Charmed Exotics in Heavy Ion Collisions

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Based on the color-spin interaction in diquarks, we argue that charmed multiquark hadrons are likely to exist. Because of the appreciable number of charm quarks produced in central nucleus-nucleus collisions at ultrarelativistic energies, production of charmed multiquark hadrons is expected to be enhanced in these collisions. Using both the quark coalescence model and the statistical hadronization model, we estimate the yield of charmed tetraquark meson $T_{cc}$ and pentaquark baryon $\Theta_{cc}$ in heavy ion collisions at RHIC and LHC. We further discuss the decay modes of these charmed exotic hadrons in order to facilitate their detections in experiments.

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I. INTRODUCTION

Possible existence of exotic mesons consisting of two quarks and two anti-quarks was first suggested by Jaffe in the framework of the MIT bag model [1]. Since then, there have been continuous discussions on whether the mesons in the scalar nonet are candidates for such tetraquark mesons. Recently, interest in tetraquark mesons has been extended to include those containing heavy quarks [2, 3], as several heavy mesons, that were observed in $B$ meson decays, do not seem to fit well within the conventional quark model [4]. Tetraquark mesons with two heavy anti-quarks ($Q\bar{Q}qq$), henceforth called $T_{QQ}$, are particularly interesting as they are explicitly exotic from flavor considerations [5]. Moreover, simple theoretical consideration based on the color-spin interaction [6] shows that for such configurations the binding energy increases as the mass of the heavy quark increases. Calculations based on the flavor-spin interaction [7, 8, 9] or the instanton induced interactions [10] also show that the mass of $T_{cc}$ is below that of two charmed mesons. For a similar reason, the chance of having a stable heavy pentaquark ($q\bar{q}qq\bar{Q}$) increases as the mass of heavy anti-quark becomes larger.

Experimental observation of such explicitly exotic hadrons is crucial in refining our understanding of multiquark interactions in low energy QCD. However, producing the $T_{QQ}$ from an elementary process is highly suppressed as it involves creating two $Q\bar{Q}$ pairs from the vacuum. In contrast, in relativistic heavy ion collisions at LHC, $cc$ pairs are expected to be abundantly produced [11]. Since the hadronization from the quark-gluon plasma produced in these collisions tends to follow a statistical description, production of exotic hadrons in heavy ion collisions at LHC is thus much more favorable than in elementary reactions [12, 13, 14].

In this work, we first give a qualitative argument why multiquark hadrons consisting of heavy quarks are likely to exist. Using both the quark coalescence model and the statistical hadronization model, we then give estimates of how many $T_{QQ}$ and charmed pentaquark baryons, if they exist, will be produced in central heavy ion collisions at both RHIC and LHC. Furthermore, possible decay modes of these charmed exotic hadrons are discussed.

II. A SCHEMATIC MODEL FOR HADRON MASS DIFFERENCES

A. Known hadrons

Sophisticated constituent quark model calculations have been performed to study possible stable multiquark hadrons that consist of heavy quarks. These results can be roughly understood in terms of simple arguments based on the color-spin interaction. To illustrate the mechanism, we introduce the following simplified form for the color-spin interaction [6]:

$$C_H \sum_{i>j} \frac{\mathbf{s}_i \cdot \mathbf{s}_j}{m_i m_j}.$$

Here $m$ and $\mathbf{s}$ are the mass and spin of the constituent quarks $i$ and $j$. The strength of the color-spin interaction $C_H$ should depend on the wave function and the exact form of the interaction as well as the color structure of either the quark-quark or quark-antiquark pair. The color factor would be $8/3$ for diquarks in the color antitriplet channel and $16/3$ for quark and anti-quark pair in the color singlet channel. This simple form with $C_H = C_R$ for a diquark and $C_H = C_M$ for a quark-antiquark pair can capture some of the essential physics in hadron masses. To illustrate this point, we assume the following constituent quark masses: $m_{u,d} = 300$ MeV, $m_s = 500$ MeV, $m_c = 1500$ MeV, and $m_b = 4700$ MeV.

Table 1 shows the mass differences between baryons that are sensitive to the color-spin interaction only. By

\begin{table}[h]
\centering
\begin{tabular}{|c|c|c|}
\hline
Baryon & Mass Difference (MeV) & Sensitivity \hline
\end{tabular}
\end{table}
The stability of $T_{q_1q_2}$ depends on whether it is energetically favorable against recombining into two mesons of $u\bar{q}_1$ and $d\bar{q}_2$. As we have discussed previously, the attraction $C_M$ between a quark-antiquark pair is stronger than $C_B$ in a diquark. This means that when both $q_1$ and $q_2$ are light, the two-meson states would be energetically much more favorable, and $T_{q_1q_2}$ will not be stable. However, when $q_1$ and $q_2$ become heavy, the attraction in the quark-antiquark pair in the meson decreases, while in $T_{q_1q_2}$ the attraction in the $ud$ diquark remains the same and the interaction in the $q_1q_2$ decreases substantially. Therefore, the tetraquark state could become stable. A simplification in working with a spin zero $ud$ diquark in $T_{q_1q_2}$ is that there is no spin-spin interaction between the $ud$ diquark and $q_1$ or $q_2$, and it is sufficient to only estimate the attractions inside the diquark or anti-diquark. If $q_1$ and $q_2$ are identical quarks, then their total spin has to be zero, because their color combination is antisymmetric in the present configuration. This means that their total spin has to be 1, which is a repulsive combination. However, the repulsion becomes smaller when quark masses become heavy. Moreover, the quantum number of $T_{q_1q_2}$ has to be $1^+$, so that it can not decay into two pseudoscalar mesons. The threshold for its decay is then the masses of the vector and pseudo scalar mesons.

### B. charmed tetraquark mesons

Using above parameters, we argue in this subsection why the doubly charmed tetraquark meson might be stable. Let us consider a tetraquark meson $T_{q_1q_2}$ that is made up of $ud\bar{q}_1\bar{q}_2$. The reason we start with the $ud$ diquark is that for a diquark the strongest attraction is expected when the two quarks are light, and their total color, flavor and spin are all in the antisymmetric states. Therefore, if there is any stable configuration, it must involve a scalar $ud$ diquark. We then add two antiquarks in the relative $s$-wave state and look for a stable configuration.

| Mass Diff | $M_\Delta - M_N$ | $M_S - M_A$ | $M_{S\bar{c}} - M_{\bar{d}}$ | $M_{D\bar{d}} - M_D$ | $M_{D\bar{d}} - M_{D\bar{d}}$ |
|-----------|------------------|-------------|------------------------|---------------------|------------------------|
| Formula   | $\frac{3C_B}{2m_{u\bar{d}}^2}$ | $\frac{C_B}{m_{u\bar{d}}^2} (1 - \frac{m_u}{m_d})$ | $\frac{C_B}{m_{u\bar{d}}^2} (1 - \frac{m_u}{m_d})$ | $\frac{C_B}{m_{u\bar{d}}^2} (1 - \frac{m_u}{m_d})$ |
| Fit       | 290 MeV          | 77 MeV      | 154 MeV                | 180 MeV             | 192 MeV                |
| Experiment| 290 MeV          | 75 MeV      | 170 MeV                | 192 MeV             | 200 MeV                |

Table [I]: Baryon mass relations. The first column is fit to experiments.

When both quarks are heavy, the value of $C_H$ is expected to become larger as the strength of the relative wave function at the origin is substantially increased. Fitting instead its value to the mass difference between $J/\psi$ and $\eta_c$, we find $C_{cc}/m_{c^2} = 117$ MeV. Assuming that the corresponding attraction between charmed diquark is three times smaller than that between the charm quark-antiquark pair as in the case of light quarks, we have $C_{cc}/m_{c^2} = 39$ MeV. We could introduce additional mass dependence in $C_H$ and in $C_M$ by fitting the mass differences in the strange, charm and bottom hadrons from Table I and II, respectively. However, these introduce only minor changes in the analysis to follow, and therefore we will just use the mass independent $C_H$’s obtained above.

### Table III: Tetraquark mesons $ud\bar{q}_1\bar{q}_2$ with spin equal to1 for $q_1 = q_2$, where $q_1$, $q_2 = s$, $c$ and $b$. Units are in MeV.

| $ud\bar{q}_1\bar{q}_2$ (spin=1) | $u\bar{q}_1$ (spin=1) | $d\bar{q}_2$ (spin=0) | $u\bar{q}_1 - u\bar{q}_2$ |
|-------------------------------|---------------------|---------------------|---------------------|
| $-\frac{3}{4} \frac{C_B}{m_{u\bar{d}}^2}$ | $\frac{1}{4} \frac{C_B}{m_{u\bar{d}}^2} + \frac{1}{4} \frac{C_B}{m_{u\bar{d}}^2}$ | $-\frac{3}{4} \frac{C_B}{m_{u\bar{d}}^2}$ | $-u\bar{q}_1 - u\bar{q}_2$ |
| $ud\bar{s}\bar{s}$              | $K^+$               | $K$                 | 63                  |
| $-127$                         | 92                  | -285               |                     |
| $ud\bar{c}\bar{c}$             | $D^+$               | $D$                 | -79                 |
| $-143$                         | 31                  | -95                |                     |
| $ud\bar{b}\bar{b}$             | $B^+$               | $B$                 | -124                |
| $-145$                         | 10                  | -30                |                     |

Table [III] shows the mass difference between a tetraquark meson with identical diquarks and the sum of vector and pseudo scalar meson masses due to the color-spin interaction of Eq. [1] with the $C_H$ parameters determined previously. As expected, the mass difference decreases as $q_1$ and $q_2$ become heavy, and the tetraquark mesons $T_{cc}$ and $T_{bb}$ with $c$ or $b$ quarks are bound. Although our result is based on a very crude estimate, essentially the same result has been obtained in the full constituent quark model calculation [8,15] and the QCD sum-rule calculation [16].

For $q_1$ and $q_2$ of different flavors, their total spin could be either zero or one. The quantum number of the tetraquark meson could then be either $0^+$ or $1^+$. Table [IV] and Table [V] show the mass differences in such cases. As in the previous case, bound tetraquark mesons with $\bar{c}\bar{b}$ could exist.
TABLE IV: Tetraquark mesons $udq_1q_2$ with spin equal to 0 for $q_1 \neq q_2$. Units are in MeV.

| $udq_1q_2$ (spin=0) | $uq_1$ (spin=0) | $duq_2$ (spin=0) | $udq_1q_2$ |
|----------------------|-----------------|-----------------|------------|
| $-\frac{3}{4} C_u - \frac{3}{4} C_u$ | $\frac{1}{4} C_M - \frac{1}{4} C_M$ | $-\frac{3}{4} C_M - \frac{3}{4} C_M$ | $-u\bar{q}_1 - u\bar{q}_2$ |
| $uds\bar{c}$         | $K$             | $D$             | 218        |
| -162                | -285            | -95             |            |
| $uds\bar{c}$         | $K$             | $B$             |            |
| -150                | -285            | -30             |            |
| $ud\bar{b}$          | $D$             | $B$             |            |
| -146                | -95             | -30             | -21        |

TABLE V: Tetraquark mesons $udq_1q_2$ with spin equal to 1 for $q_1 \neq q_2$, where $q_1, q_2 = s, c$ and $b$. Units are in MeV.

| $udq_1q_2$ (spin=1) | $uq_1$ (spin=1) | $duq_2$ (spin=0) | $udq_1q_2$ |
|----------------------|-----------------|-----------------|------------|
| $-\frac{3}{4} C_u + \frac{1}{4} C_u$ | $\frac{1}{4} C_M$ | $-\frac{3}{4} C_M$ | $-u\bar{q}_1 - u\bar{q}_2$ |
| $uds\bar{c}$         | $K^*$           | $D$             | -139       |
| -139                 | 95              | -95             |            |
| $uds\bar{b}$         | $K^*$           | $B$             | -208       |
| -143                 | 95              | -30             |            |
| $ud\bar{b}$          | $B^*$           | $D$             | -145       |
| -144                 | 10              | -95             | -59        |

TABLE VI: Charm and bottom pentaquark baryons $\Theta_q(ududq)$ ($q = c$ and $b$) with spin equal to 1. $\Delta E_{L=1} = 309$ MeV is an excitation energy of two diquarks with relative angular momentum $L = 1$. Units are in MeV.

C. charmed pentaquark baryons

Similar observations can be made for heavy pentaquark baryons. Many constituent quark model calculations show that the $\Theta^+$ [17], if it exists at all, can not be explained as a bound state of $ududs$ constituent quarks [18]. This is due to the strong attraction between the $s$ and the light quark, so that it is energetically much more favorable for $ududs$ to form a meson and a baryon. The attraction to form a meson becomes smaller if the $s$ is replaced by either a $\bar{c}$ or $\bar{b}$. Full constituent quark model calculations [19, 20] indeed find a possible stable heavy pentaquark baryon. A likely pentaquark structure would be that suggested in Ref. [21] with the two scalar diquark $ud$ combined into an $L = 1$ and color antisymmetric state. The excitation energy of a diquark in a $L = 1$ state, $\Delta E_{L=1}$, can be estimated by approximating the charmed baryon as a sum of a charm quark and a diquark, because the interaction between them is small in the heavy quark limit. Attributing the mass difference between the parity doublet partners of the posi-
III. PRODUCTION OF CHARMED EXOTICS IN RELATIVISTIC HEAVY ION COLLISIONS

As discussed above, tetraquark mesons and pentaquark baryons are more likely to exist in the heavy quark sector such as the \( T_{cc}, T_{cb}, T_{bb}, \Theta_{cs}, \) and \( \Theta_c \). It is, however, very unlikely that they can be observed in \( B \) decays or elementary processes, as the favorable exotics involve two heavy quarks. However, the abundance of heavy quarks is significantly enhanced in ultrarelativistic heavy ion collisions, e.g., in a central collision at the LHC, more than 20 \( \bar{c}c \) pairs are expected to be produced in one unit of midrapidity. Therefore, while a heavy quark produced in an elementary process will most likely find a heavy antibaryon instead of a heavy quark, the probability to find a heavy antibaryon or a heavy quark in a heavy ion collision is similar. The probability to form a \( T_{cc} \) compared to a \( J/\psi \) thus will only be suppressed by the additional statistical factor coming from combining an additional \( ud \) diquark.

A. charmed tetraquark mesons

The number of heavy tetraquark mesons produced from the quark-gluon plasma formed in relativistic heavy ion collisions can be estimated in the coalescence model \[27\], which has been shown to describe very well the pion and proton transverse momentum spectra at intermediate momenta \[28\] as well as at low momenta if resonances are included \[30\], and the yield and transverse momentum spectra of phi meson and Omega baryon \[31\] as well as the charmed meson \[32\]. We employ the formula that was previously used to calculate the yields of tetraquark \( D_sJ(2317) \) meson \[33\] and pentaquark \( \Theta^+ \) baryon \[12\] at RHIC to study \( T_{cc} \) production in central Au+Au collisions at RHIC and Pb+Pb collisions at LHC.

In this model, the \( T_{cc} \) number is given by

\[
N_{T_{cc}}^{\text{coal}} = g_{T_{cc}} \int_0^{\frac{m}{T}} \frac{1}{2} \frac{d^2 \mathbf{p}}{2\pi^2} f_q(x_i, p_i) \times f_{T_{cc}}^W(x_1, x_4; p_1, p_4). \tag{2}
\]

In the above, the color-spin-isospin factor \( g_{T_{cc}} = 3 \times 1/3 \times 1/2 \times 1 = 1/3 \) is the color-spin-isospin factor for the four quarks to form a hadron of the quantum number of the tetraquark meson and \( d\sigma \) denotes an element of a space-like hypersurface at hadronization. Assuming Bjorken correlation \( y = \eta \) between the space-time rapidity \( \eta \) and the momentum-energy rapidity \( y \) and neglecting the transverse flow as well as using the non-relativistic approximation, we obtain the following expression for the number of \( T_{cc} \) produced from quark coalescence:

\[
N_{T_{cc}} \approx 432 \frac{N_c N_c N_u N_d}{\sqrt{2}} \left( \frac{4\pi \sigma_u^3}{T_c^2 V_c} \right)^{3/2} \tag{3}
\]

where \( T_c = 170 \text{ MeV} \) is the critical temperature and \( V_c \) is the fireball volume at hadronization, which is about 1,000 fm\(^3\) in central Au+Au collisions at \( s_{NN}^{1/2} = 200 \text{ GeV} \) \[34\] and about 2,700 fm\(^3\) in central Pb+Pb collisions at \( s_{NN}^{1/2} = 5.5 \text{ TeV} \) \[11\]. The quark numbers at hadronization are denoted by \( N_u \) and \( N_d \) for light quarks and \( N_c \) and \( N_{\bar{c}} \) for heavy quarks. Their values are taken to be \( N_u = N_d = 245 \) \[33\] and \( 662 \) \[11\] as well as \( N_c = N_{\bar{c}} = 3 \) and 20 in central RHIC and LHC collisions, respectively, all in one unit of midrapidity. The charm quark numbers are based on initial hard scattering of nucleons in the colliding nuclei \[11\] \[33\]. In obtaining Eq. (3), we have used the quark momentum distribution function

\[
f_q(x, p) = 6 \delta(\eta - y) \exp(-m^2_q + p_i^2)^{1/2}/T_c \tag{4}
\]

and the tetraquark meson Wigner distribution function

\[
f_{T_{cc}}(x; p) = 8^3 \exp \left( -\sum_{i=1}^{3} \frac{y_i^2}{\sigma_i^2} - \sum_{i=1}^{3} k_i^2 \sigma_i^2 \right), \tag{5}
\]

where the relative coordinates \( y_i \) and momenta \( k_i \) are related to the quark coordinates \( x_i \) and momenta \( p_i \) by the Jacobian transformations defined in Eqs. (7) and (8) of Ref. \[33\]. The width parameter \( \sigma_i \) in the Wigner function is related to the oscillator frequency \( \omega \) by \( \sigma_i = 1/\sqrt{\hbar \omega} \) with the reduced masses \( \mu_i \) defined in Eq. (9) of Ref. \[33\].

In Fig. 1, we show the numbers of \( T_{cc} \) produced at RHIC and LHC as functions of the oscillator frequency. Because of the larger abundance of charm quarks at LHC than at RHIC, the number of \( T_{cc} \) produced at LHC is more than an order of magnitude larger than that produced at RHIC. For the oscillator frequency \( \omega = 0.3 \text{ GeV} \), determined from the size \( (r^2_{\text{ch}})_{1c} \approx 0.124 \text{ fm}^2 \) of the \( D_s^+(c\bar{s}) \) meson based on the light-front quark model \[34\], the number of \( T_{cc} \) produced at RHIC and LHC is about \( 5.5 \times 10^{-6} \) and \( 9.0 \times 10^{-5} \), respectively.
It is of interest to compare the predicted number of $T_{cc}$ mesons from the coalescence model with that from the statistical model. In this model the number of $T_{cc}$ mesons produced at hadronization is given by \(33\):

\[
N_{T_{cc}}^{\text{stat}} \approx \frac{V_H \gamma_C^2}{(2\pi)^2} \int dm \int d\tau \rho \left( \frac{\beta H \rho_{\text{PT}}}{T_C} \right)
\]

where $V_H$ and $\beta_H$ are the volume and radial flow velocity of formed hadronic matter, and $\gamma_C$ is the fugacity parameter for ensuring that the number of charm hadrons produced statistically at hadronization is same as the number of charm quarks in the quark-gluon plasma. With $V_H \approx 1.8908 \text{ fm}^3$, $T_H = 175 \text{ MeV}$, $\beta_H = 0.3c$, and the charm fugacity $\gamma_C \approx 8.4$, we obtain $N_{T_{cc}} \approx 7.5 \times 10^{-4}$ in central Au+Au collisions at RHIC. The yield of $T_{cc}$ increases to $8.6 \times 10^{-3}$ in central Pb+Pb collisions at LHC where we have used $V_H \approx 5.220 \text{ fm}^3$, $T_H = 175 \text{ MeV}$, $\beta_H = 0.47c$, and the charm fugacity $\gamma_C \approx 16.3$. Compared to those from the coalescence model, predictions from the statistical model are almost two orders of magnitude larger.

**IV. DECAY MODES OF CHARMED EXOTICS**

In this section, we discuss the observable decay modes of the tetraquark $T_{cc}$ and the pentaquark $\Theta_{cs}$. As we have discussed already, $T_{cc}$ is most likely a stable state, since its mass is below the threshold of $D^*D$. To be more general, we consider nevertheless both cases where the mass of $T_{cc}$ is above or below the threshold, and discuss in each case possible decay modes that can be realistically detected in experiments with good performance. For the $T_{cc}$ above the threshold of $D^*D$, it can decay to $D^{*-}D^0$ via a strong process \(40\). For the $T_{cc}$ below the threshold of $D^*D$ and above $DD\pi$, the decay channel to $D^{*-}D^0$ is energetically forbidden, but the $D^{*-}$ component in $T_{cc}$ can decay through a strong process, leading to the final decay mode $D^0D^0\pi^-\pi^+$. On the other hand, when $T_{cc}$ is below the threshold of $DD\pi$, the decay channel of $D^{*-}$ is closed and only the weak decay of $D^0$ component in $T_{cc}$ is allowed via $D^0 \rightarrow K^+\pi^-\pi^+$ or $K^+\pi^+\pi^-\pi^-$. Therefore, $T_{cc}$ would be detected by the decay modes $D^{*-}K^-\pi^+$ and $D^{*-}K^+\pi^-\pi^-\pi^-$. The last two decay patterns would most likely happen since the binding energy of $T_{cc}$ is estimated to be about 80 MeV as shown previously, which is sufficiently larger than the mass difference (about 6 MeV) between $D^{*-}$ and $D^0\pi^-$. Below the threshold of $DD\pi$, it may be also interesting to see the decay of $D^{*-}$ component in $T_{cc}$. Considering that $D^{*-}$ component contains a quantum number of $D^0\pi^-$, and $D^0$ decays into $K^+\pi^-$ and $K^+\pi^-\pi^-\pi^-$, we may observe the $D^0K^+\pi^-\pi^-$ and $D^0K^+\pi^-\pi^-\pi^-$ decays.
cays.

Among the weak decays below the threshold of $DD\pi$, the decay of the $\bar{D}^0$ component in $T_{cc}$ can be distinguished from that of the $D^{*-}$ component. The former has the correlations $(K^+\pi^-)(K^+\pi^-)\pi^-$ and $(K^+\pi^-\pi^+\pi^-)(K^+\pi^-)\pi^-$, and the latter has the correlations $(K^+\pi^-)(K^+\pi^-\pi^-)$ and $(K^+\pi^-)(K^+\pi^-\pi^-\pi^-)$, where brackets denote correlated particles. However, the $D^0\bar{D}^0\pi^-$ state, which would appear in $T_{cc}$ in the latter process, contains six quarks, hence further analysis is needed to discuss its stability.

The pentaquark $\Theta_{cs}$ also has interesting decay patterns. As can be seen in Table VII, the mass of $\Theta_{cs}$ could be slightly above the $\bar{D}^0\bar{D}^0$ threshold, in which case its lifetime will be shorter than that of $D_s$. Then, the only possible way to look for it is from the hadronic decay to $\Lambda + D^0$ final states. Since ALICE will be able to reconstruct the $D^0$ through its hadronic decay, it will be an excellent opportunity to search for $\Theta_{cs}$. Considering more general cases, and assuming $\Theta_{cs}$ to be above the threshold of $ND_s$, the $\Theta_{cs}$ can decay into $pD_s^-$ and $\Lambda\bar{D}^0$ or $\Lambda D^-$ via the strong process. Although the $\Sigma D$ channel is also a possible decay mode, it is more difficult to detect as compared to $ND_s$ and $\Lambda D$. When the mass of $\Theta_{cs}$ is below the $ND_s$ and above the $\Lambda D$ threshold, it decays only to $\Lambda \bar{D}^0$ or $\Lambda D^-$. On the other hand, below the threshold of $\Lambda D$, the hadronic decay channels are closed and only weak decays are possible. In this case, the lifetime of $\Theta_{cs}$ will depend on the lifetime of the different components inside the $\Theta_{cs}$, such as the $\Lambda$, $\bar{D}^0$ and $D^-$, whose lifetimes are respectively $2.6 \times 10^{-10}$, $0.41 \times 10^{-12}$ and $1.0 \times 10^{-12}$ seconds. Therefore, once the $\Theta_{cs}$ is formed as a deeply bound state, it will decay by the weak process of $\bar{D}^0$ or $D^-$. Consequently, possible final states would be $\Lambda K^+\pi^-$, $\Lambda K^+\pi^+\pi^-\pi^-$ and $\Lambda K^+\pi^-\pi^-$. Since the lifetimes of $T_{cc}$ and $\Theta_{cs}$ are in the order of $10^{-12}$ seconds, their decays occur outside the collision region and they are thus identifiable by vertex reconstruction. Therefore, $T_{cc}$ and $\Theta_{cs}$ would be identified clearly in experiments if they exist. We summarize our results on possible decay modes of $T_{cc}$ and $\Theta_{cs}$ in Tables VIII and IX.

**TABLE VIII: Possible decay modes of $T_{cc}$.** In the bottom column, we would observe correlations $(K^+\pi^-)(K^+\pi^-)\pi^-$ and $(K^+\pi^-\pi^-)(K^+\pi^-)\pi^-$ in the final states. See the text for details.

| threshold | decay mode | lifetime |
|-----------|------------|----------|
| $M_{T_{cc}} > M_{D^*} + M_D$ | $D^{*-} \bar{D}^0$ | hadronic decay |
| $2M_D + M_s < M_{T_{cc}} < M_{D^*} + M_D$ | $\bar{D}^0 D^0 \pi^-$ | hadronic decay |
| $M_{T_{cc}} < 2M_D + M_s$ | $D^{*-} K^+\pi^-, D^{*-} K^+\pi^+\pi^-\pi^-$ | $0.41 \times 10^{-12}$ sec. |

**TABLE IX: Possible decay modes of $\Theta_{cs}$.**

| threshold | decay mode | lifetime |
|-----------|------------|----------|
| $M_{\Theta_{cs}} > M_N + M_{D_s}$ | $pD_s^-$ | hadronic decay |
| $M_\Lambda + M_D < M_{\Theta_{cs}} < M_N + M_{D_s}$ | $\Lambda \bar{D}^0$ | hadronic decay |
| $M_{\Theta_{cs}} < M_\Lambda + M_D$ | $\Lambda K^+\pi^-, \Lambda K^+\pi^+\pi^-\pi^-$ | $0.41 \times 10^{-12}$ sec. |
| | $\Lambda K^+\pi^-\pi^-$ | $1.0 \times 10^{-12}$ sec. |

Lastly, we comment on the possibility to measure doubly charmed baryons in heavy ion collisions. The doubly charmed baryon $\Xi_{cc}^{++}$ have been observed by the SELEX Collaboration in the $\Lambda_c^+ K^-\pi^+$ and in the $pD_s^+ K^-$ decay modes with a mass of $(3518.7 \pm 1.7)$ MeV [35, 36]. The same collaboration has also successfully measured $\Xi_{cc}^{++}$ in the $\Lambda_c^+ K^-\pi^+\pi^+$ decay mode with a mass of 3460 MeV [37]. On the other hand, attempts by the FOCUS Collaboration in the photoproduction experiment, and by the BABAR in $e^+e^-$ annihilation experiments [38, 39] have so far failed to establish the existence of the doubly charmed baryons. Hence, it is an interesting problem.
to search for the doubly charmed baryons in heavy ion collisions. Using the coalescence model, we find that the number of $\Xi^+$ produced are $1.9 \times 10^{-5}$ at RHIC, and $3.2 \times 10^{-4}$ at LHC. Therefore, we will be able to realistically measure $\Xi_{cc}^+$ and $\Xi_{cs}^+$ through their decay vertices to $\Lambda_c^+ K^−\pi^+$ and $pD^+K^−$, and to $\Lambda_c^+ K^−\pi^+\pi^+$, respectively.

V. SUMMARY

Based on the consideration of the color-spin interaction between diquarks, which describes reasonably the mass splittings between many hadrons and their spin flipped partners, we have shown that tetraquark mesons and pentaquark baryons that consist of two charmed quarks could be bound. Using the quark coalescence model, their yields in heavy ion collisions at both RHIC and LHC are estimated. Because of the expected large charm quark number in central Pb+Pb collisions at LHC, the abundances of the tetraquark meson $T_{cc}$ and pentaquark baryon $\Theta_{cs}$ are about $10^{-4}$ and $10^{-3}$, respectively. We have also discussed their decay modes to illustrate how they can be identified in heavy ion collisions. In our studies, we have not taken into account the hadronic effect on the abundance of these charmed exotics, as hadronic reactions that affect their annihilation and production are unknown. Since the yields of $T_{cc}$ and $\Theta_{cs}$ from the coalescence model is significantly smaller than those expected from the statistical hadronization model, including the hadronic effect is expected to increase their yields substantially and reduces the differences from the predictions from the quark coalescence model and the statistical hadronization model. Also, charmed hadrons would be more abundantly produced, particularly the $T_{cc}$, if charm quarks are produced from the QGP formed in these collisions. We also comment on the possible measurement of doubly charmed baryons in heavy ion collisions, and the estimated numbers are $1.9 \times 10^{-5}$ and $3.2 \times 10^{-4}$ at RHIC and LHC, respectively. We thus expect that the open and hidden charmed hadron physics will be an interesting subject in the forthcoming heavy ion collision experiments.

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The decay to the $\bar{D}^{*0}D^-$ mode may not be a good signal in experiments, since the $\bar{D}^{*0}$ decays to $D^0\pi^0$ instead to $D^+\pi^-$ and $D^-\pi^+$, which are energetically forbidden due to mass difference.