We propose the enhancement of $\Lambda_c$ yield in heavy ion collisions at RHIC and LHC as a novel signal for the existence of diquarks in the strongly coupled quark-gluon plasma produced in these collisions as well as in the $\Lambda_c$. Assuming that stable bound diquarks can exist in the quark-gluon plasma, we argue that the yield of $\Lambda_c$ would be increased by two-body collisions between $ud$ diquarks and $c$ quarks, in addition to normal three-body collisions among $u$, $d$ and $c$ quarks. A quantitative study of this effect based on the coalescence model shows that including the contribution of diquarks to $\Lambda_c$ production indeed leads to a substantial enhancement of the $\Lambda_c/D$ ratio in heavy ion collisions.

Keywords: Relativistic heavy ion collisions; Quark-gluon plasma; Diquark; Quark coalescence; Heavy baryons.

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Recent experiments on heavy ion collisions at the Relativistic Heavy Ion Collider (RHIC) have shown that the properties of produced quark-gluon plasma (QGP) are close to those of a perfect fluid, consistent with the strongly coupled nature of QGP suggested in Ref. 2. The strong correlations in the QGP may give rise
to a rich variety of states$^{34}$. This new picture of the QGP as a strongly coupled system is now called the strongly coupled QGP (sQGP)$^{456}$. One of the challenging problems in future relativistic heavy ion collisions is to experimentally study such strong correlations. Recently, we have shown that possible existence of diquark correlations in sQGP, particularly the $[ud]$ diquark with color $ar{3}$, isospin 0, and spin 0, would lead to a significant enhanced production of $\Lambda_c$ in relativistic heavy ion collisions compared to that of charmed mesons$^7$, thus offering one possible experimental means to verify the existence of strong correlations in sQGP.

The basic idea in our study is the following. If $[ud]$ diquarks can exist in the QGP from the heavy ion collisions, the decoupling of the $[ud]$ diquark from the heavy quark in the heavy baryon$^8$ would then allow the $[ud]$ structure to be preserved during the hadronization process, thus facilitating the production of $\Lambda_c$ ($\Lambda_b$) from the QGP. In other words, in the presence of diquarks $[ud]$ the $\Lambda_c$ ($\Lambda_b$) can be formed from the two-body collision between $c$ ($b$) quark and the $[ud]$ diquark. Compared to the usual three-body collision among $c$ ($b$), $u$ and $d$ quarks, the two-body collision has a larger phase space than the three-body collision. Therefore, collisions of $[ud]$ diquarks and heavy $c$ ($b$) quarks in the QGP would enhance the yield of $\Lambda_c$ ($\Lambda_b$) in heavy ion collisions.

To estimate the yield of $\Lambda_c$, we have used the quark coalescence model$^{9101112}$. For heavy ion collisions, 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$^{13}$. It also gives a natural account for the observed constituent quark number scaling of hadron elliptic flows$^{14}$ and the large elliptic flow of charmed mesons$^{15}$. In this model, the yield of hadrons from the QGP is given by the overlap between the quark thermal distribution in the QGP and the hadron wave function$^{1617}$. Modeling the formed QGP by a fire cylinder, the number of light quarks at hadronization is then determined from assuming that they are in thermal and chemical equilibrium. For $c$ quarks, their number is estimated from initial hard nucleon-nucleon collisions$^{18}$, and they are also taken to be thermal equilibrium as they seem to interact strongly in QGP as well$^{192021}$.

Results on the yield of $\Lambda_c$ is plotted in Fig. 1 as a function of the temperature of QGP. The dashed line corresponds to the case without diquarks, while solid lines are for the cases with diquarks of masses $m_{[ud]} = 450$ MeV (bold solid line) or $600$ MeV (thin solid line). The diquark mass is estimated by assuming a constituent light quark mass of $300$ MeV and taking into account the color-spin interaction between the two quarks$^{22}$. The diquark mass of $450$ MeV corresponds to the maximum binding energy ($150$ MeV), while the diquark mass $600$ MeV corresponds to the minimum binding energy at threshold. Taking the critical temperature to be $T_C = 175$ MeV, we obtain $\Lambda_c/D^0 = 0.11$ for the case without diquarks and $\Lambda_c/D^0 = 0.44$ and $0.89$ for the cases with diquarks of masses $450$ MeV and $600$ MeV, respectively. Including diquarks in the QGP thus enhances the $\Lambda_c/D^0$ ratio
in relativistic heavy ion collisions by a factor of 4 to 8 depending on how deeply the diquark is bounded in QGP.

The predicted $\Lambda_c/D^0$ ratio is much larger than that given by the statistical model $^2_5$, which is estimated to be $(m_{\Lambda_c}/m_{D^0})^{3/2} \exp(- (m_{\Lambda_c} - m_{D^0})/T_C) \simeq 0.12$ $^{12}$. It is also larger than the value $\Lambda_c/D^0 = 0.159$ extracted from hadron yields in $p+p$ collisions by the SELEX collaboration $^{23}$ and the value $\Lambda_c/D^0 = 0.14$ determined from measured hadron yields from $B$ meson decay $^{24}$. Since the $u$ and $d$ quarks in above three cases are not correlated as a diquark, it is therefore not surprising that the $\Lambda_c/D^0$ ratios in these cases are all close to the value $\Lambda_c/D^0 = 0.11$ obtained from the coalescence model without diquarks in the QGP and the statistical hadronization model of QGP for heavy ion collisions.

The study of charmed hadron production at RHIC and LHC will be possible in the near future as the tracking system for observing charmed hadrons, which has a spatial resolution of 12 $\mu m$ with the best precision, is being developed by the ALICE collaboration at LHC $^{26}$. Also, detector upgrades are in progress for both the STAR and PHENIX collaborations at RHIC $^{27,28}$.

Although the abundance of $b$ quarks produced in heavy ion collisions is much smaller than that of $c$ quarks, bottom hadrons are also an interesting probe of the diquark correlation in produced QGP. First, the decoupling between the diquark and heavy quark holds even better as the heavy quark becomes massive. Second, the lifetime of $\Lambda_b (c\tau \sim 372 \mu m)$ is longer than that of $\Lambda_c (c\tau \sim 62 \mu m)$, and this makes its detection easier. Using the bottom quark production cross sections predicted from the pQCD for $p+p$ collisions at RHIC $^{29}$ and LHC $^{30}$, we have estimated the bottom quark numbers in corresponding heavy ion collisions. The coalescence model then gives $\Lambda_b/B = 0.098$ for the case without diquarks, and $\Lambda_b/B = 0.38$ and 0.82 for the cases with diquarks of masses 450 MeV and 600 MeV, respectively. The enhancement of the $\Lambda_b/B$ ratio due to the presence of diquarks is thus comparable to that for the $\Lambda_c/D$ ratio.

In summary, the $[ud]$ diquark correlation in the QGP produced in relativistic heavy ion collisions could be investigated through the observation of $\Lambda_c$ and $\Lambda_b$. 

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Fig. 1. The yield ratio $\Lambda_c/D^0$ as a function of temperature. See the text.
enhancement in these collisions. Our proposal may open a possible new method to investigate the formation of QGP in relativistic heavy ion collisions and to study the diquark correlation in the QGP. It can in turn also be used as an indirect evidence for the diquark structure in heavy baryons. We therefore conclude that studying \( \Lambda_c \) and \( \Lambda_b \) production at RHIC and LHC is an interesting and exciting subject.

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