNN}/(4\pi) = 13.6, g_{\pi NN}^{2}/(4\pi) = 0.84, g_{\pi NN}^{2}/(4\pi) = 20\) with
\(k = 6.1(0)\) in Eq. (8) for \(\rho (\omega)\) meson, which are used in the
Bonn nucleon-nucleon potential [63] and meson productions in nucleon-nucleon collision [64–66]. The \(\eta\) exchange is neglected in the current work due to the weak coupling of \(\eta\) or \(\phi\) to nucleons as indicated in many previous works [63, 64].
Applying standard Feynman rules, the amplitude can be written as
\begin{equation}
\mathcal{M} = i \frac{\sqrt{8m_{T_{cc}^{p}, \lambda_{p}^{a}D_{c}}} m_{D} m_{D^{+}}}{m_{T_{cc}^{p}, \lambda_{p}^{a}D_{c}}} \bar{N} \mathcal{A}_{T_{cc}^{p}, \lambda_{p}^{a}D_{c}},
\end{equation}
with
\[ \bar{A}_{1\rho'} = -\frac{1}{2} \left[ P_\rho(q^2) - P_{\omega}(q^2) \right] \psi(k_3) \epsilon_{\alpha \beta \gamma \rho'} v_3^\alpha v_3^\beta v_3^\gamma \gamma' (1 - \eta) + \frac{1}{2} \left[ P_\rho(q^2) + P_{\omega}(q^2) \right] \psi(k_2) \epsilon_{\alpha \beta \gamma \rho'} v_2^\alpha v_2^\beta v_2^\gamma \gamma' (1 - \eta) + \frac{1}{2} \left[ \psi(k_3) \epsilon_3^\alpha \cdot q + \psi(k_2) \epsilon_2^\alpha \cdot q \right] P_{\alpha}(q^2) \gamma_3 g_\lambda, \]  

(10)

with the abbreviations \( \epsilon_T^{1,2} = [\epsilon_T - (k_{2,3} - q) \cdot \epsilon_T (k_{2,3} - q)/m_\pi^2] \) and \( v_{1,2} = k_{1,2}/\sqrt{m_D m_{\pi'}} \). Here, the superscripts 2 and 3 are for the first and second parts of the wave function, respectively. \( P_i(q^2) \) is the product of the denominator of propagator of exchanged mesons 1\/(\( q^2 - m_i^2 \)), form factor \( f_i(q^2) = (m_i^2 - \Lambda^2)/(q^2 - \Lambda^2) \), and coupling constant as \( F_i = \sqrt{2g_{VNN}m_D}/m_Nf_s \) or \( F_V = 4g_{VNN}m_V\sqrt{m_D m_{\pi'}} \).

With the preparation above, we can calculate the cross section of the \( p + T_{cc}^+ \rightarrow p + D^+ + D^0 \) reaction. The results with cutoffs \( \Lambda = 0.5, 1.5, \) and 3 GeV are presented in Fig. 2. One can find that with small momentum of the coming proton, a very large cross section can be obtained. At a momentum of 1 eV, a cross section about \( 10^7 \) b can be reached. Such large cross section is from more reaction time with small speed of incoming proton. With the increase of the incoming momentum, the cross section will decrease very rapidly, and reach a cross section of an order of 10 mb at a momentum about 0.1 GeV. After that, the results become relatively stable. In the range of incoming momentum from 1 GeV to 5 GeV, the cross sections with cutoffs \( \Lambda = 0.5, 1.5, \) and 3 GeV are of an order of magnitude of 1 to 10 mb.

As show in the left panels in Fig. 3, the proton after reaction distributes in a large range of momentum. For example, at \( p_p = 3 \) GeV, the final proton can carry momentum from about 1 to 3 GeV. More events can be observed at high momentum range, which means small energy loss. Due to the symmetry in the wave function, the distributions of final \( D^0 \) and \( D^+ \) are analogously. For the diagram in Fig. 1, which corresponds to the first term of wave function in Eq. (1), the final \( D^0 \) meson is almost unaffected, which is shown in the \( k_{\rho'} - k_D \) (right) planes, showing the momentum \( k_i = |k_i| \) of the final meson \( i \). The colorbox means the ratio of event number in a bin of 0.01 GeV\( \times 0.01 \) GeV to the total number of events. The results are obtained with \( 10^8 \) simulation.

FIG. 2: Cross section of the \( p + T_{cc}^+ \rightarrow p + D^+ + D^0 \) reaction as a function of momentum of incoming proton \( p_p \) = \( |p_p| \). The results with cutoffs \( \Lambda = 3, 1.5, \) and 0.5 GeV are given as full (blue), dashed (black), and dotted (red) lines.

FIG. 3: The momentum distributions of final particles for the \( p + T_{cc}^+ \rightarrow p + D^+ + D^0 \) reaction with cutoff \( \Lambda = 1 \) GeV. For each example choice of \( p_p \), the figures represent the \( k_p - k_{\rho'} \) (left) and \( k_{\rho'} - k_D \) (right) planes, showing the momentum \( k_i = |k_i| \) of the final meson \( i \). The colorbox means the ratio of event number in a bin of 0.01 GeV\( \times 0.01 \) GeV to the total number of events. The results are obtained with \( 10^8 \) simulation.
III. DISCUSSION AND CONCLUSION

As good candidate of exotic states, the newly observed $T_{cc}^+$ [1, 2] not only confirms the former prediction of double charm tetraquark [3–34], but also has aroused theorists’ interest in further revealing its property combing experimental data [35–56]. Since experimental precision is not enough to definitely conclude whether or not the $T_{cc}^+$ is a $DD^*$ molecular state, we should pay more effort to find peculiar phenomenon relevant to the $T_{cc}^+$ molecular state. Although mass, decay, and production are important aspects to reflect the inner structure of the $T_{cc}^+$, it is not the whole aspect of exploring the $T_{cc}^+$ property. Just considering the situation of the study of the $T_{cc}^+$, we propose that the reaction of the $T_{cc}^+$ with a nucleon is an approach to reveal the nature of the $T_{cc}^+$. Focusing on such a research issue, the concise study is still not enough.

With the great interest of the reaction of the $T_{cc}^+$ in this work, we study the reaction of a nucleon and a double charm $T_{cc}$. Under the assumption of the $T_{cc}$ as a molecular state of $D^*D$, the reaction of the nucleon and $T_{cc}$ is mediated by exchanges of $\pi$, $\eta$, $\rho$, and $\omega$ meson, which results in split of the $T_{cc}$ state with two $D$ mesons in final state. With the help of the effective Lagrangians, the cross section of $p + T_{cc} \rightarrow p + D^* + D^0$ process is calculated, and a very large cross section can be obtained with very small incoming momentum of proton. It decrease rapidly with the increase of the momentum to about 10 mb at momenta of order of GeV.

Such large cross section suggests that the $T_{cc}$ molecular state is very easy to decay and transit to two $D$ mesons induced by a proton. We call this peculiar phenomenon as quasi-fission of double charm $T_{cc}^+$ molecular state induced by nucleon, which can be applied to test the molecular state assignment to the $T_{cc}^+$. In summary, we predicted a quasi-fission phenomenon of double charm $T_{cc}^+$ molecular state induced by nucleon, which can meet the physics aim of the forthcoming PANDA experiment at FAIR. Searching for the quasi-fission phenomenon of the $T_{cc}^+$ induced by nucleon can shed light on the nature of the $T_{cc}^+$, which is crucial step when constructing exotic hadron family.

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