Λ_c Enhancement from Strongly Coupled Quark-Gluon Plasma

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We propose the enhancement of Λ_c as a novel quark-gluon plasma signal in heavy ion collisions at the BNL Relativistic Heavy Ion Collider and the CERN Large Hadron Collider. Assuming a stable bound diquark state in the strongly coupled quark-gluon plasma near the critical temperature, we argue that the direct two-body collision between a c quark and a $[ud]$ diquark would lead to an enhanced Λ_c production in comparison with the normal three-body collision among independent c, u, and d quarks. In the coalescence model, we find that the Λ_c/D yield ratio is enhanced substantially due to the diquark correlation.

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The quark-gluon plasma (QGP) is one of the most actively pursued subjects in strong interaction physics. Recent experimental and theoretical studies have revealed intriguing properties of QGP. These range from the realization of the perfect fluid behavior [1] and consequently of the strong coupling nature of QGP [2] to the lattice findings suggesting that the $c\bar{c}$ bound state could survive up to temperatures well above the critical temperature T_C [3,4]. Thus a new picture of QGP with nontrivial correlations has emerged, and this state is nowadays called the strongly coupled QGP [4–6].

Although the lattice QCD indicates the absence of $q\bar{s}$ bound states in QGP [7], the color nonsinglet qq, qg, gg bound states may exist if there are attractive channels between the constituents [6]. Among them, the diquark qq with color multiplets $\bar{\mathbf{3}}_c$ and $\mathbf{6}_c$ is the simplest one [8]. In flavor $SU(3)_f$, the $\bar{\mathbf{3}}_c$ diquarks are classified into a scalar with $\bar{\mathbf{3}}_f$ ("good" diquark) and a vector with $\mathbf{6}_f$ ("bad" diquark) [8], which are in the attractive and repulsive channels, respectively, according to the one-gluon exchange (OGE) picture. Concerning $\mathbf{6}_c$, the diquarks belong to either the scalar with $\mathbf{6}_f$ or the vector with $\bar{\mathbf{3}}_f$. Although the latter is in an attractive channel, its strength is only one-sixth of that in the attractive $\bar{\mathbf{3}}_c$ state according to the OGE. Recent lattice calculations support the diquark correlation in vacuum [9].

The diquark not only has relevance to the color superconductivity at high density [10] and to the Bose-Einstein condensate in the strong coupling regime [11] but also is an interesting object for understanding heavy baryons Qqq with one heavy quark $Q = c, b$ and two light quarks $q = u, d$ [12]. Generally, in the heavy quark mass limit, the light quarks are almost decoupled from the heavy quark [12], as the Qq color-spin interaction is suppressed in OGE by the heavy quark mass [13] and in the instanton model by the small coupling between the heavy quark and the instanton vacuum as a result of the absence of zero-energy modes [14]. Therefore, Qqq baryons only have a strong correlation within the light quark sector as in the conventional diquark model [15–19] and in models that treat the triquark $q\bar{q}\bar{q}$ in exotic D_s mesons as a color nonsinglet state [12,20]. In this viewpoint, Λ_c (Λ_b) can be regarded as an ideal two-body system composed of the c (b) quark and the $[ud]$ diquark, i.e., $c[ud]$ ($b[ud]$). In contrast, the Λ with an s quark may not be such a simple quark-diquark system because $SU(3)_f$ symmetry allows interactions among the three quarks.

In heavy ion collisions, open and hidden charmed hadrons are interesting observables for studying the QGP [21], particularly at the CERN Large Hadron Collider (LHC) as an appreciable number of $c\bar{c}$ pairs is expected to be produced. Moreover, the ALICE detector at LHC is designed to measure charmed particles with enhanced vertex tracking system, which has a spatial resolution of 12 μm with the best precision [22]. For the planned upgrade of STAR and PHENIX detectors at the BNL Relativistic Heavy Ion Collider (RHIC), additional vertex detectors will be added to achieve direct vertex reconstruction of charmed particles [23,24]. With such precise measurement of the vertices, even the measurement of open and hidden bottomed hadrons is possible.

The existence of diquark correlations in QGP can be probed by studying their effects on Λ_c production in relativistic heavy ion collisions [25]. One of the important findings from RHIC is that a new hadronization mechanism, based on the coalescence of constituent quarks, is operative in heavy ion collisions [26–30]. Here, instead of fragmentation, hadronization takes place by the recombination of partons in QGP or by their collisions into final hadrons. The coalescence model has been quite successful in describing the pion and proton transverse momentum spectra at intermediate momenta as well as at low momenta if resonances are included [31]. It also gives a natural account for the observed constituent quark number scaling of hadron elliptic flows [32] and the large elliptic flow of charmed mesons [33]. In such a picture, the Λ_c is formed from the three-body collisions among the c, u, and d quarks at the critical temperature of QGP. If there are strong diquark correlations in QGP at this temperature, then Λ_c could be additionally formed from the two-body collisions between the c quark and the $[ud]$ diquark. Here, the diquark structure in Λ_c is essential to the direct two-body production of Λ_c because additional process is needed to break up the diquark correlation if the diquark is absent inside Λ_c. Since the two-body collision generally dominates over multibody collisions we thus expect an enhanced Λ_c yield in heavy ion collisions if there are diquark correlations, and this could be a new signal for the search of the QGP.

The binding energy of the lightest scalar $\bar{\mathbf{3}}_f$ and $\bar{\mathbf{3}}_c$ $[ud]$ diquark can be estimated using a simplified constituent quark model based on the color-spin interaction. This model has been shown to describe very well the mass differences between various hadrons including the charmed ones [34]. In vacuum, the color-spin interaction between two quarks gives the $[ud]$ diquark mass as $m_{[ud]} = m_u + m_d - C\vec{s}_u \cdot \vec{s}_d / m_u m_d$ with the quark mass $m_u = m_d = 0.3$ GeV, the spin operator $\vec{s}_i$ $(i = u, d)$, and a constant $C/m_u^2 = 0.193$ GeV fitted to the $N - \Delta$ splitting [34]. The color-spin interaction effectively contains the nonperturbative dynamics in vacuum, and hence gives the maximum binding energy 0.145 GeV of the diquark in the strong coupling limit. The diquark mass is, however, expected to increase in QGP where the coupling would become smaller than that in vacuum. In the analysis of Ref. [6], the zero binding of diquark occurs slightly above T_C. Since the strength of the color-spin interaction is of the same order as the critical temperature $T_C \simeq 0.17$ GeV, the diquark correlation could still be present near T_C. Therefore, we use the diquark mass ranging from $m_{[ud]} = 0.455$ GeV for the maximum binding to $m_{[ud]} = 0.6$ GeV for the threshold.

For the dynamics of heavy ion collisions, we follow the expanding fire-cylinder model, which leads to the volume $V_C \simeq 1000\ \mathrm{fm}^3$ in central Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV [35] and $V_C \simeq 2700\ \mathrm{fm}^3$ in central Pb + Pb collisions at $\sqrt{s_{NN}} = 5.5$ TeV [36]. At $T_C = 0.175$ GeV, the equilibrium light quark numbers in QGP are $N_u = N_d \simeq 245$ [35] and 662 [36] in collisions at RHIC and LHC, respectively, all in one unit of midrapidity. The equilibrium diquark numbers at RHIC and LHC for this temperature are estimated as $N_{[ud]} \simeq 77$ and 208, respectively, for $m_{[ud]} = 0.455$ GeV, and $N_{[ud]} \simeq 44$ and 119, respectively, for $m_{[ud]} = 0.6$ GeV. For the charm quark number at the phase transition temperature, we take it to be the same as that produced from the initial hard scattering of nucleons in the colliding nuclei, and their numbers in one unit of midrapidity are $N_c \simeq 3$ and 20, respectively, at RHIC [35] and LHC [36]. We thus neglect charm production from QGP, which is unimportant at RHIC but could be significant at LHC if the initial temperature of QGP is high [36]. The charm quarks are assumed to reach thermal equilibrium in QGP, and this is consistent with the observed large elliptic flow of the electrons from the decay of charmed mesons in heavy ion collisions at RHIC [37,38], which requires that charm quarks interact strongly in QGP and are thus likely to reach thermal equilibrium [39–41].

For coalescence of c quarks with independent or uncorrelated u and d quarks in QGP, the contribution to the number of produced Λ_c is given by [35,42]

$$N^{\mathrm{coal}}_{\Lambda_c(cud)} = g_{\Lambda_c(cud)} \int_{\sigma_C} \prod_{i=1}^{n=3} \frac{p_i d\sigma_i d^3\mathbf{p}_i}{(2\pi)^3 E_i} f_q(x_i, p_i) \times f^W_{\Lambda_c}(x_1, \ldots, x_n; p_1, \ldots, p_n), \quad (1)$$

where $g_{\Lambda_c(cud)} = 2 \times 1/3^3 \times 1/2^3 = 1/108$ is the color-spin-isospin factor for the three quarks to form Λ_c, and $d\sigma$ denotes an element of a spacelike hypersurface of QGP at hadronization. Following Ref. [35], we adopt the u and d as well as the c quark momentum distribution function $f_q(x, p)$ with Bjorken correlation between the space-time rapidity and the momentum-energy rapidity, and the Λ_c Wigner distribution function $f^W_{\Lambda_c(cud)}(x; p) = 8^2 \exp(-\sum_{i=1}^2 \mathbf{y}_i^2/\sigma_i^2 - \sum_{i=1}^2 \mathbf{k}_i^2 \sigma_i^2)$, 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 Eqs. (7) and (8) of Ref. [35]. 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 Eq. (9) of Ref. [35]. Neglecting the transverse flow as well as using the nonrelativistic approximation, we obtain [35]

$$N^{\mathrm{coal}}_{\Lambda_c(cud)} \simeq g_{\Lambda_c(cud)} N_c N_u N_d \prod_{i=1}^{2} \frac{(4\pi\sigma_i^2)^{3/2}}{V_C(1 + 2\mu_i T_C \sigma_i^2)}. \quad (2)$$

We note that the Wigner function of Λ_c used in the above does not take into account the $[ud]$ diquark correlation. This correlation would reduce the width parameter for the relative wave function of u and d quarks. Because the number of produced Λ_c is proportional to the third power of the width parameter, treating u and d as independent quarks in the Λ_c thus gives an upper bound for the yield of Λ_c from the coalescence of three independent c, u, and d quarks in QGP.

The contribution from coalescence of c quarks with $[ud]$ diquarks in QGP to the number of Λ_c can be obtained by setting $n = 2$ in Eq. (1), and replacing the Wigner function of Λ_c by $f^W_{\Lambda_c(c[ud])}(x; p) = 8 \exp(-\mathbf{y}^2/\sigma^2_{c[ud]} - \mathbf{k}^2 \sigma^2_{c[ud]})$, where $\mathbf{y}$ and $\mathbf{k}$ are the relative coordinate and momentum for the two-body $c[ud]$ system, and $\sigma_{c[ud]} = 1/\sqrt{\mu_{c[ud]}\omega}$ with $\mu_{c[ud]} = m_c m_{[ud]}/(m_c + m_{[ud]})$. Then the result is

$$N^{\rm coal}_{\Lambda_c(c[ud])} \simeq g_{\Lambda_c(c[ud])} N_c N_{[ud]} \frac{(4\pi\sigma^2_{c[ud]})^{3/2}}{V_C(1+2\mu_{c[ud]}T_C\sigma^2_{c[ud]})}, \tag{3}$$

with $g_{\Lambda_c(c[ud])} = 2 \times 1/3^2 \times 1/2 = 1/9$. Contrary to the coalescence of independent c, u, and d quarks from QGP, where the $[ud]$ diquark substructure of Λ_c is neglected, it is here considered as a single entity as assumed for the $[ud]$ diquark in QGP. The effect of finite structure of the $[ud]$ diquark in both QGP and Λ_c is expected to reduce the yield of Λ_c in comparison to that obtained from Eq. (3). The latter thus also gives an upper bound for Λ_c production in the diquark picture.

The total yield of Λ_c is given by the sum of above two contributions, i.e., $N^{\rm coal}_{\Lambda_c} = N^{\rm coal}_{\Lambda_c(cud)} + N^{\rm coal}_{\Lambda_c(c[ud])}$. The Λ_c yield can be compared with the D meson yield, which is not affected by the ud diquark correlation and is determined by an equation similar to Eq. (3) using instead the statistical factor $g_{D^0} = 1 \times 1/3^2 \times 1/2^2 = 1/36$, the u quark number N_u, the reduced mass $\mu_{cu} = m_c m_u/(m_c + m_u)$, and the oscillator constant $\sigma_{cu} = 1/\sqrt{\mu_{cu}\omega}$.

Using the oscillator frequency $\omega = 0.3$ GeV, determined from the size $\langle r^2_{D_s}\rangle_{ch} \simeq 0.124\ {\rm fm}^2$ of the $D_s^+(c\bar{s})$ meson based on the light-front quark model [43], the resulting yield ratio $N^{\rm coal}_{\Lambda_c}/N^{\rm coal}_{D^0}$ (Λ_c/D^0), which is the same in heavy ion collisions at RHIC and LHC, is plotted in Fig. 1 as a function of the hadronization temperature. It is seen that the yield ratio Λ_c/D^0 at $T_C = 0.175$ GeV is $\simeq 0.11$ without diquarks in QGP (dashed line), and it increases to $\simeq 0.44$ in the presence of the diquark $[ud]$ with mass $m_{[ud]} = 0.6$ GeV (thin solid line), corresponding to a loosely bound state which can hardly exist near T_C. If the diquark mass has the minimum value $m_{[ud]} = 0.455$ GeV (bold solid line), the Λ_c/D^0 ratio becomes even larger and has a value of about 0.89 at T_C. Therefore, the diquarks in QGP raise the Λ_c/D^0 ratio by about a factor 4–8 in comparison with the case without diquarks. For a QGP with a finite baryon chemical potential, there are more quarks than antiquarks and this would lead to a reduction of the D^0 yield and an increase of the Λ_c/D^0 ratio. The expected enhancement of Λ_c/D^0 ratio is still seen if we change the size of Λ_c by a reasonable amount. Because the enhanced Λ_c/D^0 ratio is robust with respect to changes in the binding energy of the diquark and the size of Λ_c, more sophisticated models are not expected to modify our conclusion.

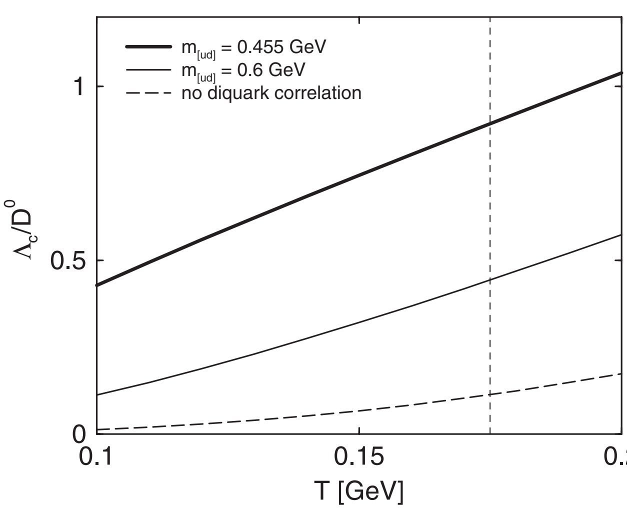

FIG. 1. The yield ratios Λ_c/D^0 as functions of temperature.

From a simple application of the statistical hadronization model [44], the yield ratio Λ_c/D^0 is roughly estimated as $2(m_{\Lambda_c}/m_{D_0})^{3/2}\exp(-(m_{\Lambda_c} - m_{D^0})/T_C) \simeq 0.24$ at the hadronization temperature of $T_C = 0.175$ GeV [34]. Although this value is a factor of 2 larger than that from the above three-body coalescence of independent c, u, and d quarks, it is smaller than the case that includes diquarks. A smaller production ratio is also observed in elementary processes. In $p + p$ collisions, 1630 Λ_c's and 10 210 D^0's have been measured by SELEX at Fermi Lab, and this gives a yield ratio $\Lambda_c/D^0 \simeq 0.159$ [45]. In inclusive decay processes of a B meson, the ratios are $\Lambda_c/D^0 \simeq 0.03$ and $\Lambda_c/D^- \simeq 0.14$ from the measured fractions: 79% of $\bar{D}^0X$ and 2.8% of $\bar{\Lambda}_c^-X$ in the B^+ decay, and 36.9% of D^-X and 5.0% of $\bar{\Lambda}_c^-X$ in the B^0 decay, with arbitrary hadrons X [46]. Since these experimental ratios include Λ_c and D^0 from decays of charmed resonances, a more quantitative comparison requires the inclusion of the resonances contribution in both the statistical and the coalescence model [47].

The Λ_c produced in QGP may change into a D meson in the hadronic phase due to collisions such as $\Lambda_c\pi \rightarrow ND(D^*)$. With the pion threshold momentum $p_{\rm th} \simeq 0.43$ GeV in the $\Lambda_c\pi \rightarrow ND$ process, which is larger than the typical energy scale T_C, the conversion time due to this process is estimated as $1/\tau = \Gamma_{\rm th} = 3\int_{p_{\rm th}}^{\infty}\sigma n(p)d^3p/(2\pi)^3$, with 3 being the isospin factor, σ the cross section, and $n(p) \simeq \exp(-\sqrt{p^2 + m_\pi^2}/T)$. With $\sigma = 5$ mb as a reasonable value suggested from the J/ψ dissociation [48] and $T = T_C$ for simplicity, we obtain $\tau \simeq 17.8$ fm, which is comparable with the lifetime of the hadronic phase $t_H \simeq 10$ fm [42], leading to a suppression factor $e^{-t_H/\tau} \simeq 0.57$ for the Λ_c yield. Since the temperature in the hadronic phase is lower than T_C, the actual suppression factor will be closer to 1. Therefore, the Λ_c enhancement is expected to survive the hadronic processes.

In summary, assuming the existence of stable bound diquarks in the strongly coupled QGP, we have discussed the enhancement of the Λ_c yield in heavy ion collisions, which is induced by the two-body collision between the c quark and the $[ud]$ diquark. The Λ_c enhancement would open a new way to find the existence of QGP in heavy ion collisions and also provide an experimental tool to probe the diquark correlation in QGP. This would, in turn, confirm the diquark structure in heavy baryons with a single heavy quark. It is interesting to note that the observed suppression of the D meson yield at RHIC [37,38] could be partially a consequence of the enhanced production of Λ_c [49].

Our study can be straightforwardly extended to Λ_b production. Using the bottom quark production cross sections predicted from the perturbative QCD for $p + p$ collisions at RHIC [50] and LHC [51], we estimate the bottom quark numbers in one unit of midrapidity for corresponding heavy ion collisions to be ~0.02 and ~0.8, respectively. This leads to Λ_b/B^0 ratios of 0.098, 0.38, and 0.82 for the three scenarios of no diquark correlation and diquark masses of 0.6 and 0.45 GeV, respectively. As in the case of Λ_c, the diquark correlation gives rise to a large enhancement in the Λ_b/B_0 ratio in heavy ion collisions. Although the yield of Λ_b in these collisions is much smaller than that of Λ_c, its enhancement is a better signal to be detected for QGP as the diquark picture would be more valid than in Λ_c, and its much longer lifetime ($\tau \simeq$ 372 μm) than that of Λ_c ($\tau \simeq 62$ μm) will also facilitate its detection. To study the enhancement of Λ_c and Λ_b production is thus an interesting and challenging subject at RHIC and LHC.

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