**Λ_c enhancement from strongly coupled quark-gluon plasma**

Su Houngh Lee, Kazuaki Ohnishi, Shigehiro Yasui, In-Kwon Yoo and Che Ming Ko

1Institute of Physics and Applied Physics, Yonsei University, Seoul 120-749, Republic of Korea
2Department of Physics, National Taiwan University, Taipei 10617, Taiwan
3Pusan National University, Pusan 609-735, Republic of Korea
4Cyclotron Institute and Physics Department, Texas A&M University, College Station, TX 77843, U.S.A.

We propose the enhancement of Λ_c as a novel QGP signal in heavy ion collisions at RHIC and LHC. Assuming a stable bound diquark state in the strongly coupled QGP 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.

PACS numbers: 12.38.Mh, 14.20.Lq, 12.38.Qk

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 c̄c bound state could survive up to temperatures well above the critical temperature \[3\]. Thus a new picture of QGP with non-trivial correlations has emerged, and this state is nowadays called the strongly coupled QGP (sQGP) \[4, 5, 6\].

Although the lattice QCD indicates the absence of q̅q bound states in QGP \[4\], the color non-singlet qq, qg, gg bound states may exist if there are attractive channels between the constituents \[4\]. Among them, the diquark q̅q with color multiplets 3_c and 6_c is the simplest one \[5\]. In flavor SU(3)_f, the 3_c diquarks are classified into a scalar with \[\bar{3}_c\] (= “good” diquark) and a vector with \[6_c\] (“bad” diquark) \[6\], which are in the attractive and repulsive channels, respectively, according to the one-gluon exchange (OGE) picture. Concerning 6_c, the diquarks belong to either the scalar with \[6_f\] or the vector with \[\bar{6}_c\]. Although the latter is in an attractive channel, its strength is only one-sixth of that in the attractive \[3_c\] state according to the OGE. Recent lattice calculations support the diquark correlation in vacuum \[6\].

The diquark not only has relevance to the color superconductivity at high density \[10\] and to the Bose-Einstein Condensate (BEC) in the strong coupling regime \[11\] but also is an interesting object for understanding heavy baryons Qqq with one heavy quark \(Q = c, b, d\) 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 with the light quark sector as in the conventional diquark model \[15\] and in models that treat the triquark q̅q̅q in exotic \(D_s\) mesons as a color non-singlet 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 LHC as an appreciable number of c̄c 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 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 RHIC is that a new hadronization mechanism, based on the coalescence of constituent quarks, is operative in heavy ion collisions \[26, 27, 28, 29, 30\]. 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 \(\Lambda_c\) is essential to the direct two-body production of \(\Lambda_c\), because additional process is needed to break up the diquark correlation if the diquark is absent inside \(\Lambda_c\). Since the two-body collision generally dominates over multi-body collisions we thus expect an enhanced \(\Lambda_c\) 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 3\(_c\) and 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 \(m_{[ud]} = m_u + m_d - C\delta_u \cdot \delta_d/m_au/ma\), with the quark mass \(m_u = m_d = 0.3\) GeV, the spin operator \(\delta_i \equiv (u, d)\), and a constant \(C/m_\sigma^2 = 0.193\) GeV fitted to the \(N-\Delta\) splitting [34]. The color-spin interaction effectively contains non-perturbative 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. [3], 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 \(T_c \approx 0.17\) 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 \(V_C \approx 1000\) fm\(^3\) in central Au+Au collisions at \(\sqrt{s_{NN}} = 200\) GeV [33] and \(V_C \approx 2700\) fm\(^3\) in central Pb+Pb collisions at \(\sqrt{s_{NN}} = 5.5\) TeV [39]. At \(T_C = 0.175\) GeV, the equilibrium light quark numbers in QGP are \(N_u = N_d = 245\) [32] and 662 [30] 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 \(N_{[ud]} \approx 77\) and 208, respectively, for \(m_{[ud]} = 0.455\) GeV, and \(N_{[ud]} \approx 44\) 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 \(N_c \approx 3\) and 20, respectively, at RHIC [32] and LHC [30]. 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 [33]. 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, 40, 41].

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

\[
N_{\text{coal}} \approx g_{\Lambda_c} \int_{\sigma_C} n_{p_i} \frac{d\sigma_{[ud]}^p}{p_1} f_q(x_i, p_i) \times f_W^1(x_1, x_2; p_1, p_2),
\]

where \(g_{\Lambda_c} = 2 \times 1/3 \times 1/2 = 1/108\) is the color-spin-isospin factor for the three quarks to form \(\Lambda_c\), and \(d\sigma\) denotes an element of a space-like hypersurface of QGP at hadronization. Following Ref. [33], 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 \(\Lambda_c\) Wigner distribution function \(f_W^1(x_i; p) = 8\exp(-\sum_{i=1}^{2} x_i^2/\sigma_i^2 - \sum_{i=1}^{2} k_i^2/\sigma_i^2)\), where the relative coordinates \(x_i\) 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. [35]. Neglecting the transverse flow as well as using the non-relativistic approximation, we obtain [32]:

\[
N_{\text{coal}} \approx g_{\Lambda_c} N_c N_u N_d \prod_{i=1}^{2} \frac{(4\pi \sigma_i^2)^{3/2}}{V_C (1 + 2 \mu_i T_C \sigma_i^2)}.
\]

We note that the Wigner function of \(\Lambda_c\) 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 \(\Lambda_c\) is proportional to the third power of the width parameter, treating \(u\) and \(d\) as independent quarks in the \(\Lambda_c\) thus gives an upper bound for the yield of \(\Lambda_c\) 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 \(\Lambda_c\) can be obtained by setting \(n = 2\) in Eq. (11), and replacing the Wigner function of \(\Lambda_c\) by \(f_W^1\) for \(f_W^1\) [\(|ud|\)] \(x; p) = 8\exp(-y^2/\sigma^2_{[ud]} - k^2/\sigma^2_{[ud]}),\) where \(y\) and \(k\) are the relative coordinate and momentum for the two-body \([ud]\) system, and \(\sigma_{[ud]} = 1/\sqrt{m_{[ud]} \sigma}\) with \(m_{[ud]} = m_{[ud]}/(m_c + m_{[ud]})\). Then the result is

\[
N_{\text{coal}} \approx g_{\Lambda_c} N_c N_{[ud]} \frac{(4\pi \sigma_{[ud]}^2)^{3/2}}{V_C (1 + 2 \mu_{[ud]} T_C \sigma_{[ud]}^2)}
\]

with \(g_{\Lambda_c} \approx 2 \times 1/3\), because the coalescence of independent \(c\), \(u\), and \(d\) quarks from QGP, where the \([ud]\) diquark substructure of \(\Lambda_c\) 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 $\Lambda_c$ is expected to reduce the yield of $\Lambda_c$ in comparison to that obtained from Eq. (3). The latter thus also gives an upper bound for $\Lambda_c$ production in the diquark picture.

The total yield of $\Lambda_c$ is given by the sum of above contributions, i.e., $N_{\Lambda_c} = N_{\Lambda_c(\text{cd})} + N_{\Lambda_c(\text{cu})}$. The $\Lambda_c$ 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 hadronization process. From a simple application of the statistical hadronization model [44], the yield ratio $\Lambda_c/D^0$ is roughly estimated as $2(m_{\Lambda_c}/m_{D^0})^{3/2} \exp(-m_{\Lambda_c}-m_{D^0})/T(c) \approx 0.24$ at the hadronization temperature of $T_c = 0.175$ GeV [34]. Although this value is a factor of two 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 $\Lambda_c$’s and 10210 $D^0$’s have been measured by SELEX at Fermi Lab, and this gives a yield ratio $\Lambda_c/D^0 \approx 0.159$ [45]. In inclusive decay processes of a $B$ meson, the ratios are is $\Lambda_c/D^0 \approx 0.03$ and $\Lambda_c/D^\pm \approx 0.14$ from the measured fractions: 79% of $D^0X$ and 28% of $\Lambda^-X$ in the $B^+$ decay, and 36.9% of $D^-X$ and 5.0% of $\Lambda^-X$ in the $D^0$ decay, with arbitrary hadrons $X$ [46]. Since these experimental ratios include $\Lambda_c$ 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 $\Lambda_c$ produced in QGP may change into a $D$ meson in the hadronic phase due to collisions such as $\Lambda_c\pi \rightarrow ND(D^\ast)$. With the pion threshold momentum $p_{th} \approx 0.43$ 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 $\tau = 1/T_c = 3\int p_{th}^\infty \sigma(p)(d^3p/2\pi)^3$, with $\sigma$ the cross section, and $n(p) \approx \exp(-\sqrt{p^2+m_B^2}/T)$. With $\sigma = 5$ mb as a reasonable value suggested from the $J/\psi$ dissociation [48] and $T = T_c$ for simplicity, we obtain $\tau \approx 17.8$ fm, which is comparable with the lifetime of the hadronic phase $\tau_H \approx 10$ fm [12], leading to a suppression factor $e^{-\tau_H/\tau} \approx 0.57$ for the $\Lambda_c$ yield. Since the temperature in the hadronic phase is lower than $T_c$, the actual suppression factor will be closer to one. Therefore, the $\Lambda_c$ 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 $\Lambda_c$ yield in heavy ion collisions, which is induced by the two-body collision between the $c$ quark and the $[ud]$ diquark. The $\Lambda_c$ 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 [35,38] could be partially a consequence of the enhanced production of $\Lambda_c$ [40].

Our study can be straightforwardly extended to $\Lambda_b$ production. Using the bottom quark production cross sections predicted from the perturbative QCD for $p+p$ production at RHIC [50] and LHC [51], we estimate the bottom quark numbers in one unit of midrapidity for corresponding heavy ion collisions to be $\approx 0.02$ and $\approx 0.8$,
respectively. This leads to $\Lambda_b/B^0$ 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 $\Lambda_c$, the diquark correlation gives rise to a large enhancement in the $\Lambda_b/B^0$ ratio in heavy ion collisions. Although the yield of $\Lambda_b$ in these collisions is much smaller than that of $\Lambda_c$, its enhancement is a better signal to be detected for QGP as the diquark picture would be more valid than in $\Lambda_c$, and its much longer lifetime ($\tau \approx 372\mu$m) than that of $\Lambda_c$ ($\tau \approx 62\mu$m) will also facilitate its detection. To study the enhancement of $\Lambda_c$ and $\Lambda_b$ production is thus an interesting and challenging subject at RHIC and LHC.

We thank Yongseok Oh for helpful discussions. The work was supported by the Korea Research Foundation KRF-2006-C00011 and KRF-2007-313-C00175, and the US National Science Foundation under Grant No. PHY-0457265 and the Welch Foundation under Grant No. A-1358.

[1] D. Teaney et al., Phys. Rev. Lett. 86, 4783 (2001); P. F. Kolb et al., Phys. Lett. B 500, 232 (2001).
[2] G. Policastro et al., Phys. Rev. Lett. 87, 081601 (2001).
[3] S. Datta et al., Nucl. Phys. Proc. Suppl. 119, 487 (2003).
[4] M. Asakawa and T. Hatsuda, Phys. Rev. Lett. 92, 012001 (2004).
[5] T. Hatsuda and T. Kunihiro, Phys. Rev. Lett. 55, 158 (1985).
[6] E. V. Shuryak and I. Zahed, Phys. Rev. C 70, 021901 (2004); Phys. Rev. D 70, 054507 (2004).
[7] V. Koch et al., Phys. Rev. Lett. 95, 182301 (2005).
[8] R. L. Jaffe, Phys. Rev. D 15, 267 (1977); R. L. Jaffe and F. Wilczek, Phys. Rev. Lett. 91, 232003 (2003).
[9] C. Alexandrou et al., Phys. Rev. Lett. 97, 222002 (2006).
[10] M. G. Alford et al., Phys. Lett. B 422, 247 (1998); R. Rapp et al., Phys. Rev. Lett. 81, 53 (1998).
[11] Y. Nishida and H. Abuki, Phys. Rev. D 72, 096004 (2005).
[12] R. L. Jaffe, Phys. Rept. 409, 1 (2005) [Nucl. Phys. Proc. Suppl. 142, 343 (2005)]; Phys. Rev. D 72, 074508 (2005).
[13] A. De Rujula et al., Phys. Rev. D 12, 147 (1975).
[14] M. Oka and S. Takeuchi, Phys. Rev. Lett. 63, 1780 (1989); Nucl. Phys. A 524, 649 (1991).
[15] M. Gell-Mann, Phys. Lett. 8, 214 (1964); M. Ida and R. Kobayashi, Prog. Theor. Phys. 36 (1966) 846; D. B. Lichtenberg and L. J. Tassie, Phys. Rev. 155 (1967) 1601.
[16] D. B. Lichtenberg et al., Phys. Rev. Lett. 48, 1653 (1982).
[17] C. Semay and B. Silvestre-Brac, Z. Phys. C 61, 271 (1994).
[18] D. Ebert et al., Z. Phys. C 71, 329 (1996).
[19] E. Santopinto, Phys. Rev. C 72, 022201 (2005).
[20] S. Yasui and M. Oka, Phys. Rev. D 76, 034009 (2007).
[21] T. Matsui and H. Satz, Phys. Lett. B 178, 416 (1986).
[22] “ALICE Technical Design Report of the Inner Tracking System (ITS)”, CERN / LHCC 99-12, ALICE TDR 4, 1999.
[23] http://www.star.bnl.gov/STARcentral/presentations/Hep2007/rlcigars/Thomas_Jim.pdf
[24] http://www.phenix.bnl.gov/phenix/WWW/publish/adion/HEP2007/Alan_Dion_HEP2007.pdf
[25] K. S. Sateesh, Phys. Rev. D 45, 866 (1992).
[26] T. S. Biró et al., Phys. Lett. B 347, 6 (1995); Phys. Rev. C 59, 1574 (1999); P. Lévai et al., New J. Phys. 2, 32 (2000).
[27] D. Molnar and S. A. Voloshin, Phys. Rev. Lett. 91, 092301 (2003).
[28] R. C. Hwa and C. B. Yang, Phys. Rev. C 67, 034902 (2003).
[29] V. Greco et al., Phys. Rev. Lett. 90, 202302 (2003); Phys. Rev. C 68, 034904 (2003).
[30] R. J. Fries et al., Phys. Rev. Lett. 90, 202303 (2003).
[31] V. Greco and C. M. Ko, Phys. Rev. C 70, 024901 (2004).
[32] P. R. Kolb et al., Phys. Rev. C 69, 051901(R) (2004).
[33] V. Greco et al., Phys. Lett. B 595, 202 (2004).
[34] S. H. Lee et al., Phys. Rev. D 65, 014906 (2005).
[35] B. W. Zhang et al., Phys. Rev. C 77, 024901 (2008).
[36] S. S. Adler et al. [PHENIX Collaboration], Phys. Rev. C 72, 024901 (2005).
[37] F. Lane (for the STAR Collaboration), J. Phys. G 31, S27 (2005).
[38] B. Zhang, L. W. Chen and C. M. Ko, Phys. Rev. C 72, 024906 (2005); Nucl. Phys. A 774, 665 (2006).
[39] H. van Hees and R. Rapp, Phys. Rev. C 71, 034907 (2005).
[40] D. Molnar, J. Phys. G 31, S421 (2005).
[41] L. W. Chen et al., Phys. Lett. B 601, 34 (2004).
[42] C. W. Hwang, Eur. Phys. J. C 33, 585 (2002).
[43] A. Andronic et al., [arXiv:0708.1488] [nucl-th].
[44] A. Kushnirenko et al. [SELEX Collaboration], Phys. Rev. Lett. 86, 5243 (2001).
[45] W. M. Yao et al. [Particle Data Group], J. Phys. G 33, 1 (2006).
[46] S. Yasui et al., to be published.
[47] W. Liu et al., Phys. Rev. C 65, 015203 (2002); Y. Oh et al., Phys. Rev. C 75, 064903 (2007).
[48] P. Sorenson and X. Dong, Phys. Rev. C 74, 024902 (2006); G. Martinez-García et al., arXiv:hep-ph/0710.2152.
[49] M. Cacciari et al., Phys. Rev. Lett. 95, 122001 (2005).
[50] A. Accardi et al., hep-ph/0308248 p.79.