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

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Abstract 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^*D, the reaction of the nucleon and T_{cc} is mediated by exchanges of π, η, ρ, and ω 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 $p + T_{cc}^+ \to p + D^+ + D^0$ 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 induced by a proton the T_{cc}^+ state is very easy to decay and transit to two D mesons. In the rest frame of the T_{cc}^+ 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}^+ state. This novel quasi-fission phenomenon of double charm molecular T_{cc}^+ state induced by a proton can be accessible at High-Luminosity Large Hadron Collider.

1 Introduction

Recently, the T_{cc}^+ state was discovered by the LHCb Collaboration [1,2]. As a very narrow resonance structure, the T_{cc}^+ with the significance over 10σ exists in the $D^0D^0\pi^+$ 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

$$\delta = m_{T_{cc}^+} - (m_{D^0} + m_{D^{*+}}) = -273 \pm 61 \pm 5^{+11}_{-14}\ \text{keV},$$
$$\Gamma = 410 \pm 165 \pm 43^{+18}_{-38}\ \text{keV},$$

respectively. The observation of the T_{cc}^+ confirmed the existence of double charm tetraquark [3–34], and inspired further discussions of its properties [35–52,54–60]. 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 [53–57] 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.

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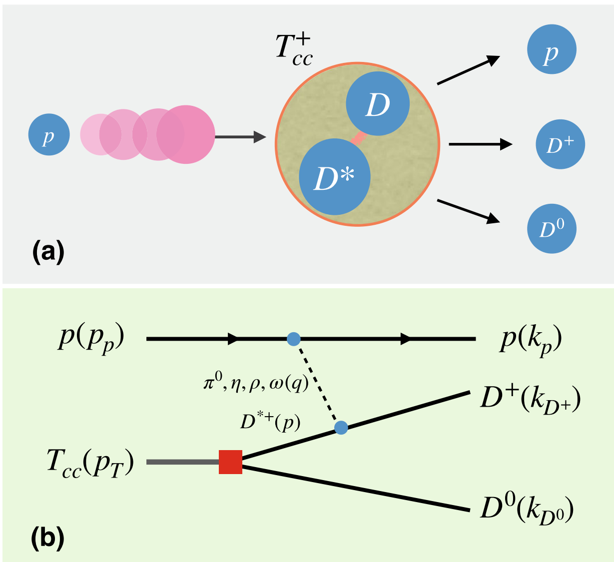

Fig. 1 The reaction of $p + T_{cc}^{+} \to p + D^{+} + D^{0}$. **a** The sketch map of the reaction. **b** The Feynman diagram of the reaction, the denotations of the momenta of particles are also given

In realistic calculation, we select a simple but typical reaction $p + T_{cc}^{+} \to p + D^{+} + D^{0}$ to illustrate how this reaction occurs, by which future experimental exploration of such a reaction is suggested. Among the running and forthcoming experiments, High-Luminosity Large Hadron Collider, which will be upgraded to reach an instantaneous luminosity up to 7×10^{34} cm^{-2}s^{-1}, has a potential to find out the reaction of $p + T_{cc}^{+} \to p + D^{+} + D^{0}$. 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}^{+}.

2 Reaction of the T_{cc}^{+} with a proton

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

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

Attacked by an incoming proton, the T_{cc}^{+} molecular state can be split into its constituents. The reaction mechanism for the precess $p + T_{cc}^{+} \to p + D^{+} + D^{0}$ 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^{+} meson. The proton also possibly attacks on the D^{0} meson, which leads to another process with a final D^{*} meson. However, since no transition of the D^{*} meson to D meson happens, it is not a quasifssion process with extra energy release. Moreover, in the current work, only the process with D mesons, which are more stable, is considered. Hence, such process is not included in the current work.

In the current work, the most important physical quantity is the cross section of the discussed reaction process, which describes the possibility of the reaction of a proton and a T_{cc}^{+} molecular state. In the rest frame of the T_{cc}^{+}, the cross section for the reaction $p + T_{cc}^{+} \to p + D^{+} + D^{0}$ reads as,

$$d\sigma = \frac{1}{4[(p_1 \cdot p_2)^2 - m_1^2 m_2^2]^{1/2}} \frac{1}{6} \sum_{\lambda_p \lambda_{T_{cc}} \lambda'_p} |\mathcal{M}_{\lambda_p \lambda_{T_{cc}}, \lambda'_p}|^2 d\Phi_3, \quad (2)$$

with the $p_{1,2}$ and $m_{1,2}$ being the momentum and mass of incoming proton or T_{cc}^{+}. With the help of GENEV code in FAWL, the phase space $d\Phi_3$ is produced as

$$R_3 = (2\pi)^5 d\Phi_3 = \prod_{i}^{3} \frac{d^3 k_i}{2E_i} \delta^4 \left(\sum_{i}^{n} k_i - P\right),$$

where the k_i and E_i are the momentum and energy of final particle i. The reaction of proton and the T_{cc}^{+} can be described by a split of the T_{cc}^{+} into two constituents and the scattering $pD^{*+} \to pD^{+}$. For the first term of the wave function in Eq. (1), as shown in Fig. 1 the amplitude of total reaction can be written with an amplitude $\mathcal{A}_{\lambda_{T_{cc}}, \lambda_{D^{*+}}}$ for $T_{cc}^{+} \to D^{*+}D^{0}$ and an amplitude $\mathcal{A}'_{\lambda_p \lambda_{\bar{D}^{*+}}, \lambda'_p}$ for $pD^{*+} \to pD^{+}$ as

$$\mathcal{M}_{\lambda_p \lambda_{T_{cc}}, \lambda'_p} = \sum_{\lambda_{D^{*+}}} \frac{\mathcal{A}_{\lambda_{T_{cc}}, \lambda_{D^{*+}}} \mathcal{A}'_{\lambda_p \lambda_{D^{*+}}, \lambda'_p}}{p^2 - m_{D^*}^2}, \quad (3)$$

where the λ_p, λ'_p, $\lambda_{T_{cc}}$, and $\lambda_{D^{*+}}$ are helicities for incoming proton, final proton, initial T_{cc}^{+} state, and intermediate D^{*+} meson. The p and $m_{D^*}^2$ are the momentum and mass of intermediate D^{*+} meson.

First, we need to deduce the amplitude $\mathcal{A}_{\lambda_{T_{cc}}, \lambda_{D^{*+}}}$ for the split of the T_{cc}^{+}. The coupling of the molecular state to its constituents can be related to the binding energy [61]. Hence, the amplitude can be determined by the scattering length a as [62],

$$\mathcal{A}_{\lambda_{T_{cc}}, \lambda_{D^{*+}}} = \sqrt{\frac{16\pi m_{T_{cc}} m_{D^*} m_D}{\mu^2 a}} \epsilon_{\lambda_{T_{cc}}} \cdot \epsilon^{*}_{\lambda_{D^{*+}}}, \quad (4)$$

where $m_{T_{cc}, D^*, D}$ is the mass of the T_{cc}^{+}, and the constituent (D^{*+} or D^{0}). The $\epsilon_{\lambda_{T_{cc}}}$ and $\epsilon_{\lambda_{D^{*+}}}$ are the polarized vectors for T_{cc}^{+} and D^{*+}, 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. [63], 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., $\psi(\boldsymbol{k}) = \sqrt{8\pi/a}/(\boldsymbol{k}^2 + 1/a^2)$ with normalization $\int d^3k/(2\pi)^3|\psi(k)|^2 = 1$ [64], as

$$\frac{\mathcal{A}_{\lambda_{T_{cc}},\lambda_{D^{*+}}}}{p^2 - m_{D^*}^2} \simeq -\frac{\sqrt{8m_{T_{cc}}m_{D^*}m_D}}{m_{T_{cc}} - m_D + m_{D^*}}\psi(\boldsymbol{k}_3)\epsilon_{\lambda_{T_{cc}}} \cdot \epsilon^*_{\lambda_{D^{*+}}}. \quad (5)$$

Applying standard Feynman rules, the amplitude can be written as

$$\mathcal{M}_{\lambda_p\lambda_{T_{cc}},\lambda'_p} = i\frac{\sqrt{8m_T m_{D^*}m_D}}{m_T - m_D + m_{D^*}}\bar{u}_{\lambda'_p}\tilde{\mathcal{A}}_{\lambda_{T_{cc}}}u_{\lambda_p}, \quad (9)$$

with

$$\begin{aligned}\tilde{\mathcal{A}}_{\lambda_{T_{cc}}} = &-\frac{1}{2}\left[P_\rho(q^2) - P_\omega(q^2)\right]\psi(\boldsymbol{k}_3)i\varepsilon_{\alpha\beta\rho\sigma}v_3^\alpha q^\beta\epsilon^\rho_{\lambda_{T_{cc}}}\gamma^\sigma(1-\not{q})\\ &+\frac{1}{2}\left[P_\rho(q^2) + P_\omega(q^2)\right]\psi(\boldsymbol{k}_2)i\varepsilon_{\alpha\beta\rho\sigma}v_2^\alpha q^\beta\epsilon^\rho_{\lambda_{T_{cc}}}\gamma^\sigma(1-\not{q})\\ &+\frac{1}{2}\left[\psi(\boldsymbol{k}_3)\tilde{\epsilon}^3_{\lambda_{T_{cc}}}\cdot q + \psi(\boldsymbol{k}_2)\tilde{\epsilon}^2_{\lambda_{T_{cc}}}\cdot q\right]P_\pi(q^2)\gamma_5\not{q},\end{aligned} \quad (10)$$

Besides the split of the T_{cc}^+, we need describe the scattering $pD^{*+} \to pD^+$ as shown in Fig. 1. To depict the scattering, the following Lagrangians under the heavy quark and chiral symmetries are adopted to construct the vertex of D^*, D, and light meson [65],

$$\mathcal{L}_{\mathcal{P}^*\mathcal{P}\mathbb{P}} = -\frac{2g}{f_\pi}(\mathcal{P}_b\mathcal{P}^{*\dagger}_{a\lambda} + \mathcal{P}^*_{b\lambda}\mathcal{P}^\dagger_a)\partial^\lambda\mathbb{P}_{ba},$$
$$\mathcal{L}_{\mathcal{P}^*\mathcal{P}\mathbb{V}} = -2\sqrt{2}\lambda g_V v^\lambda\varepsilon_{\lambda\alpha\beta\mu}(\mathcal{P}_b\mathcal{P}^{\mu\dagger}_a + \mathcal{P}^{*\mu}_b\mathcal{P}^\dagger_a)\partial^\alpha\mathbb{V}^\beta_{ba}, \quad (6)$$

where $\mathcal{P}^{(*)T} = (D^{(*)+}, D^{(*)0})$ is the fields for $D^{(*)}$ meson. And $\mathbb{P}$ and $\mathbb{V}$ are two by two pseudoscalar and vector matrices

$$\mathbb{P} = \begin{pmatrix}\frac{\sqrt{3}\pi^0+\eta}{\sqrt{6}} & \pi^+\\ \pi^- & \frac{-\sqrt{3}\pi^0+\eta}{\sqrt{6}}\end{pmatrix}, \quad \mathbb{V} = \begin{pmatrix}\frac{\rho^0+\omega}{\sqrt{2}} & \rho^+\\ \rho^- & \frac{-\rho^0+\omega}{\sqrt{2}}\end{pmatrix}.$$

The parameters involved here were determined in the literature as $g = 0.59$, $\beta = 0.9$, $\lambda = 0.56$ GeV^{-1}, $g_V = 5.9$, and $f_\pi = 132$ MeV [65,66].

The Lagrangians for the vertex of nucleon and light meson are

$$\mathcal{L}_{\mathbb{P}NN} = -\frac{g_{\mathbb{P}NN}}{\sqrt{2}m_N}\bar{N}_b\gamma_5\gamma_\mu\partial_\mu\mathbb{P}_{ba}N_a, \quad (7)$$

$$\mathcal{L}_{\mathbb{V}NN} = -\sqrt{2}g_{\mathbb{V}NN}\bar{N}_b\left(\gamma_\mu + \frac{\kappa}{2m_N}\sigma_{\mu\nu}\partial^\nu\right)\mathbb{V}^\mu_{ba}N_a, \quad (8)$$

where $N^T = (p, n)$ is field for nucleon. The coupling constants $g^2_{\pi NN}/(4\pi) = 13.6$, $g^2_{\rho NN}/(4\pi) = 0.84$, $g^2_{\omega NN}/(4\pi) = 20$ with $\kappa = 6.1$ (0) in Eq. (8) for ρ (ω) meson, which are used in the Bonn nucleon–nucleon potential [67] and meson productions in nucleon–nucelon collision [68–70]. The η exchange is neglected in the current work due to the weak coupling of η or ϕ to nucleons as indicated in many previous works [67,68].

with the abbreviations $\tilde{\epsilon}^{3,2}_{\lambda_{T_{cc}}} = [\epsilon_{\lambda_{T_{cc}}} - (k_{2,3}-q)\cdot\epsilon_{\lambda_{T_{cc}}}(k_{2,3}-q)/m^2_{D^*}]$ and $v_{3,2} = k_{3,2}/\sqrt{m_D m_{D^*}}$. 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 $F_\pi = \sqrt{2}gg_{\mathbb{P}NN}\sqrt{m_D m_{D^*}}/m_N f_\pi$ or $F_{\mathbb{V}} = 4g_{\mathbb{V}NN}\lambda g_V\sqrt{m_D m_{D^*}}$.

With the preparation above, we can calculate the cross section of the $p + T_{cc}^+ \to p + D^+ + D^0$ 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. Such large cross section at small incoming momentum is a characteristic of the fission phenomenon. Of coarse, such small momentum of the proton is rare in real physical processes. Here, we

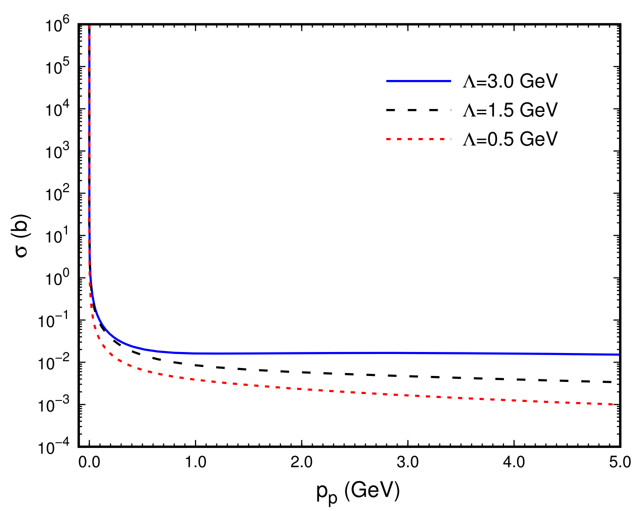

Fig. 2 Cross section of the $p + T_{cc}^+ \to p + D^+ + D^0$ reaction as a function of momentum of incoming proton $p_p = |\boldsymbol{p}_p|$. The results with cutoffs $\Lambda = 3$, 1.5, and 0.5 GeV are given as full (blue), dashed (black), and dotted (red) lines

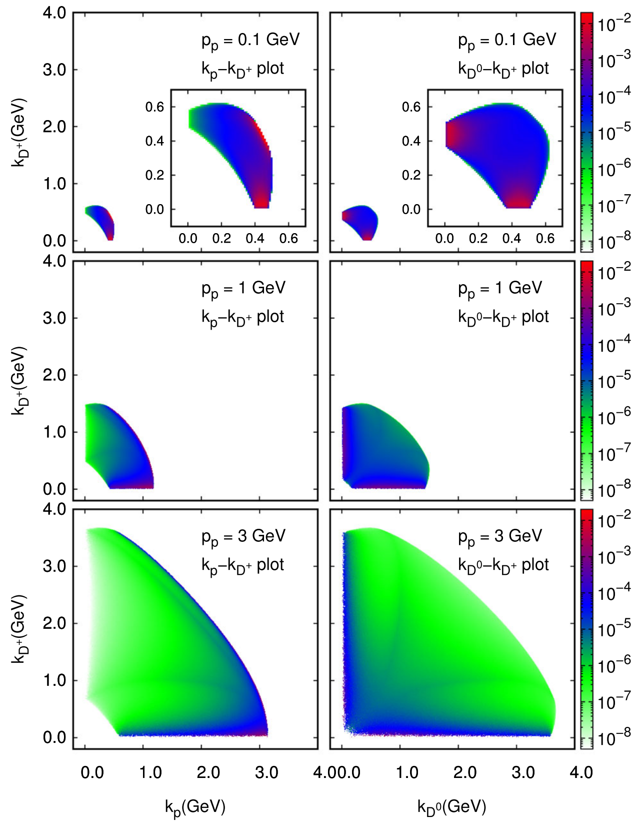

Fig. 3 The momentum distributions of final particles for the $p+T_{cc}^{+} \rightarrow p+D^{+}+D^{0}$ reaction with cutoff $\Lambda = 1$ GeV. For each example choice of $\mathrm{p_p}$, the figures represent the $\mathrm{k}_p - \mathrm{k}_{D^+}$ (left) and $\mathrm{k}_{D^0} - k_{D^+}$ (right) planes, showing the momentum $\mathrm{k}_i = |\boldsymbol{k}_i|$ 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

provide the results at very small momenta for theoretical completeness. 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 becomes relatively stable. In the range of incoming momentum from 1 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.

In Fig. 3, we present the momentum distributions of final particles for the $p + T_{cc}^{+} \rightarrow p + D^{+} + D^{0}$ reaction at the momentum of incoming proton p_p=0.1, 1, and 3 GeV. As expected, the distributions of the momenta become broader with the increase of the momentum of incoming proton. At a momentum of 0.1 GeV, the momenta of final particles are in a range smaller than 0.5 GeV while at a large momentum such as 3 GeV, the final particle can have a momentum about 3 GeV.

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^+ is 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 $\mathrm{k}_{D^0} - k_{D^+}$ plane as the vertical stripe with $\mathrm{k}_{D^0} \sim 0$ GeV. The final D^+ meson is from the D^{*+} meson struck by the proton, and has a broader distribution. The horizontal strip in the $\mathrm{k}_{D^0} - k_{D^+}$ plane reflects the second term of the wave function where D^{*0} is struck and D^+ is almost unaffected.

In Fig. 4, we also present the Dalitz plot against the invariant masses of the final particles. Here, three initial momenta of the proton are still chosen as 0.1, 1, and 3 GeV while the event distributes against momenta $\mathrm{k}_p - \mathrm{k}_{D^+}$ and $\mathrm{k}_{D^0} - k_{D^+}$ are replaced by invariant masses $m_{D^+D^0} - m_{pD^0}$ and $m_{pD^+} - m_{pD^0}$. The analogy distributions for m_{pD^+} and m_{pD^0} can be found which is also from the symmetry in the wave function. Obvious concentration of events is found especially with higher incoming momentum due to the D^* meson in the exotic state being almost static. For example, for the diagram in Fig. 1, with an incoming momentum $\mathrm{p}_p = 3$ GeV, the m_{pD^+} shown can be obtained as $m_{pD^+} = \sqrt{(p_p + p)^2} = 4.19$ GeV with an assumption of a static D^* meson in T_{cc}^{+}. An obvious strip can be found at such m_{pD^+} in the plot.

3 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 [35–60]. 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 concrete 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 π, η, ρ, and ω meson, which results in

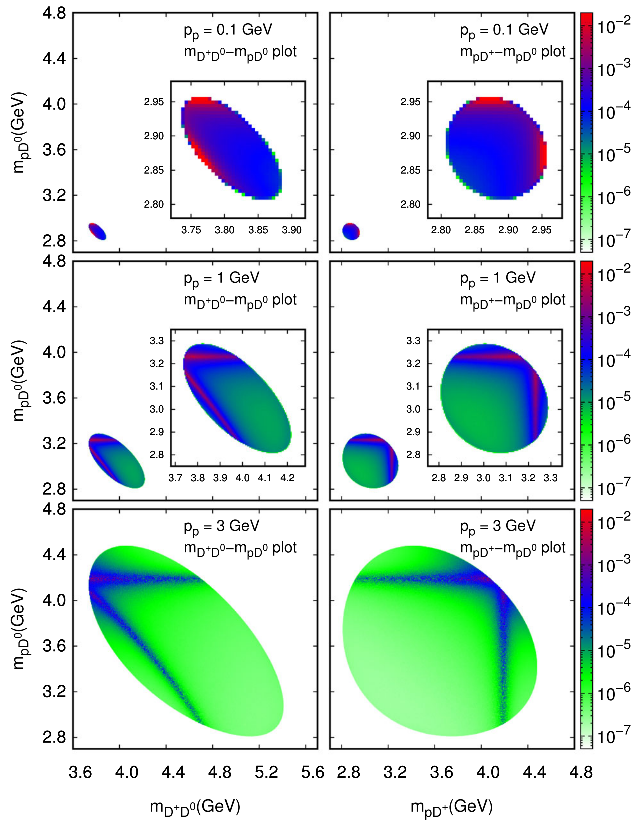

Fig. 4 The Dalitz plot for the $p + T_{cc}^{+} \to p + D^{+} + D^{0}$ reaction with cutoff $\Lambda = 1$ GeV. For each example choice of p_p, the figures represent the $m_{D^+D^0} - m_{pD^0}$ (left) and $m_{pD^+} - m_{pD^0}$ (right) planes, showing the invariant mass $m_{ij} = \sqrt{(k_i + k_j)^2}$ of the final mesons i and j. The colorbox means the ratio of event number in a bin of 0.005 GeV $\times$ 0.005 GeV to the total number of events. The results are obtained with 10^8 simulation

split of the T_{cc}^{+} state with two D mesons in final state. With the help of the effective Lagrangians, the cross section of $p + T_{cc}^{+} \to p + D^{+} + D^{0}$ 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}^{+}.

The T_{cc}^{+} was observed at LHCb in proton-proton collision. Naturally, it can be produced in the ion-ion collision. The $X(3872)$ was observed at LHCb in Pb-Pb Collision [72]. The production of T_{cc}^{+} was also discussed in the literature [54]. In the nulceon-rich environment, the interaction of the nucleon and the produced exotic state will become important. The results in the current work can be a basis for further studies about such effects.

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 High-Luminosity Large Hadron Collider. 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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References

1. R. Aaij et al. (LHCb Collaboration), Observation of an exotic narrow doubly charmed tetraquark. arXiv:2109.01038
2. R. Aaij et al. (LHCb Collaboration), Study of the doubly charmed tetraquark T_{cc}^{+}. arXiv:2109.01056
3. L. Heller, J.A. Tjon, On the existence of stable dimensions. Phys. Rev. D **35**, 969 (1987)
4. J. Carlson, L. Heller, J.A. Tjon, Stability of dimesons. Phys. Rev. D **37**, 744 (1988)
5. B. Silvestre-Brac, C. Semay, Systematics of L = 0 $q^2\bar{q}^2$ systems. Z. Phys. C **57**, 273–282 (1993)
6. C. Semay, B. Silvestre-Brac, Diquonia and potential models. Z. Phys. C **61**, 271–275 (1994)
7. M.A. Moinester, How to search for doubly charmed baryons and tetraquarks. Z. Phys. A **355**, 349–362 (1996)
8. S. Pepin, F. Stancu, M. Genovese, J.M. Richard, Tetraquarks with color blind forces in chiral quark models. Phys. Lett. B **393**, 119–123 (1997)
9. B.A. Gelman, S. Nussinov, Does a narrow tetraquark $cc\bar{u}\bar{d}$ state exist? Phys. Lett. B **551**, 296–304 (2003)
10. J. Vijande, F. Fernandez, A. Valcarce, B. Silvestre-Brac, Tetraquarks in a chiral constituent quark model. Eur. Phys. J. A **19**, 383 (2004)
11. D. Janc, M. Rosina, The $T_{cc} = DD^*$ molecular state. Few Body Syst. **35**, 175–196 (2004)

12. F.S. Navarra, M. Nielsen, S.H. Lee, QCD sum rules study of $QQ\bar{u}\bar{d}$ mesons. Phys. Lett. B **649**, 166–172 (2007)
13. J. Vijande, E. Weissman, A. Valcarce, N. Barnea, Are there compact heavy four-quark bound states? Phys. Rev. D **76**, 094027 (2007)
14. D. Ebert, R.N. Faustov, V.O. Galkin, W. Lucha, Masses of tetraquarks with two heavy quarks in the relativistic quark model. Phys. Rev. D **76**, 114015 (2007)
15. S.H. Lee, S. Yasui, Stable multiquark states with heavy quarks in a diquark model. Eur. Phys. J. C **64**, 283–295 (2009)
16. Y. Yang, C. Deng, J. Ping, T. Goldman, S-wave $QQ\bar{q}\bar{q}$ state in the constituent quark model. Phys. Rev. D **80**, 114023 (2009)
17. N. Li, Z.F. Sun, X. Liu, S.L. Zhu, Coupled-channel analysis of the possible $D^{(*)}D^{(*)}$, $\overline{B}^{(*)}\overline{B}^{(*)}$ and $D^{(*)}\overline{B}^{(*)}$ molecular states. Phys. Rev. D **88**(11), 114008 (2013)
18. S.Q. Luo, K. Chen, X. Liu, Y.R. Liu, S.L. Zhu, Exotic tetraquark states with the $qq\bar{Q}\bar{Q}$ configuration. Eur. Phys. J. C **77**(10), 709 (2017)
19. M. Karliner, J.L. Rosner, Discovery of doubly-charmed Ξ_{cc} baryon implies a stable $(bb\bar{u}\bar{d})$ tetraquark. Phys. Rev. Lett. **119**(20), 202001 (2017)
20. E.J. Eichten, C. Quigg, Heavy-quark symmetry implies stable heavy tetraquark mesons $Q_iQ_j\bar{q}_k\bar{q}_l$. Phys. Rev. Lett. **119**(20), 202002 (2017)
21. Z.G. Wang, Analysis of the axialvector doubly heavy tetraquark states with QCD sum rules. Acta Phys. Polon. B **49**, 1781 (2018)
22. W. Park, S. Noh, S.H. Lee, Masses of the doubly heavy tetraquarks in a constituent quark model. Nucl. Phys. A **983**, 1–19 (2019)
23. P. Junnarkar, N. Mathur, M. Padmanath, Study of doubly heavy tetraquarks in lattice QCD. Phys. Rev. D **99**(3), 034507 (2019)
24. C. Deng, H. Chen, J. Ping, Systematical investigation on the stability of doubly heavy tetraquark states. Eur. Phys. J. A **56**(1), 9 (2020)
25. M.Z. Liu, T.W. Wu, M. Pavon Valderrama, J.J. Xie, L.S. Geng, Heavy-quark spin and flavor symmetry partners of the X(3872) revisited: what can we learn from the one boson exchange model? Phys. Rev. D **99**(9), 094018 (2019)
26. L. Maiani, A.D. Polosa, V. Riquer, Hydrogen bond of QCD in doubly heavy baryons and tetraquarks. Phys. Rev. D **100**(7), 074002 (2019)
27. G. Yang, J. Ping, J. Segovia, Doubly-heavy tetraquarks. Phys. Rev. D **101**(1), 014001 (2020)
28. Y. Tan, W. Lu, J. Ping, Systematics of $QQ\bar{q}\bar{q}$ in a chiral constituent quark model. Eur. Phys. J. Plus **135**(9), 716 (2020)
29. Q.F. Lü, D.Y. Chen, Y.B. Dong, Masses of doubly heavy tetraquarks $T_{QQ'}$ in a relativized quark model. Phys. Rev. D **102**(3), 034012 (2020)
30. E. Braaten, L.P. He, A. Mohapatra, Masses of doubly heavy tetraquarks with error bars. Phys. Rev. D **103**(1), 016001 (2021)
31. D. Gao, D. Jia, Y.J. Sun, Z. Zhang, W.N. Liu, Q. Mei, Masses of doubly heavy tetraquark states with isospin = $\frac{1}{2}$ and 1 and spin-parity $1^{+\pm}$. arXiv:2007.15213
32. J.B. Cheng, S.Y. Li, Y.R. Liu, Z.G. Si, T. Yao, Double-heavy tetraquark states with heavy diquark–antiquark symmetry. Chin. Phys. C **45**(4), 043102 (2021)
33. S. Noh, W. Park, S.H. Lee, The doubly-heavy tetraquarks $(qq'\bar{Q}\bar{Q}')$ in a constituent quark model with a complete set of harmonic oscillator bases. Phys. Rev. D **103**, 114009 (2021)
34. R.N. Faustov, V.O. Galkin, E.M. Savchenko, Heavy tetraquarks in the relativistic quark model. Universe **7**(4), 94 (2021)
35. S.S. Agaev, K. Azizi, H. Sundu, M. Temizer, Hadronic molecule model for the doubly charmed state T_{cc}^+. arXiv:2201.02788
36. H.W. Ke, X.H. Liu, X.Q. Li, Possible molecular states of $D^{(*)}D^{(*)}$ and $B^{(*)}B^{(*)}$ within the Bethe–Salpeter framework. arXiv:2112.14142
37. K. Chen, B. Wang, S.L. Zhu, Heavy flavor molecular states with strangeness. arXiv:2112.13203
38. C. Deng, S.L. Zhu, T_{cc}^+ and its partners. arXiv:2112.12472
39. M.J. Zhao, Z.Y. Wang, C. Wang, X.H. Guo, Investigation of the possible $D\bar{D}^*/B\bar{B}^*$ and $DD^*/\bar{B}\bar{B}^*$ molecule states. arXiv:2112.12633
40. N. Santowsky, C.S. Fischer, Four-quark states with charm quarks in a two-body Bethe–Salpeter approach. arXiv:2111.15310
41. M. Albaladejo, T_{cc}^+ coupled channel analysis and predictions. arXiv:2110.02944
42. K. Chen, R. Chen, L. Meng, B. Wang, S.L. Zhu, Systematics of the heavy flavor hadronic molecules. arXiv:2109.13057
43. H. Ren, F. Wu, R. Zhu, Hadronic molecule interpretation of T_{cc}^+ and its beauty-partners. arXiv:2109.02531
44. X. Chen, Doubly heavy tetraquark states $cc\bar{u}\bar{d}$ and $bb\bar{u}\bar{d}$. arXiv:2109.02828
45. X.K. Dong, F.K. Guo, B.S. Zou, A survey of heavy-heavy hadronic molecules. Commun. Theor. Phys. **73**(12), 125201 (2021)
46. R. Chen, Q. Huang, X. Liu, S.L. Zhu, Predicting another doubly charmed molecular resonance $T_{cc}'^+(3876)$. Phys. Rev. D **104**(11), 114042 (2021). https://doi.org/10.1103/PhysRevD.104.114042. arXiv:2108.01911 [hep-ph]
47. T. Guo, J. Li, J. Zhao, L. He, Mass spectra of doubly heavy tetraquarks in an improved chromomagnetic interaction model. Phys. Rev. D **105**(1), 014021 (2022)
48. S.S. Agaev, K. Azizi, H. Sundu, Newly observed exotic doubly charmed meson T_{cc}^+. Nucl. Phys. B **975**, 115650 (2022)
49. L. Meng, G.J. Wang, B. Wang, S.L. Zhu, Probing the long-range structure of the T_{cc}^+ with the strong and electromagnetic decays. Phys. Rev. D **104**(5), 051502 (2021)
50. S. Fleming, R. Hodges, T. Mehen, T_{cc}^+ decays: differential spectra and two-body final states. Phys. Rev. D **104**(11), 116010 (2021)
51. M.J. Yan, M.P. Valderrama, Subleading contributions to the decay width of the T_{cc}^+ tetraquark. Phys. Rev. D **105**(1), 014007 (2022)
52. X.Z. Ling, M.Z. Liu, L.S. Geng, E. Wang, J.J. Xie, Can we understand the decay width of the T_{cc}^+ state? Phys. Lett. B **826**, 136897 (2022)
53. Q. Qin, Y.F. Shen, F.S. Yu, Discovery potentials of double-charm tetraquarks. Chin. Phys. C **45**(10), 103106 (2021)
54. Y. Hu, J. Liao, E. Wang, Q. Wang, H. Xing, H. Zhang, Production of doubly charmed exotic hadrons in heavy ion collisions. Phys. Rev. D **104**(11), L111502 (2021)
55. Y. Jin, S.Y. Li, Y.R. Liu, Q. Qin, Z.G. Si, F.S. Yu, Color and baryon number fluctuation of preconfinement system in production process and T_{cc} structure. Phys. Rev. D **104**(11), 114009
56. Y. Huang, H.Q. Zhu, L.S. Geng, R. Wang, Production of T_{cc}^+ exotic state in the $\gamma p \to D^+ T_{cc}^- \Lambda_c^+$ reaction. Phys. Rev. D **104**(11), 116008 (2021)
57. A. Feijoo, W.H. Liang, E. Oset, $D^0 D^0 \pi^+$ mass distribution in the production of the Tcc exotic state. Phys. Rev. D **104**(11), 114015 (2021)
58. K. Azizi, U. Özdem, Magnetic dipole moments of the T_{cc}^+ and Z_V^{++} tetraquark states. Phys. Rev. D **104**(11), 114002 (2021)
59. U. Ozdem, Magnetic moments of the doubly charged axial-vector T_{cc}^{++} states. arXiv:2112.10402 [hep-ph]
60. M.L. Du, V. Baru, X.K. Dong, A. Filin, F.K. Guo, C. Hanhart, A. Nefediev, J. Nieves, Q. Wang, Coupled-channel approach to Tcc+ including three-body effects. Phys. Rev. D **105**(1), 014024 (2022)
61. S. Weinberg, Elementary particle theory of composite particles. Phys. Rev. **130**, 776–783 (1963)
62. E. Braaten, M. Kusunoki, S. Nussinov, Production of the X(3870) in B meson decay by the coalescence of charm mesons. Phys. Rev. Lett. **93**, 162001 (2004)
63. J. He, X. Liu, The open-charm radiative and pionic decays of molecular charmonium Y(4274). Eur. Phys. J. C **72**, 1986 (2012)

64. M.B. Voloshin, Interference and binding effects in decays of possible molecular component of X(3872). Phys. Lett. B **579**, 316–320 (2004)
65. R. Casalbuoni, A. Deandrea, N. Di Bartolomeo, R. Gatto, F. Feruglio, G. Nardulli, Phenomenology of heavy meson chiral Lagrangians. Phys. Rep. **281**, 145–238 (1997)
66. R. Chen, Z.F. Sun, X. Liu, S.L. Zhu, Strong LHCb evidence supporting the existence of the hidden-charm molecular pentaquarks. Phys. Rev. D **100**(1), 011502 (2019)
67. R. Machleidt, Phys. Rev. C **63**, 024001 (2001). https://doi.org/10.1103/PhysRevC.63.024001 arXiv:nucl-th/0006014
68. X. Cao, B.S. Zou, H.S. Xu, Phys. Rev. C **81**, 065201 (2010). https://doi.org/10.1103/PhysRevC.81.065201 arXiv:1004.0140 [nucl-th]
69. K. Tsushima, A. Sibirtsev, A.W. Thomas, G.Q. Li, Phys. Rev. C **59**, 369–387 (1999) [erratum: Phys. Rev. C **61**, 029903 (2000)]. https://doi.org/10.1103/PhysRevC.59.369. arXiv:nucl-th/9801063
70. A. Engel, A.K. Dutt-Mazumder, R. Shyam, U. Mosel, Nucl. Phys. A **603**, 387–414 (1996). https://doi.org/10.1016/0375-9474(96)80008-F. arXiv:nucl-th/9601026
71. H.X. Chen, W. Chen, X. Liu, S.L. Zhu, The hidden-charm pentaquark and tetraquark states. Phys. Rep. **639**, 1–121 (2016)
72. A.M. Sirunyan et al. [CMS], Phys. Rev. Lett. **128**(3), 032001 (2022). https://doi.org/10.1103/PhysRevLett.128.032001. arXiv:2102.13048 [hep-ex]