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Charmed exotics in heavy ion collisions

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Abstract. 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, the 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 mesons, T_{cc}, and pentaquark baryons, Θ_{cs}, 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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1 Introduction

The possible existence of exotic mesons consisting of two quarks and two antiquarks was first suggested by Jaffe in the framework of the MIT bag model [1, 2]. 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 [3, 4], as several heavy mesons that were observed in B meson decays do not seem to fit well within the conventional quark model [5]. Tetraquark mesons with two heavy antiquarks ($qq\bar{Q}\bar{Q}$), henceforth called T_{QQ}, are particularly interesting, as they are explicitly exotic from flavor considerations [6]. Moreover, a simple theoretical consideration based on the color–spin interaction [7] shows that for such configurations the binding energy increases as the mass of the heavy quark increases. Calculations based on the flavor–spin interaction [8–10] or the instanton induced interactions [11] 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 ($qqqq\bar{Q}$) increases as the mass of heavy antiquark becomes larger.

The 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 $\bar{Q}Q$ pairs from the vacuum. In contrast, in relativistic heavy ion collisions at LHC, $\bar{c}c$ pairs are expected to be abundantly produced [12]. Since the hadronization from the quark–gluon plasma produced in these collisions tends to follow a statistical description, the production of exotic hadrons in heavy ion collisions at LHC is thus much more favorable than in elementary reactions [13–15].

In this work, we first give a qualitative argument that 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.

2 A schematic model for hadron mass differences

2.1 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

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interaction [7]:

$$C_H \sum_{i>j} \vec{s}_i \cdot \vec{s}_j \frac{1}{m_i m_j} \,. \quad (1)$$

Here m and $\vec{s}$ 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 antiquark pair in the color singlet channel. This simple form with $C_H = C_B$ 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: $m_{u,d} = 300\,\text{MeV}$, $m_s = 500\,\text{MeV}$, $m_c = 1500\,\text{MeV}$, and $m_b = 4700\,\text{MeV}$.

Table 1 shows the mass differences between baryons that are sensitive to the color–spin interaction only. By fitting C_B to $M_\Delta - M_N$, we obtain $C_B/m_u^2 = 193\,\text{MeV}$ and find that the mass differences $M_\Sigma - M_\Lambda$ and $M_{\Sigma_c} - M_{\Lambda_c}$ are well reproduced. This is in no way an attempt to make a best fit, but the point is that with typically accepted constituent quark masses, the mass splitting is larger than C_B, reflecting that the quark and antiquark correlation is about three times stronger than that between two quarks.

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/ψ and η_c, we find $C_{c\bar{c}}/m_c^2 = 117\,\text{MeV}$. 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 $C_{cc}/m_c^2 = 39\,\text{MeV}$. We could introduce an additional mass dependence in C_B and in C_M by fitting the mass differences in the strange, charm and bottom hadrons from Tables 1 and 2, respectively. However, these introduce only minor changes in the analysis to follow, and therefore we will just use the mass independent C_H obtained above.

Table 1. Baryon mass differences. The first column is a fit to the approximate difference between experimental Δ and N masses. Units are in MeV

Diff.	$\Delta - N$	$\Sigma - \Lambda$	$\Sigma_c - \Lambda_c$	$\Sigma_b - \Lambda_b$
Form.	$\frac{3C_B}{2m_u^2}$	$\frac{C_B}{m_u^2}\left(1-\frac{m_u}{m_s}\right)$	$\frac{C_B}{m_u^2}\left(1-\frac{m_u}{m_c}\right)$	$\frac{C_B}{m_u^2}\left(1-\frac{m_u}{m_b}\right)$
Fit	290	77	154	180
Exp.	290	75	170	192

Table 2. Meson mass differences. The first column is a fit to the approximate difference between experimental ρ and π masses. Units are in MeV

Diff.	$\rho - \pi$	$K^* - K$	$D^* - D$	$B^* - B$
Form.	$\frac{C_M}{m_u^2}$	$\frac{C_M}{m_u m_s}$	$\frac{C_M}{m_u m_c}$	$\frac{C_M}{m_u m_b}$
Fit	635	381	127	41
Exp.	635	397	137	46

2.2 Charmed tetraquark mesons

Using the above parameters, we argue in this subsection that the doubly charmed tetraquark meson might be stable. Let us consider a tetraquark meson $T_{q_1 q_2}$ 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.

The stability of $T_{q_1 q_2}$ 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 $T_{q_1 q_2}$ 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 $T_{q_1 q_2}$ the attraction in the ud diquark remains the same and the interaction in the $\bar{q}_1\bar{q}_2$ decreases substantially. Therefore, the tetraquark state could become stable. A simplification in working with a spin zero ud diquark in $T_{q_1 q_2}$ 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 antidiquark. 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 $T_{q_1 q_2}$ has to be 1^+, so that it cannot decay into two pseudoscalar mesons. The threshold for its decay is then the masses of the vector and pseudoscalar mesons.

Table 3 shows the mass difference between a tetraquark meson with identical diquarks and the sum of vector and pseudoscalar meson masses due to the color–spin interaction of (1) with the C_H parameters determined previously.

Table 3. Tetraquark mesons $T_{q_1 q_2}(ud\bar{q}_1\bar{q}_2)$ with spin $S=1$ for $q_1 = q_2$, where q_1, $q_2 = s$, c and b. Units are in MeV

$T_{q_1 q_2}$ $(S=1)$ $-\frac{3}{4}\frac{C_B}{m_u^2} + \frac{1}{4}\frac{C_B}{m_{q_1}^2}$	$u\bar{q}_1$ $(S=1)$ $\frac{1}{4}\frac{C_M}{m_u m_{q_1}}$	$d\bar{q}_2$ $(S=0)$ $-\frac{3}{4}\frac{C_M}{m_u m_{q_1}}$	$T_{q_1 q_2}$ $-u\bar{q}_1 - u\bar{q}_2$
T_{ss}	K^*	K	
−127	92	−285	63
T_{cc}	D^*	D	
−143	31	−95	−79
T_{bb}	B^*	B	
−145	10	−30	−124

Table 4. Tetraquark mesons $T_{q_1q_2}(ud\bar{q}_1\bar{q}_2)$ with spin $S=0$ for $q_1 \neq q_2$. q_1, $q_2 = s$, c and b. Units are in MeV

$T_{q_1q_2}$ $(S=0)$ $-\frac{3}{4}\frac{C_B}{m_u^2} - \frac{3}{4}\frac{C_B}{m_{q_1}m_{q_2}}$	$u\bar{q}_1$ $(S=0)$ $-\frac{3}{4}\frac{C_M}{m_u m_{q_1}}$	$d\bar{q}_2$ $(S=0)$ $-\frac{3}{4}\frac{C_M}{m_u m_{q_2}}$	$T_{q_1q_2}$ $-u\bar{q}_1 - u\bar{q}_2$
T_{sc}	K	D	
−162	−285	−95	218
T_{sb}	K	B	
−150	−285	−30	165
T_{cb}	D	B	
−146	−95	−30	−21

Table 5. Tetraquark mesons $T_{q_1q_2}(ud\bar{q}_1\bar{q}_2)$ with spin $S=1$ for $q_1 \neq q_2$, where q_1, $q_2 = s$, c and b. Units are in MeV

$T_{q_1q_2}$ $(S=1)$ $-\frac{3}{4}\frac{C_B}{m_u^2} + \frac{1}{4}\frac{C_B}{m_{q_1}m_{q_2}}$	$u\bar{q}_1$ $(S=1)$ $\frac{1}{4}\frac{C_M}{m_u m_{q_1}}$	$d\bar{q}_2$ $(S=0)$ $-\frac{3}{4}\frac{C_M}{m_u m_{q_2}}$	$T_{q_1q_2}$ $-u\bar{q}_1 - u\bar{q}_2$
	K^*	D	
T_{sc}	95	−95	−139
−139	D^*	K	
	31	−285	114
	K^*	B	
T_{sb}	95	−30	−208
−143	B^*	K	
	10	−285	132
	D^*	B	
T_{cb}	31	−30	−145
−144	B^*	D	
	10	−95	−59

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 [9, 16] and the QCD sum-rule calculation [17].

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^+. Tables 4 and 5 show the mass differences in such cases. As in the previous case, bound tetraquark mesons with $\bar{c}\bar{b}$ could exist.

2.3 Charmed pentaquark baryons

Similar observations can be made for heavy pentaquark baryons. Many constituent quark model calculations show that the Θ^+ [18], if it exists at all, cannot be explained as a bound state of $udud\bar{s}$ constituent quarks [19]. This is due to the strong attraction between the $\bar{s}$ and the light quark, so that it is energetically much more favorable for $udud\bar{s}$ to form a meson and a baryon. The attraction to form a meson becomes smaller if the $\bar{s}$ is replaced by either a $\bar{c}$ or $\bar{b}$. Full constituent quark model calculations [20–22] indeed find a possible stable heavy pentaquark baryon. A likely pentaquark structure would be that suggested in [23] 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 positive parity Λ_c^+ (2286 MeV) and the negative parity Λ_c^{*+} (2595 MeV) to the $L=1$ excitation of the diquark, as the heavy charm quark would act as the center of mass, leads to $\Delta E_{L=1} = 309$ MeV. Applying this $L=1$ excitation energy to the relative excitation of two diquarks, we find that while a strange pentaquark baryon is very unlikely to exist, the heavy pentaquark baryons Θ_c and Θ_b could be closer to the threshold as shown in Table 6, consistent with the full constituent quark model calculation [20–22, 24] and the QCD sum-rules study [25], in which a possible stable heavy pentaquark baryon has been found.

For a pair of ud and us diquarks in $\Theta_{cs}(udus\bar{c})$, they do not have to be in the $L=1$ state, and hence there is no additional contribution from the orbital energy [26]. The result from our simple estimates are given in Table 7. Previous experiments [27, 28] have tried to search for this pentaquark baryon assuming that it is bound and has a lifetime similar to that of D_s. The experiment could only determine an upper bound greater than 0.02 for its production cross section relative to that for the D_s, which is larger than typical theoretical estimates. From a simple application of statistical hadronization model, the number of Θ_{cs} relative to that of D_s is roughly $\exp(-(m_{\Theta_{cs}} - m_{D_s})/T) \sim \exp(-5) = 0.007$, assuming a hadronization temperature of

Table 6. Strange, charm and bottom pentaquark baryons $\Theta_q(udud\bar{q})$ ($q = s$, c and b) with spin $S = 1/2$ or $3/2$. $\Delta E_{L=1} = 309$ MeV is an excitation energy of two diquarks with relative angular momentum $L=1$. Units are in MeV

Θ_q $2(-\frac{3}{4}\frac{C_B}{m_u^2}) + \Delta E_{L=1}$	uud $-\frac{3}{4}\frac{C_M}{m_u^2}$	$d\bar{q}_2$ $-\frac{3}{4}\frac{C_M}{m_u m_q}$	$\Theta_q - uud - d\bar{q}$
Θ_s	N	K	
$-290 + \Delta E_{L=1}$	−145	−286	$141 + \Delta E_{L=1}$
Θ_c	N	D	
$-290 + \Delta E_{L=1}$	−145	−95	$-50 + \Delta E_{L=1}$
Θ_b	N	B	
$-290 + \Delta E_{L=1}$	−145	−30	$-114 + \Delta E_{L=1}$

Table 7. Charm– and bottom–strange pentaquark baryons $\Theta_{qs}(udus\bar{q})$ ($q=c$ and b) with spin $S=1/2$. Units are in MeV

	N $-\frac{3}{4}\frac{C_M}{m_u^2}$	$s\bar{q}$ $-\frac{3}{4}\frac{C_M}{m_u m_q}$	$\Theta_{qs}-N-s\bar{q}$
Θ_{qs} $-\frac{3}{4}\frac{C_B}{m_u^2}-\frac{3}{4}\frac{C_B}{m_u m_s}$	Σ $\frac{1}{4}\frac{C_B}{m_u^2}-\frac{C_B}{m_u m_s}$	$d\bar{q}$ $-\frac{3}{4}\frac{C_M}{m_u m_q}$	$\Theta_{qs}-\Sigma-d\bar{q}$
	Λ $-\frac{3}{4}\frac{C_B}{m_u^2}$	$u\bar{q}$ $-\frac{3}{4}\frac{C_M}{m_u m_q}$	$\Theta_{qs}-\Lambda-u\bar{q}$
	N -145	D_s -57	$\Theta_{cs}-N-D_s$ -30
Θ_{cs} -232	Σ -67	D -95	$\Theta_{cs}-\Sigma-D$ -69
	Λ -145	D -95	$\Theta_{cs}-\Lambda-D$ 8
	N -145	B_s -18	$\Theta_{bs}-N-B_s$ -68
Θ_{bs} -232	Σ -67	B -30	$\Theta_{bs}-\Sigma-B$ -133
	Λ -145	B -30	$\Theta_{bs}-\Lambda-B$ -56

$T=200$ MeV. This is smaller than the experimental upper bound, and therefore further search is essential.

3 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}, Θ_{cs}, and Θ_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 $c\bar{c}$ 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 antiquark instead of a heavy quark, the probability to find a heavy antiquark or a heavy quark in a heavy ion collision is similar. The probability to form a T_{cc} compared to a J/ψ thus will only be suppressed by the additional statistical factor coming from combining an additional ud diquark.

3.1 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 [29, 30], which has been shown to describe very well the pion and proton transverse momentum spectra at intermediate momenta [31, 32] as well as at low momenta if resonances are included [33–35], and the yield and transverse momentum spectra of the phi meson and the Omega baryon [36] as well as the charmed meson [37]. We employ the formula that was previously used to calculate the yields of tetraquark $D_{sJ}(2317)$ meson [38] and pentaquark Θ^+ baryon [13] 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

$$N_{T_{cc}}^{\mathrm{coal}} = g_{T_{cc}} \int_{\sigma_{\mathrm{C}}} \prod_{i=1}^{4} \frac{p_i\,\mathrm{d}\sigma_i\,\mathrm{d}^3\mathbf{p}_i}{(2\pi)^3 E_i} f_q(x_i,p_i) \times f_{T_{cc}}^{W}(x_1,\ldots,x_4;p_1,\ldots,p_4)\,. \tag{2}$$

In the above, the color–spin–isospin factor $g_{T_{cc}} = 3\times 1/3^4 \times 1/2^4 = 1/432$ is the color–spin–isospin factor for the four quarks to form a hadron of the quantum number of the tetraquark meson and $\mathrm{d}\sigma$ denotes an element of a space-like hypersurface at hadronization. Assuming the Bjorken correlation $y=\eta$ between the space-time rapidity η 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:

$$N_{T_{cc}} \simeq \frac{1}{432}\frac{N_{\bar{c}}N_{\bar{c}}N_u N_d}{2} \prod_{i=1}^{3} \frac{\left(4\pi\sigma_i^2\right)^{3/2}}{V_{\mathrm{C}}\left(1+2\mu_i T_{\mathrm{C}}\sigma_i^2\right)}\,, \tag{3}$$

where $T_{\mathrm{C}}=170$ MeV is the critical temperature and V_{C} is the fireball volume at hadronization, which is about $1000\,\mathrm{fm}^3$ in central Au + Au collisions at $s_{NN}^{1/2} = 200$ GeV [38] and about $2700\,\mathrm{fm}^3$ in central Pb + Pb collisions at $s_{NN}^{1/2} = 5.5$ TeV [12]. 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 $N_u = N_d = 245$ [38] and 662 [12] 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 [12, 38]. In obtaining (3), we have used the quark momentum distribution function

$$f_q(x,p) = 6\delta(\eta - y)\exp\left(-\left(m_q^2 + p_\mathrm{T}^2\right)^{1/2}/T_\mathrm{C}\right) \quad (4)$$

and the tetraquark meson Wigner distribution function

$$f^W_{T_{cc}}(x;p) = 8^3 \exp\left(-\sum_{i=1}^{3}\frac{\mathbf{y}_i^2}{\sigma_i^2} - \sum_{i=1}^{3}\mathbf{k}_i^2\sigma_i^2\right), \quad (5)$$

where the relative coordinates $\mathbf{y}_i$ and momenta $\mathbf{k}_i$ are related to the quark coordinates $\mathbf{x}_i$ and momenta $\mathbf{p}_i$ by the Jacobian transformations defined in (7) and (8) of [38]. The width parameter σ_i in the Wigner function is related to the oscillator frequency ω by $\sigma_i = 1/\sqrt{\mu_i\omega}$ with the reduced masses μ_i defined in (9) of [38].

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 $\omega = 0.3$ GeV, determined from the size $\langle r^2_{D_s}\rangle_\mathrm{ch} \approx 0.124\,\mathrm{fm}^2$ of the $D_s^+(c\bar{s})$ meson based on the light-front quark model [39], the number of T_{cc} produced at RHIC and LHC is about 5.5×10^{-6} and 9.0×10^{-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 [38]

$$N^\mathrm{stat}_{T_{cc}} \approx \frac{V_H\gamma_\mathrm{C}^2}{(2\pi)^2}\int \mathrm{d}m_T\, m_T^2 \mathrm{e}^{-\frac{\bar{\gamma}_H m_T}{T_H}} I_0\left(\frac{\bar{\gamma}_H\bar{\beta}_H p_\mathrm{T}}{T_\mathrm{C}}\right), \quad (6)$$

where V_H and $\bar{\beta}_H$ are the volume and radial flow velocity of the formed hadronic matter, and γ_C is the fugacity parameter for ensuring that the number of charmed hadrons produced statistically at hadronization is same as the number of charm quarks in the quark–gluon plasma. With $V_H \approx 1908\,\mathrm{fm}^3$, $T_H = 175$ MeV, $\bar{\beta}_H = 0.3c$, and the charm fugacity $\gamma_\mathrm{C} \approx 8.4$ [38], we obtain $N_{T_{cc}} \sim 7.5\times10^{-4}$ in central Au + Au collisions at RHIC. The yield of T_{cc} increases to 8.6×10^{-3} in central Pb + Pb collisions at LHC, where we have used $V_H \approx 5220\,\mathrm{fm}^3$, $T_H = 175$ MeV, $\bar{\beta}_H = 0.47c$, and the charm fugacity $\gamma_\mathrm{C} \approx 16.3$ [12]. Compared to those from the coalescence model, predictions from the statistical model are almost two orders of magnitude larger.

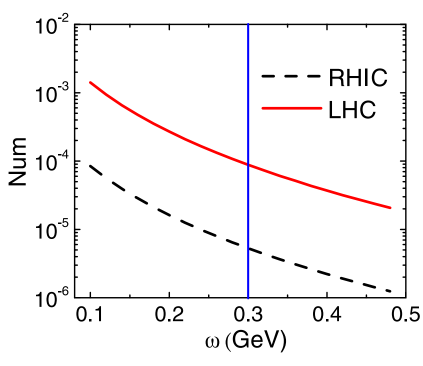

Fig. 1. Numbers of T_{cc} produced at RHIC and LHC as functions of the oscillator frequency used for the quark wave functions in T_{cc}

3.2 Charmed pentaquark baryons

For the yield of the pentaquark baryon $\Theta_{cs}(udus\bar{c})$, the coalescence model gives

$$N_{\Theta_{cs}} \simeq \frac{1}{3888} N_{\bar{c}} \frac{N_s N_u N_u N_d}{2} \prod_{i=1}^{4} \frac{\left(4\pi\sigma_i^2\right)^{3/2}}{V_\mathrm{C}\left(1 + 2\mu_i T_\mathrm{C}\sigma_i^2\right)}. \quad (7)$$

Using again the oscillator frequency $\omega = 0.3$ GeV and taking the antistrange quark numbers to be 150 [38] and 405 [12] at RHIC and LHC, respectively, the numbers of Θ_{cs} produced at RHIC and LHC are about 1.2×10^{-4} and 7.9×10^{-4}, respectively.

Since the predicted numbers of D_s mesons from the coalescence model are about 5.3×10^{-2} at RHIC and 0.58 at LHC, the estimated ratio of numbers of Θ_{cs} and D_s is about 2.3×10^{-3} at RHIC and LHC. This is consistent with the Boltzmann factor due to the uud component in Θ_{cs}. In fact, extracting the $s\bar{c}$ component from $udus\bar{c}$, the remaining $uud \sim N$ component has a Boltzmann factor $\mathrm{e}^{-m_N/T} \simeq 4.0\times10^{-3}$ with $T = 170$ MeV. A similar estimate also works for the case of the Λ and D in Θ_{cs}. Using the value 0.16 and 1.1 for the D meson numbers at RHIC and LHC, respectively, the calculated ratio of numbers between Θ_{cs} and D is about 0.74×10^{-3}, while the uds component has a Boltzmann factor of $\mathrm{e}^{-m_\Lambda/T} \simeq 1.4\times10^{-3}$.

In the statistical model, the yield of $\Theta_{\bar{c}s}$ is given by a formula similar to (6) except for the power in the charm fugacity parameter γ_C. Since there is only one charm quark in Θ_{cs}, the yield is only proportional to γ_C. Using same parameters for evaluating the yield of T_{cc}, we obtain 4.5×10^{-3} and 2.7×10^{-2} for Θ_{cs} produced in central Au + Au collisions at RHIC and central Pb + Pb collisions at LHC, respectively. These values are again significantly larger than those predicted from the coalescence model.

4 Decay modes of charmed exotics

In this section, we discuss the observable decay modes of the tetraquark T_{cc} and the pentaquark Θ_{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 in which the mass of T_{cc} is above or below the threshold, and we 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 $D^{*-}\bar{D}^0$

Table 8. Possible decay modes of T_{cc}. In the bottom row, we would observe the correlations $(K^+\pi^-)(K^+\pi^-)\pi^-$ and $(K^+\pi^+\pi^+\pi^-)(K^+\pi^-)\pi^-$ 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
$2M_D + M_\pi < M_{T_{cc}} < M_{D^*} + M_D$	$\bar{D}^0\bar{D}^0\pi^-$	hadronic decay
$M_{T_{cc}} < 2M_D + M_\pi$	$D^{*-}K^+\pi^-$, $D^{*-}K^+\pi^+\pi^-\pi^-$	0.41×10^{-12} s

Table 9. Possible decay modes of Θ_{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
	ΛD^-	hadronic decay
$M_{\Theta_{cs}} < M_\Lambda + M_D$	$\Lambda K^+\pi^-$, $\Lambda K^+\pi^+\pi^-\pi^-$	0.41×10^{-12} s
	$\Lambda K^+\pi^-\pi^-$	1.0×10^{-12} s

via a strong process.[1] For the T_{cc} below the threshold of D^*D and above $DD\pi$, the decay channel to $D^{*-}\bar{D}^0$ is energetically forbidden, but the D^{*-} component in T_{cc} can decay through a strong process, leading to the final decay mode $\bar{D}^0\bar{D}^0\pi^-$. 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 the $\bar{D}^0$ component in T_{cc} is allowed via $\bar{D}^0 \to K^+\pi^-$ 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 occur 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 $\bar{D}^0\pi^-$. Below the threshold of $DD\pi$, it may also be interesting to see the decay of D^{*-} component in T_{cc}. Considering that the D^{*-} component contains a quantum number of $\bar{D}^0\pi^-$, and $\bar{D}^0$ decays into $K^+\pi^-$ and $K^+\pi^+\pi^-\pi^-$, we may observe the $\bar{D}^0K^+\pi^+\pi^-$ and $\bar{D}^0K^+\pi^+\pi^+\pi^-\pi^-$ decays.

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 $(K^+\pi^-)(K^+\pi^+\pi^-\pi^-\pi^-)$, where brackets denote correlated particles. However, the $\bar{D}^0\bar{D}^0\pi^-$ 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 Θ_{cs} also has interesting decay patterns. As can be seen in Table 7, the mass of Θ_{cs} could be slightly above the $\Lambda\bar{D}^0$ 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 $\Lambda + \bar{D}^0$ final states. Since ALICE will be able to reconstruct the $\bar{D}^0$ through its hadronic decay, it will be an excellent opportunity to search for Θ_{cs}. Considering more general cases, and assuming Θ_{cs} to be above the threshold of ND_s, the Θ_{cs} can decay into pD_s^- and $\Lambda\bar{D}^0$ or ΛD^- via the strong process. Although the ΣD channel is also a possible decay mode, it is more difficult to detect as compared to ND_s and ΛD. When the mass of Θ_{cs} is below the ND_s and above the ΛD threshold, it decays only to $\Lambda\bar{D}^0$ or ΛD^-. On the other hand, below the threshold of ΛD, the hadronic decay channels are closed and only weak decays are possible. In this case, the lifetime of Θ_{cs} will depend on the lifetime of the different components inside the Θ_{cs}, such as the Λ, $\bar{D}^0$ and D^-, whose lifetimes are respectively 2.6×10^{-10}, 0.41×10^{-12} and 1.0×10^{-12} s. Therefore, once the Θ_{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 Θ_{cs} are in the order of 10^{-12} s, their decays occur outside the collision region and they are thus identifiable by vertex reconstruction. Therefore, T_{cc} and Θ_{cs} would be identified clearly in experiments if they exist. We summarize our results on possible decay modes of T_{cc} and Θ_{cs} in Tables 8 and 9.

Lastly, we comment on the possibility to measure doubly charmed baryons in heavy ion collisions. The doubly charmed baryon Ξ_{cc}^{++} have been observed by the SELEX Collaboration in the $\Lambda_c^+K^-\pi^+$ and in the pD^+K^- decay modes with a mass of (3518.7 ± 1.7) MeV [40, 41]. The same collaboration has also successfully measured Ξ_{cc}^+ in the $\Lambda_c^+K^-\pi^+\pi^+$ decay mode with a mass of 3460 MeV [42]. On the other hand, attempts by the FOCUS Collaboration in the photoproduction experiment and by the BABAR Collaboration in e^+e^- annihilation experiments [43, 44] 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 num-

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

ber of Ξ_{cc}^{+} produced are 1.9×10^{-5} at RHIC, and 3.2×10^{-4} at LHC. Therefore, we will be able to realistically measure Ξ_{cc}^{+} and Ξ_{cc}^{++} through their decay vertices to $\Lambda_c^+K^-\pi^+$ and pD^+K^-, and to $\Lambda_c^+K^-\pi^+\pi^+$, respectively.

5 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 Θ_{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 Θ_{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 1.9×10^{-5} and 3.2×10^{-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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References

1. R.J. Jaffe, Phys. Rev. D **15**, 267 (1977)
2. R.L. Jaffe, Phys. Rev. D **17**, 1444 (1978)
3. S. Zouzou, B. Silvestre-Brac, C. Gignoux, J.M. Richard, Z. Phys. C **30**, 457 (1986)
4. C. Semay, B. Silvestre-Brac, Z. Phys. C **61**, 271 (1994)
5. S.L. Zhu, arXiv:hep-ph/0703225
6. A.V. Manohar, M.B. Wise, Nucl. Phys. B **399**, 17 (1993)
7. A. De Rujula, H. Georgi, S.L. Glashow, Phys. Rev. D **12**, 147 (1975)
8. L.Y. Glozman, D.O. Riska, Phys. Rep. **268**, 263 (1996)
9. S. Pepin, F. Stancu, M. Genovese, J.M. Richard, Phys. Lett. B **393**, 119 (1997)
10. D.M. Brink, F. Stancu, Phys. Rev. D **57**, 6778 (1998)
11. S. Chernyshev, M.A. Nowak, I. Zahed, Phys. Rev. D **53**, 5176 (1996)
12. B.W. Zhang, C.M. Ko, W. Liu, arXiv:0709.1684 [nucl-th]
13. L.W. Chen, V. Greco, C.M. Ko, S.H. Lee, W. Liu, Phys. Lett. B **601**, 34 (2004)
14. C. Nonaka, B. Muller, M. Asakawa, S.A. Bass, R.J. Fries, Phys. Rev. C **69**, 031 902 (2004)
15. L. Maiani, A.D. Polosa, V. Riquer, C.A. Salgado, Phys. Lett. B **645**, 138 (2007)
16. B. Silvestre-Brac, C. Semay, Z. Phys. C **59**, 457 (1993)
17. F.S. Navarra, M. Nielsen, S.H. Lee, Phys. Lett. B **649**, 166 (2007)
18. LEPS Collaboration, T. Nakano et al., Phys. Rev. Lett. **91**, 012 002 (2003)
19. E. Hiyama, M. Kamimura, A. Hosaka, H. Toki, M. Yahiro, Phys. Lett. B **633**, 237 (2006)
20. F. Stancu, Phys. Lett. B **595**, 269 (2004)
21. F. Stancu, Phys. Lett. B **598**, 295 (2004) [Erratum]
22. F. Stancu, AIP Conf. Proc. **775**, 32 (2005)
23. R.L. Jaffe, F. Wilczek, Phys. Rev. Lett. **91**, 232 003 (2003)
24. K. Maltman, Phys. Lett. B **604**, 175 (2004)
25. Y. Sarac, H. Kim , S.H. Lee, Phys. Rev. D **73**, 014 009 (2006)
26. H.J. Lipkin, Phys. Lett. B **195**, 484 (1987)
27. E791 Collaboration, E.M. Aitala et al., Phys. Rev. Lett. **81**, 44 (1998)
28. E791 Collaboration, E.M. Aitala et al., Phys. Lett. B **448**, 303 (1999)
29. R. Mattiello, A. Jahns, H. Sörge, H. Stöcker, W. Greiner, Phys. Rev. Lett. **74**, 2180 (1995)
30. R. Mattiello, H. Sörge, H. Stöcker, W. Greiner, Phys. Rev. C **55**, 1443 (1997)
31. R.J. Fries, B. Müller, C. Nonaka, S.A. Bass, Phys. Rev. Lett. **90**, 202 303 (2003)
32. R.C. Hwa, C.B. Yang, Phys. Rev. C **67**, 034 902 (2003)
33. V. Greco, C.M. Ko, P. Lévai, Phys. Rev. Lett. **90**, 202 302 (2003)
34. V. Greco, C.M. Ko, P. Lévai, Phys. Rev. C **68**, 034 904 (2003)
35. V. Greco, C.M. Ko, R. Rapp, Phys. Lett. B **595**, 202 (2004)
36. L.W. Chen, C.M. Ko, Phys. Rev. C **73**, 044903 (2005)
37. V. Greco, C.M. Ko, R. Rapp, Phys. Lett. B **595**, 202 (2004)
38. L.W. Chen, C.M. Ko, W. Liu, M. Nielsen, Phys. Rev. C **76**, 014 906 (2007)
39. C.W. Hwang, Eur. Phys. J. C **23**, 585 (2002)
40. SELEX Collaboration, M. Mattson et al., Phys. Rev. Lett. **89**, 112 001 (2002)
41. SELEX Collaboration, A. Ocherashvili et al., Phys. Lett. B **628**, 18 (2005)
42. SELEX Collaboration, J.S. Russ, arXiv:hep-ex/0209075
43. S.P. Ratti, Nucl. Phys. Proc. Suppl. **115**, 33 (2003)
44. BABAR Collaboration, B. Aubert et al., Phys. Rev. D **74**, 011 103 (2006)