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Perfect DD^* Molecular Prediction Matching the T_{cc} Observation at LHCb

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In 2012, we investigated the possible molecular states composed of two charmed mesons [Phys. Rev. D 88 (2013) 114008; 2012 arXiv:1211.5007 [hep-ph]]. The D^*D system with the quantum numbers of $I(J^P) = 0(1^+)$ was found to be a good candidate of the loosely bound molecular state. This state is very close to the D^*D threshold with a binding energy around 0.47 MeV. This prediction was confirmed by the new LHCb observation of T_{cc}^+ [see Franz Muheim's talk at the European Physical Society conference on high energy physics 2021].

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Since the Belle Collaboration discovered the $X(3872)$ in 2003,[1] a series of charmonium-like XYZ states which are close to the thresholds of two hadrons have been observed. There exists difficulty to describe these states in the traditional hadron picture, which has posed a big challenge and brought valuable opportunities to the whole community. The study of these new exotic hadron states has become the hot new frontier of the hadron physics.

Especially, in the last three years, the LHCb Collaboration has been playing a key role in finding new hadronic states. In 2019, the characteristic mass spectrum of three P_c states, the $P_c(4312)^+$, $P_c(4440)^+$ and $P_c(4457)^+$[2] provide strong evidence of the existence of the hidden-charm molecular pentaquark. Additionally, LHCb reported the evidence of the $P_{cs}(4459)$[3] in the $J/\psi\Lambda$ invariant mass distribution. And then, several hidden-charm tetraquark candidates [the $Z_{cs}(4000)^+$ and $Z_{cs}(4220)^+$[4]] and possible single-charm tetraquarks, the $d\bar{c}u\bar{s}$ tetraquarks [$X_0(2900)$ and $X_1(2900)$[5,6]] were observed. All these measurements have attracted much attention from both theorists and experimentalists.[7,8]

Although so many multiquark state candidates have been reported in experiment, it is not the end of whole story. At the European Physical Society conference on high energy physics 2021, Franz Muheim gave a talk on the "LHCb Highlights", which shows that LHCb observed the T_{cc}^+ by analyzing the $D^0D^0\pi^+$ invariant mass spectrum.[9] The difference between mass of this state and the $D^{*+}D^0$ threshold is $-273 \pm 61 \pm 5^{+11}_{-14}$ keV, and its width is $410 \pm 165 \pm 43^{+18}_{-38}$ keV.[9] Obviously, as the first observation of the double-charm tetraquark, the T_{cc} has the $cc\bar{u}\bar{d}$ configuration. In this note we shall briefly introduce our previous work[10] on this topic. An extensive review of the T_{cc} system can be found in Ref. [11].

In 2012, we investigated the system of the $D^{(*)}D^{(*)}[I(J^P) = 0(1^+)]$ very carefully by taking into account the coupled channel effect and the S–D mixing effect, which play an important role in the formation of the loosely bound deuteron.[12] With the one-pion-exchange force only, we found a loosely $D^*D[I(J^P) = 0(1^+)]$ bound state with the binding energy 1.24 MeV for a reasonable cutoff 1.05 GeV, which is introduced to suppress the very high-momentum or short-range contribution. The corresponding root-mean-square radius is 3.11 fm, which is comparable to the size of the well-known deuteron (about 2.0 fm). There exists a small contribution around 2.79% from the $D^*D^*(^3S_1)$ channel because of the large mass gap (about 140 MeV) between the thresholds of DD^* and D^*D^*. However, the probability of the D-wave interaction is tiny, 0.73% for the $DD^*(^3D_1)$ and 0.08% for the $D^*D^*(^3D_1)$, which indicates that the $D^*D[I(J^P) = 0(1^+)]$ molecular state is almost dominated by the s-wave interaction. We should mention that for the pion exchange in the crossed channel, the potential is complex because the exchanged pion is on-shell due to the large mass difference between D and D^*. With the same approach in the study of $X(3872)$, we keep the real part of the potential. Such a formal-

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ism has no effects on the spectrum of the DD^* system.

When the heavier ρ and ω exchanges are included, the binding becomes deeper for the same cutoff as that with the one-pion-exchange potential only. With a smaller cutoff 0.95 GeV, there exists a loosely $D^{(*)}D^{(*)}[I(J^P) = 0(1^+)]$ state with a binding energy 0.47 MeV and hence with the mass 3875.38 MeV, which can be identified as the newly observed T_{cc} by the LHCb Collaboration. In such a case, the heavier ρ and ω exchanges cancel each other significantly since for the isospin-zero system the isospin factor of the ρ meson exchange is -3 while that of the ω meson exchange is 1, and the residual force is helpful to strengthen the binding. Additionally, the contributions from the η and σ exchanges are very small. The T_{cc} and $X(3872)$ shares the same one-pion-exchange potential. Their long-range dynamics is similar and correlated to each other. If the $X(3872)$ is a loosely bound molecular state, the existence of the $X(3872)$ implies the existence of the T_{cc}. Numerically, the binding energy of the T_{cc} depends weakly on the cutoff, which is similar to the case of the $X(3872)$. For example, the binding energy of the T_{cc} is 0.47 MeV for the cutoff = 0.95 GeV and 18.72 MeV for cutoff = 1.05 GeV.

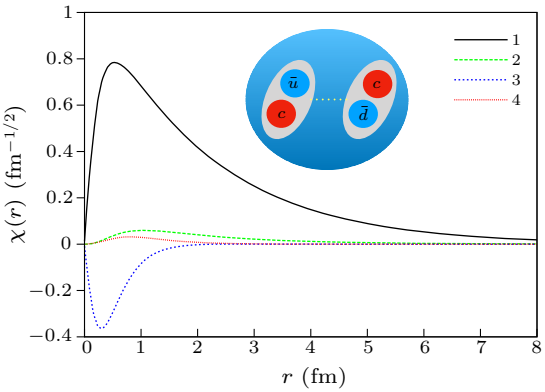

Fig. 1. (The wave function $[\chi(r) = r\psi(r)]$ of the $D^{(*)}D^{(*)}I(J^P) = 0(1^+)$. Here 1 stands for the channel $[DD^*(^3S_1)]$, 2 for $[DD^*(^3D_1)]$, 3 for $[D^*D^*(^3S_1)]$ and 4 for $D^*D^*(^3D_1)]$.

The effects of the σ, ρ and ω exchanges are also analyzed by turning off the contribution of the π and η exchanges. A loosely bound state with a binding energy 0.78 MeV and root-mean-square radius 3.74 fm was obtained when the cutoff parameter is tuned to be 1.44 GeV, which is larger than 1.05 GeV used for the one-pion-exchange case. The contribution of the long-range pion exchange is larger than that of the heavier vector meson exchange in the formation of the loosely bound $D^{(*)}D^{(*)}[I(J^P) = 0(1+)]$ state. The wave function is shown in Fig. 1, from which one can see that there is no node except the origin. In other words, it is really a ground state.

In summary, in 2012 we predicted a loosely bound state of the $DD^*[I(J^P) = 0(1^+)]$ which can be perfectly identified as the newly observed T_{cc} by the LHCb Collaboration. For this state, the probability of the D-wave interaction is very small, and it arises from the s-wave interaction. There is small contribution from the D^*D^* channel. The long-range pion exchange is strong enough to form the loosely bound state, and the medium-range η and σ exchanges and the short-range ρ and ω exchanges are helpful to strengthen the binding.

In Ref. [13], the authors also studied the doubly charmed systems within the hidden gauge formalism in a coupled-channel unitary approach. For the D^*D^* system with $C = 2$, $S = 0$ and $I = 0$, they only obtained a bound state with quantum number $I(J^P) = 0(1^+)$. However, the pole appeared at 3969 MeV, which is about 100 MeV larger than our result. In contrast, we considered the coupled channel effect between the DD^* and D^*D^*. Actually, what we obtained is a DD^* bound state instead of a D^*D^* bound state.

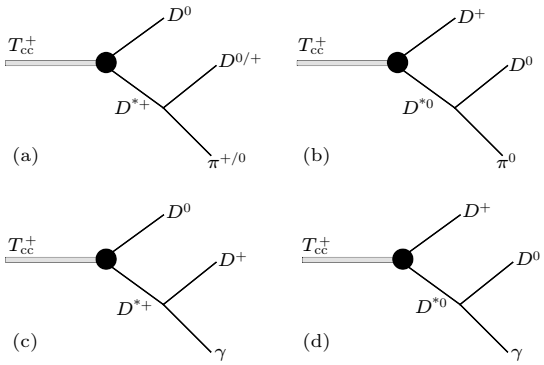

Fig. 2. The allowed strong and radiative decays of T_{cc}.

The state $DD^*[0(1^+)]$ cannot decay into a double charm baryon plus a light baryon. The masses of the lightest doubly-charmed baryon and light baryon are 3518 MeV and 938 MeV, respectively, corresponding to Ξ_{cc}^+ and proton as listed in Particle Data Group.[14] The mass of the molecular state is around 3875 MeV, much smaller than the sum of the masses of a doubly-charmed baryon and a light baryon. Therefore such a decay is kinematically forbidden. However, the heavy vector meson D^* within the exotic molecular state mainly decays to $D\pi$ via the strong interaction as shown in Figs. 2(a) and 2(b). It also decays into $D\gamma$, which is illustrated in Figs. 2(c) and 2(d). The main decay modes should be $DD\gamma$ and $DD\pi$, and the $D^{(*)}$ meson may also decay via the weak interaction.

The above typical decay modes provide important information to experimental investigation of the properties of T_{cc}. With further theoretical and experimental progress, we shall gain new insights into this structure. The observation of this doubly charmed structure has opened a new window for the exotic hadron

states in this exciting era, which is beyond the hidden charm "exotic" states which have been widely investigated since the $X(3872)$ was first observed in 2003 by the Belle Collaboration.

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