Production and detection of doubly charmed tetraquarks

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The feasibility of tetraquark detection is studied. For the \( cc\bar{d} \) tetraquark we show that in present (SELEX, Tevatron, RHIC) and future facilities (LHCb, ALICE) the production rate is promising and we propose some detectable decay channels.

I. Introduction

The purpose of this paper is to assess the possibility of detecting certain tetraquarks in present and future facilities. Among many possible tetraquarks, the double charm tetraquark \( T_{cc} = cc\bar{d} = DD^* \) with quantum numbers \( IS^P=01^+ \) is particularly interesting since it is very sensitive to the chosen effective interaction:

- It is very delicate, it is either weakly bound or slightly unbound with respect to the two-body hadronic decay \( D + D^* \).
- Its structure can be either predominantly “molecular” or predominantly “atomic” with consequences for the production and decay.

Double charm tetraquarks were intensively studied by many authors. Various approaches were applied, from lattice QCD and chiral heavy quark effective theories to nonrelativistic potential models. It was shown that, although the predictions of these theories agree in the barion and meson sector, they give dramatically different results for tetraquarks. For this reason, the double charm tetraquarks present an important laboratory for discriminating between different hadronic models.

Moreover, our estimates for the production cross section of such states gives us some hope that they can be experimentally detected in near future.

The most important ingredient in the production of the \( T_{cc} \) tetraquark is double charm production. Experimental data for such events are very puzzling. The production of prompt \( J/\psi \) at \( B \) factories as well as the production of \( \Xi_{cc} \) at SELEX are much larger than expected. Therefore the comparison of \( T_{cc} \) production with \( J/\psi cc \) at \( B \) factories and the comparison \( T_{cc} \) production with \( \Xi_{cc} \) at SELEX could shed some new light on the mechanism responsible for such large hadronic production.

In Section 2 we present our results for the \( T_{cc} \) production at high energy colliders were we believe that the dominant mechanism for the initial double charm production is double gluon fusion. From experimental data we also estimate phenomenologically the production of the \( T_{cc} \) tetraquark at \( B \) factories and at SELEX. The results of detailed four body calculations in nonrelativistic constituent quark model (Section 3) encourage us to further investigate this state. Since we found the \( T_{cc} \) tetraquark to be weakly bound, we propose (Section 4) the branching ratio between hadronic and radiative decays as the most promising mechanism for the detection of these states.

II. Production of Double Charm at Various Facilities

The most promising mechanism for the production of the \( T_{cc} \) tetraquark is the formation of the \( cc \) diquark followed by hadronisation into \( cc\bar{d} \). An alternative mechanism would exploit binding of \( D \) and \( D^* \) mesons if when they are produced with small relative momenta. One might expect that the latter mechanism could drastically enlarge the production rate if the dominant configuration is molecular. Due to the very messy environment in hadron colliders, however, such a weakly bound system would too soon dissociate into free mesons by the interaction with surrounding partons of initial hadrons.

The first step is to create two \( cc \) pairs with the \( c \) quarks close in the phase space and in colour antisymmetric state, so that in the second step they bind into the \( cc \) diquark. The binding energy of such a system is \( \sim 200 \) MeV [1]. In the third step the diquark gets dressed either with a light \( u \) or \( d \) quark into a \( ccu\bar{u} \) or \( cc \bar{d} \) baryon or with a light \( \bar{u}d \) antidiquark into the \( cc\bar{d} \) tetraquark. The probabilities for this two types of dressing can be estimated using the analogy of a single heavy quark fragmentation.

The branching ratio of the \( b \rightarrow B \) and \( b \rightarrow \Lambda_b \) production at the Fermilab and at LEP experiment is 0.9 and 0.1 [12], respectively, therefore we expect the same ratio in the hadronisation \( cc \rightarrow \Xi_{cc} \) and \( cc \rightarrow T_{cc} \), respectively.

The double charmed baryons were probably detected at SELEX [11]. It was estimated that 40% of the singly charmed baryons they see result from the decay of doubly charmed baryons. The most probable mechanism for the double charm production at SELEX is production of the single \( cc \) pair in the processes \( gg \rightarrow cc \) or \( q\bar{q} \rightarrow cc \) while the second \( cc \) pair is created in the fragmentation of the heavy quark \( c \rightarrow cc\bar{c} \). However, theoretically it is still unclear why the SELEX has such a large cross section for double charm production. Since SELEX is a fixed target experiment the \( cc \) diquark is most likely
to be produced with high lab momenta which might be helpful in the detection as discussed in [2]. But since SELEX found, with their cuts, only about fifty candidates for double charmed baryons, the statistics for detecting double charmed tetraquarks should be improved.

Next, we look at the production and detection of the $T_{cc}$ tetraquark in B-factories. Since the total mass of four $D$ mesons is close to the c.m. energy, the $c$ quarks created in this process have small relative momenta which is very important in $T_{cc}$ production. This feature also ensures a smaller number of additional pions created in the $e^+e^-$ annihilation and thus a cleaner reconstruction of $T_{cc}$. Belle [13], [14] has reported a measurement of prompt $J/\psi$ production in $e^+e^-$ annihilation at $\sqrt{s} = 10.6$ GeV and found that the most of the observed $J/\psi$ production is due to the double $c\bar{c}$ production

$$\sigma(e^+e^- \rightarrow J/\psi c\bar{c})/\sigma(e^+e^- \rightarrow J/\psi X) = 0.59^{+0.15}_{-0.13} \pm 0.12$$

which correspond to [13], [14]

$$\sigma(e^+e^- \rightarrow J/\psi c\bar{c}) = 0.87^{+0.21}_{-0.19} \pm 0.17 \text{ pb}$$

or to about 2000 events from their 46.2 fb$^{-1}$ data sample.

The theoretical nonrelativistic QCD prediction for this process is an order of magnitude smaller [3], [4], [5], [6], so this process is still not well understood [7]. But it is very likely that the analogous mechanism would also enlarge the cross section for the prompt production of $cc$ diquark and thus the $\Xi_{cc}$ baryon and $T_{cc}$ tetraquark. The $cc$ diquark production cross section can then be estimated to be $\sim 0.15$ pb, which correspond to $\sim 10^4 \Xi_{cc}$ [8] and about $\sim 10^3 T_{cc}$ per year.

We now present our calculation for the $T_{cc}$ production at high energy colliders. The two colliding nucleons in TeV machines can be considered as two packages of virtual gluons whose number is huge for low Bjorken-$x$. Therefore we expect [9], [10] that in these facilities the dominant mechanism for double charm production would be a double gluon-gluon fusion: $(g+g) + (g+g) \rightarrow (c+c) + (c+c)$.

The usual hard production mechanism is heavy quark production followed by fragmentation, however this mechanism does not include all the possible Feynman diagrams. In ref. [9], [10] it has been shown that at high energy collider a significant rate of events with double heavy quark pairs is expected. To compute all the fourth order $\alpha_s$ Feynman diagrams we have to consider the two different mechanisms leading to the same final state: the usual single parton scatterings and the double parton scatterings. At high energy in single parton interactions the partonic sub-process is dominated by the gluon-gluon fusion $gg \rightarrow c\bar{c}c\bar{c}$ while the double parton interactions are dominated by the process $(g+g) + (g+g) \rightarrow (c+c) + (c+c)$ where the two distinct interactions occur in the same hadronic event.

We give an estimate of the production cross section at high energy in the region of small transverse momenta where the multiple parton interactions provide the leading contribution to the cross section [9], [10]. We compute the production cross section of two $c$-quarks, $c_1, c_2$, very close in momentum space $|p_{1j} - p_{2j}| < \Delta$, $j = x, y, z$, as a function of $\Delta$. We consider the heavy quark production in the kinematical range of the LHCb ($\sqrt{s} = 14$ TeV, $1.8 < \eta < 4.9$), and for completeness for the ALICE ($\sqrt{s} = 14$ TeV, $|\eta| < 0.9$), Tevatron ($\sqrt{s} = 1.8$ TeV, $|y| < 1$) and RHIC ($\sqrt{s} = 200$ GeV, $|\eta| < 1.6$) experiments; in the last case we calculate also the production cross sections in proton-nucleus interactions [7]. The results are shown in Fig 1 One can notice that the cross section $\sigma d\sigma/d^3p$ at small $\Delta$ is almost uniform and then it is approximately proportional to the momentum volume $\Delta^3$.

FIG. 1: Production cross section of two $c$ quarks in momentum space $\Delta$ at LHC (LHCb and ALICE), at Tevatron and at RHIC.

In the second step, the two $c$ quarks join into a diquark. We assume simultaneous production of two independent $c$ quarks with momenta $\vec{p}_1, \vec{p}_2$. Since they appear wherever within the nucleon volume, we modulate their wave functions with a Gaussian profile with the “oscillator parameter” $B = \sqrt{2/3\sqrt{\langle r^2 \rangle}} = 0.09$ fm corresponding to the nucleon rms radius

$$N_B e^{-(\vec{r}_a - \vec{r}_a')^2/2B^2 + i \vec{p}_1 \vec{r}_1} N_B e^{-(\vec{r}_2 + \vec{r}_a')^2/2B^2 + i \vec{p}_2 \vec{r}_2} \equiv N_B e^{-(\vec{r} - \vec{r}_a')^2/2(B/\sqrt{\beta})^2 + i \vec{p}_1 \vec{r}_1} N_B e^{-(\vec{r} - \vec{r}_a')^2/2(B/\sqrt{\beta})^2 + i \vec{p}_2 \vec{r}_2}$$

where the normalisation factor $N_B = \pi^{-3/2} \beta^{-3/2}$. Here $\vec{r}_a$ is the average distance between two nucleons in the target nucleus for proton-nucleus experiment at RHIC and we use the value $\vec{r}_a = 0$ fm or zero otherwise.

We make an impulse approximation that this two-quark state is instantaneously transformed in any of the
eigenstates of the two-quark Hamiltonian. Then the amplitude of the diquark formation $M$ is equal to the overlap between the two free quarks and the diquark with the same centre-of-mass motion. By approximating the diquark wave function with a Gaussian with the oscillator parameter $\beta = 0.41$ fm we get

$$M(p) = \int d^3 r \, N_B \sqrt{2} e^{-(r-r_\alpha)^2/2(B_\sqrt{2}^2 - i \beta^2)} N_{\beta e} e^{(-r^2/2\beta^2)}$$

For the production cross section we take into account that $d\sigma/d^3 p$ is practically constant and can be taken out of the integral

$$\sigma = \frac{3}{\mathcal{M}_0^2} \frac{3}{4} \int d^3 p \, d\sigma d^3 p \left[ \frac{2\sqrt{1/8}}{\sqrt{2B_\beta^2 + \beta^2}} \right] e^{-r_\alpha^2/2B^2}$$

where factors in front of the integral are due to the projection on the colour and spin triplet states. If we insert the values of $d\sigma/d^3 p$ obtained from the Fig 1, we get $\sigma \approx 27$ nb and 58 nb for LHCb and ALICE at LHC, $\sigma \approx 21$ nb at Tevatron and $\sigma \approx 4$ nb and 63 nb at RHIC for proton-proton and proton-nucleus interaction, respectively.

The last step of the $T_{cc}$ production is dressing of the heavy diquark. It either acquires one light quark to become the doubly-heavy baryon ccu, ccd or ccs, or two light antiquarks to become a tetraquark. With this we neglect the possible dissociation of the heavy diquark into a $DD$ pair so the results are the upper estimate for the real $T_{cc}$ production. Assuming that the probability for dressing the cc diquark into the $cc\bar{u}\bar{d}$ tetraquark is 0.1 [12], as pointed out at the beginning of the section, yields the production rate of the dimeson 20900, 9700, 600 and 1 events/hour for LHC at luminosity $10^{33}$ cm$^{-2}$s$^{-1}$, Tevatron at luminosity $8 \times 10^{31}$ cm$^{-2}$s$^{-1}$ and RHIC at $d-Au$ luminosity 0.2 : $10^{28}$ cm$^{-2}$s$^{-1}$, respectively.

### III. STRUCTURE OF $T_{cc}$

The structure of the $T_{cc}$ tetraquark has been studied in ref. [26]. We summarize here those features which are particularly relevant for the detection.

There are two extreme spatial configurations of quarks in a tetraquark. The first configuration which we call atomic is similar to $\Lambda_c$, with a compact cc diquark instead of $c$, around which the two light antiquarks are moving in a similar manner as in the $\Lambda_c$ baryon. The second configuration which we call molecular resembles deuteron, the two heavy quarks are well separated and the two light antiquarks are bound to them as if we had two almost free mesons. The atomic configuration is more likely to appear in strongly bound tetraquarks while the molecular configuration can be expected in weakly bound systems.

We present results using two different one-gluon exchange potentials. The Bhaduri potential [18] quite successfully describes the spectroscopy of the meson, as well as baryon ground states. This is an important condition since in the tetraquarks we have both quark-quark and quark-antiquark interactions. The AL1 potential [19] slightly improves the meson spectra by introducing a mass-dependent smearing of the colour-magnetic term.

We expand tetraquark wave function with Gaussians of three sets of Jacobi coordinates. In this basis we were able to reconstruct the wave functions of deeply bound tetraquarks as well as of two free mesons - the threshold state. This is important if one is searching for weakly bound tetraquarks with molecular structure. We found that the $T_{cc}$ is weakly bound for both the Bhaduri and AL1 potential in contrast to the results of calculations in harmonic oscillator basis [21] where asymptotic channel cannot be accommodated as shown in Table I.

| Potential | $E_{\text{th}}$ (MeV) | $R_{cc}$ (fm) |
|-----------|----------------|--------------|
| Bhaduri   | 3905.3         | 3904.7       | 3931         | 2.4 |
| AL1       | 3878.6         | 3875.9       | 1.6          |

In Fig. 2 we present the probability densities $\rho_{ij}$ for finding (anti)quark $i$ and (anti)quark $j$ at the interquark distance $r_{ij}$ and the ratio of the projections on colour sextet state $|6_{12}3_{34}\rangle_C$ and colour triplet state $|3_{12}3_{34}\rangle_C$ where e.g.

$$\rho_{ij}^{\text{(trip)}}(r) = \langle \psi |3_{12}3_{34}\rangle_C \langle 3_{12}3_{34}|C\delta(r-r_{ij})|\psi\rangle$$

Here particles 1 and 2 are the two heavy quarks $c$ and particles 3 and 4 the light antiquarks $\bar{u}$ and $\bar{d}$. The wave function between heavy quarks is broad and has an exponential tail $\sim e^{-\kappa r}$ at large distances where $\kappa = \sqrt{|E_h|/M_{\text{red}}/c}$, $E_h$ is the binding energy of the system and $M_{\text{red}}$ the reduced mass of the $D$ and $D^*$ mesons. At small distances the dominant colour configuration is $3_{12}3_{34}$. Here we have a diquark-antidiquark structure and this region present about a third of the total probability while for $r > 1$ fm sextet colour configuration become larger. The ratio of these two configurations stabilise at 2, since here we have a molecular structure of the two colour singlet mesons which has in diquark antidiquark basis $|1_{34}1_{24}\rangle = \sqrt{1/3}|3_{12}3_{34}\rangle + \sqrt{2/3}|6_{12}3_{34}\rangle$ colour decomposition, while octet configuration $|8_{13}8_{24}\rangle = -\sqrt{2/3}|3_{12}3_{34}\rangle + \sqrt{1/3}|6_{12}3_{34}\rangle$ is negligible.

Now we show that additional weak three-body interaction can transform the molecular structure of the $T_{cc}$ tetraquark into atomic. For the radial part we take the simplest possible radial dependence – the smeared delta function of the coordinates of the three interacting particles [20]. The colour factor in the two-body Bhaduri or AL1 potential is proportional to the first (quadratic)
come dominant and the \textit{lar} structure, the triplet-triplet colour configurations be-

\[ U_{cc} \]

where the binding energy of the tetraquark becomes similar to \( U_{cc} \). In the baryon sector such an interaction would merely lower the states by about \( U_{cc} \) so it would have no dramatic effect nor would it spoil the fit to experimental data. Since the predicted energies of ground state baryons for the Bhaduri and AL1 potential are above the experimental values, this is actually a desirable feature.

![Figure 2](image2.png)

**FIG. 2:** Results for the AL1 potential. Probability density of the two heavy quarks \( \rho_{cc} \), of the two light antiquarks \( \rho_{bb} \) and of a light antiquark and a heavy quark \( \rho_{qc} \) in \( T_{cc} \) as a function of the interquark distance. The ratio of the projection on colour sextet and colour triplet configurations is also shown.

The Casimir operator \( C^{(1)} \), \( C^{(1)} = \lambda \cdot \lambda \). It is then natural that we introduce in the three-body potential the second \( C^{(2)} \) (cubic) Casimir operator \( C^{(2)} = d^{abc} \lambda_a \cdot \lambda_b \cdot \lambda_c \). A deeper discussion of the properties that the colour dependent three-body interaction must fulfil can be found in [22–24].

In the baryon sector the three-body interaction was used to better reproduce the baryon ground state spectroscopy [19]. A colour structure is there irrelevant since there is only one colour singlet state and thus the colour factor is just a constant which can be included into the strength of the potential. In tetraquarks the situation is different since there are two colour singlet states: \( \tilde{3}_{1234} \) and \( \tilde{6}_{1234} \) (or \( 1_{1234} \) and \( 8_{1234} \) after recoupling). The three-body force operates differently on these two states and one can anticipate that in the case of the weak binding it can produce large changes in the structure of the tetraquark. This cannot be otherwise produced simply by reparameterization of the two-body potential, so the weakly bound tetraquarks are a very important labora-

![Figure 3](image3.png)

**FIG. 3:** Results for the Bhaduri potential. Probability density between two c quarks \( \rho_{cc} \) in the \( T_{cc} \) tetraquark as a function of interquark distance for three different values of the strength of the three-body potential.

**IV. DETECTION**

In order to identify a weakly bound \( T_{cc} \) tetraquark we have to distinguish the pion or photon emitted by the \( D^{*} \) meson bound inside the tetraquark from the one resulting from free \( D^{*} \) meson decay. We can exploit the fact that the phase space for \( D^{*} \to D + \pi \) decay is very small. This has a strong impact on the branching ratio between radiative and hadronic decay. Since the \( D^{*} \) meson inside the tetraquark with molecular structure is not significantly influenced by the other D meson in the tetraquark, we expect that the partial width for the magnetic dipole M1 transition would be very close to the width of the free meson while the width for hadronic \( D^{*} \to D + \pi \) decay will decrease with stronger binding and will become energetically forbidden below the \( D + \pi \) threshold. The hadronic decay of the \( T_{cc} \) tetraquark is a three-body decay which is commonly represented by the Dalitz plot.

If the \( T_{cc} \) tetraquark is below the \( D + D^{*} \) threshold but above the \( D + D + \gamma \) and \( D + D + \pi \), as was the case in our nonrelativistic potential models, the partial decay rate for the \( T_{cc} \to D + D + \pi \) is given by

\[
d\Gamma = \frac{1}{(2\pi)^3} \frac{1}{32M^3} |M|^2 dm_{12} dm_{23}
\]

where particles 1 and 2 are two final \( D \) mesons and particle 3 is a \( \pi \) emerging from the decaying tetraquark. Here \( m_{12}^2 = (p_D + p_D)^2 \) and \( m_{23}^2 = (p_D + p_\pi)^2 \) and \( M \) is the mass of the tetraquark. Since the total masses of the \( D^{*} + D \) and \( 2D + \pi \) are so close there is a strong isospin violation in the decay which cannot be reproduced with the Bhaduri or AL1 potential where the \( D^{*} \)
of the Dalitz plot case, the allowed region will be uniformly populated with $T$ energy but we shall rather work with the experimental masses dependence of the decay on the isospin of the particles, and the $D$ isospin doublets are degenerate. We shall not try to modify the interaction to accommodate the dependence of the decay on the isospin of the particles, but we shall rather work with the experimental masses taken from the PDG [25] where we see that $m_{D^{*+}} - m_{D^+} - m_{\pi^0} = 5.6 \pm 0.1$ MeV, $m_{D^{0*}} - m_{D^0} - m_{\pi^0} = 7.1 \pm 0.1$ MeV, $m_{D^{*+}} - m_{D^{0*}} - m_{\pi^0} = 5.87 \pm 0.02$ MeV. The allowed region of integration over $dm_1^2$ and $dm_2^2$ for three different binding energies is plotted in Fig. 4. If we assume $|M|^2$ is constant, which is very plausible in our case, the allowed region will be uniformly populated with experimental events so that the measured partial decay rate $\Gamma$ will be proportional to the kinematically allowed area from Fig. 4. This is shown in Fig. 5, where we assumed that for the molecular state, the width of the $T_{cc}$ tetraquark with zero binding energy would be the same as the width of the free $D^*$ meson.

Let us now consider also the possibility that $T_{cc}$ is not a bound $DD^*$ state but a resonant state above the $D + D^*$ threshold. Then if the resonance is situated near the threshold, there will be a significant fraction of hadronic $T_{cc} \to D + D^* \pi$ decays beside the $T_{cc} \to D + D^*$ decay. This region of positive binding energy is also presented in Fig. 4 and Fig. 5.

In order to estimate the decay width we make a comparison with charmonium. The charmonium state $\psi(3770)$ has the width of $25.3 \pm 2.9$ MeV and is 36 MeV above $DD$ threshold, which is also the dominant decay mode. Let us assume, that the $T_{cc}$ tetraquark resonant state, which would be 36 MeV above the $D + D^*$ threshold would have the same partial width for the decay into $D$ and $D^*$ meson The area of the integrated Dalitz plot for the binding energy $E_b = +36$ MeV is then 37 times larger then at the threshold $E_b = 0$. Since the experimental width for $D^* \to D \pi$ is $96 \pm 4 \pm 22$ keV [25] we can estimate that the decay width for the $T_{cc} \to D \pi D$ three-body decay would be $\Gamma \sim 37 \cdot 96$ keV = 3.6 MeV. So we expect about 15% direct $T_{cc} \to D + D^* \pi$ decays. The Dalitz plot would not be uniformly populated but there will be a strong band where $m_{23} = m_{D^*}$ reflecting the appearance of the $T_{cc} \to D D^* \to D \pi D$ decay chain. In this estimation we have neglected the interference between these two decay mechanism, since the width of the $D^*$ is three orders of magnitude smaller then the width of the tetraquark.

**V. CONCLUSION**

We have shown that the $T_{cc}$ tetraquark production is comparable to double charm baryon production (possibly 10%). Therefore they may be seen in SELEX if statistics is improved. Similarly, it is comparable to prompt $J/\psi c\bar{c}$ production which is reasonably abundant in $B$-factories. In high energy colliders we may expect an optimistic number of events due to double $c\bar{c}$ production via double two-gluon fusion (see Sect.2). Therefore time has come to start the hunt!

Regarding the detection of the $T_{cc} = DD^*$ tetraquark we propose a nice opportunity – the very small phase space of the $D^* \to D \pi$ decay which is very sensitive to the binding energy of $D^*$ to $D$. One possibility would be to measure the branching ratio between the pionic and gamma decay of $D^*$.

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