Quarkonium Production and Medium Effects in High Energy Nuclear Collisions

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Color screening and regeneration are both hot medium effects on quarkonium production in high energy nuclear collisions. However, they affect in an opposite way the finally observed quarkonium spectra. Due to the competition of the two dynamical effects, the ratio of the integrated quarkonium yield between nuclear and elementary nucleon collisions loses its sensitivity. Once the information of quarkonium transverse motion is included, on the other hand, the ratio of averaged transverse momentum square reveals the nature of the QCD medium created in high energy nuclear collisions.

The existence of a deconfined partonic phase has been well established in $\sqrt{s_{NN}} = 200$ GeV Au+Au collisions at RHIC \cite{1-5} as well as in $\sqrt{s_{NN}} = 2.76$ TeV Pb+Pb collisions at LHC \cite{6-8}. The study of high energy nuclear collisions has entered a new era where current physics programs at both RHIC and LHC focus on the properties of the new form of matter and how the hot matter undergoes the transition from the quark gluon plasma to the hadronic gas. Due to color screening, quarkonium suppression in nuclear collisions in comparison with the elementary p+p collisions has been proposed to "provide an unambiguous signature of quark gluon plasma formation" \cite{9}. Regeneration \cite{10-13}, that is quarkonium production in the hot medium via coalescence process, on the other hand, ruins the simplistic picture.

For the final quarkonium distributions emerging from high energy nuclear collisions there are several genuine contributors, namely, (1) initial production via pQCD process; (2) cold nuclear matter effects before the formation of the hot medium including the shadowing effect \cite{14-16}, Cronin effect \cite{17-19}, and nuclear absorption \cite{20}; and (3) Debye screening and regeneration. While screening and regeneration are both hot nuclear matter effects, they affect the quarkonium production in an opposite way. The yield is suppressed by the former but enhanced by the latter.

While the regeneration is negligible and the initial production is dominant for low energy collisions \cite{13, 21}, both initial production and regeneration are important for nuclear collisions at high energies. The nuclear modification factor $R_{AA} = N_{AA}/(n_{bin}N_{pp})$ is used commonly to study the nuclear matter effects on the quarkonium production, where $n_{bin}$ is the number of binary collisions, $N_{pp}$ and $N_{AA}$ are the integrated quarkonium yields in p+p and A+A collisions, respectively. This quantity has been measured at all collision energies at SPS, RHIC and LHC. Starting at about unity in peripheral collisions, the $R_{AA}$ decreases towards more central collisions. Although the collision dynamics from SPS to LHC energy is dramatically different, there is no clear energy dependence in the integrated $R_{AA}$ \cite{22}.

In order to study the medium effects in high energy nuclear collisions, one clearly needs a new observable with higher sensitivity to the underlying collision dynamics. We start with the introduction to the model we used in this analysis. To extract medium information from the quarkonium motion, both the medium and the quarkonia created in high energy nuclear collisions must be treated dynamically. Since a quarkonium is heavy, its phase space distribution $f_\Psi(p,\mathbf{x}, t)$ is governed by a Boltzmann-type transport equation \cite{23, 24},

$$\frac{\partial f_\Psi}{\partial t} + \mathbf{v}_\Psi \cdot \nabla f_\Psi = -\alpha_\Psi f_\Psi + \beta_\Psi, \quad (1)$$

where both the initially produced and regenerated quarkonia are taken into account through the initial distribution $f_\Psi$ at the medium formation time $\tau_0$ and the gain term $\beta_\Psi(p, \mathbf{x}, t)$, and $\mathbf{v}_\Psi = p_\Psi/E_\Psi$ is the quarkonium velocity. The reduction of quarkonium due to the Debye screening is described by the lose term $\alpha_\Psi(p, \mathbf{x}, t)$. The cold nuclear matter effects change the initial quarkonium distribution and heavy quark distribution at $\tau_0$. The interaction between the quarkonia and the medium is reflected in the lose and gain terms and depends on the local temperature $T(\mathbf{x}, t)$ and velocity $u_\mu(\mathbf{x}, t)$ of the medium which are controlled by the hydrodynamics \cite{25, 26}.

The Debye radius depends strongly on the properties of the medium such as temperature as well as the strength of the binding potential of the quarkonium states. By solving the Schrödinger equation for the bound state of a pair of heavy quarks, one obtains the quarkonium dissociation temperature $T_d$ \cite{27}. From the hydrodynamic solution $T(\mathbf{x}, t)$ of the fireball created in heavy ion collisions, one can extract the dissociation radius $R_d(\tau, y)$ determined by

$$T(R_d, y, \tau) = T_d \quad (2)$$

in the transverse plane as a function of the proper time $\tau$ and rapidity $y$. Fig. 1 shows the mid-rapidity $R_d(\tau)$ for central Au+Au collisions at RHIC (dotted lines) and Pb+Pb collisions at LHC (solid lines). The quarkonium state is destroyed if it is in the region $r < R_d$. The dissociation temperatures used in Fig. 1 are taken...
as $T_d/T_c = 4, 1.8, 1.6, 2.3$ and $1.1$ for $\Upsilon_{1S}, \Upsilon_{1P}, \Upsilon_{2S}, J/\psi$ and $\psi'(\chi_c)$ \cite{24,28}, respectively, scaled by the critical temperature of deconfined phase transition $T_c = 165$ MeV \cite{29}. The temperature of the medium created at LHC is expected to be much hotter than that at RHIC. As a result one finds $R_d(\text{LHC}) > R_d(\text{RHIC})$ for all quarkonium states. Since $T_d$ is chosen so high for $\Upsilon(1S)$ and $J/\psi$, the directly produced $\Upsilon(1S)$'s are not destroyed even at LHC and some of $J/\psi$s can survive at RHIC.

In the most violent collisions, quark-gluon plasma is formed and the emerging hadrons are created via coalescence process. For quarkonia it is the regeneration that dominates the production at high energies. Different from the light hadrons which are produced at the hadronization surface determined by $T(x,t) = T_c$, the quarkonium regeneration happens continuously in the parton phase. The fraction of the regenerated $J/\psi$s,

$$g_{AA} = \frac{N_{AA}^{\text{reg}}}{N_{AA}},$$

(3)

calculated from the transport equation \cite{11}, is shown in Fig. 2 as a function of the medium evolution time $\tau$ in central Au+Au collisions at RHIC (dashed lines) and Pb+Pb collisions at LHC (solid lines).

Fig. 1: (color online) Averaged quarkonium dissociation radius $R_d$ in transverse plane as a function of the medium evolution time $\tau$ in central Au+Au collisions at RHIC (dashed lines) and Pb+Pb collisions at LHC (solid lines).

In order to understand the quarkonium production and suppression mechanisms in heavy ion collisions, transverse motion is developed during the dynamical evolution of the system. The microscopically high particle density and multiple scatterings are essential for the finally observed transverse momentum distributions. The distributions are therefore sensitive to the medium properties, like the equation of state. The study on the transverse motion has been well documented in light quark sectors at all energies \cite{1-4,30}. In order to understand the quarkonium production and suppression mechanisms and extract the properties of the medium, we propose to construct a new ratio of the second moment of the transverse momentum distribution. The ratio $r_{AA}$ is defined as

$$r_{AA} = \frac{\langle p^2_{T,AA} \rangle}{\langle p^2_{T,pp} \rangle}.$$  

(4)

The reason to choose $\langle p_T^2 \rangle$ instead of $\langle p_T \rangle$ is that we are interested in the medium induced change in the shape of the transverse momentum distribution not only its average value.

Fig. 2 shows the ratio $r_{AA}$ as a function of the number of participant nucleons $N_{\text{part}}$ for collisions at SPS \cite{31}, RHIC \cite{32} and LHC \cite{33}. Starting from the very small number of participants, there is a clear rise in $r_{AA}$ at all collision energies. It is believed due to the initial gluon multiple scatterings before the quarkonium formation \cite{17,18}, and the enhancement seems more important for collisions at lower energies.

The energy dependence of $r_{AA}$ clearly reflects the underlying $J/\psi$ production and suppression mechanisms in high energy nuclear collisions. At lower collision energy where thecharm cross section is small and the regeneration is negligible, almost all of the observed $J/\psi$s are from direct production at the initial impact and the decay contribution from the excited states $\psi'$ and $\chi_c$. In
they lose energy (momentum) when passing through the medium \[36, 39\]. Therefore, as a consequence of the increasing regeneration fraction with colliding energy, see Fig.\[2\] the competition between the initial production which controls high \(p_t\) charmonium production and the regeneration which inherits the low momentum of thermalized heavy quarks leads to the decrease of the values of the ratio \(r_{AA}\) from SPS to LHC. As shown in the upper panel of Fig.\[3\] the predicted \(r_{AA}\) at mid rapidity for heavy ion collisions at LHC is below unity and decreases toward more central collisions. The prediction has been confirmed by the experimental results at somewhat forward rapidity window as shown in the lower panel of Fig.\[3\] \[33\]. At RHIC energy, the competition between the initial gluon scattering and the final stage regeneration leads to a weak centrality dependence for the mid-rapidity \(r_{AA}\). On the other hand, at the forward-rapidity, due to the lower heavy quark production cross section, the regeneration gives its way to the initial gluon scattering, and \(r_{AA}\), shown in the lower panel of Fig.\[3\] becomes higher than unity and increases as a function of \(N_{\text{part}}\). Since the heavy quark production cross section is large at LHC, even at the forward-rapidity, the \(r_{AA}\) remains lower than unity.

this case, the initial state gluon scattering, \textit{i.e.} the Cronin effect \[17, 18\] is dominant and tends to increase the transverse momentum of the finally observed \(J/\psi\). Since the Cronin effect is proportional to the gluon traveling length in the nuclei \[34, 35\], \(r_{AA}\) is always above unity and increases monotonically versus collision centrality, see upper panel of Fig.\[3\]. In the truly high energy nuclear collisions, on the other hand, charm quarks are copiously produced and the regeneration for charmonia, \textit{i.e.} coalescence of heavy quark and anti-quark pair inside the quark gluon plasma, can be significant. Although these initially produced heavy quarks carry high transverse momentum,
between the solid and dashed lines, the hatched band, is the results of shadowing effect [13]. At RHIC energy the band becomes very narrow.

Comparing to the yield $R_{AA}$, the $p_t$ $r_{AA}$ lends additional sensitivity to the transverse dynamics. It is known that transverse motion plus local properties of the medium are extremely important for hadron productions, including quarkonia, in heavy ion collisions. Since the fireballs created in heavy ion collisions at RHIC and LHC energies are so hot, the quarkonium suppression and regeneration in the hadron phase at later stage is assumed to be neglected and all of the effects shown in Fig.4 are originated from the partonic phase.

Except the mass difference, our results for $J/\psi$ should also work qualitatively for heavier $\Upsilon$. The $\Upsilon$ $r_{AA}$ is shown in Fig.2 at RHIC and LHC energies. Since the degree of both suppression and regeneration for $J/\psi$ at lower energies is similar to that for $\Upsilon_{1S}$ at RHIC (LHC), see the comparison between Fig.1 and the upper panel of Fig.3. For the excited state $\Upsilon_{2S}$, its dissociation temperature is much lower than the fireball temperature at LHC, therefore, the initial production is significantly suppressed and the dominant regeneration leads to a very small $p_t$ $r_{AA}$. These predictions will be checked by the future experimental data from RHIC and LHC.

To summarize we argue that in high energy nuclear collisions the quarkonium transverse momentum distribution can be used as a sensitively probe for studying the properties of the quark gluon plasma. The Debye screening and regeneration are both medium induced effects but affect the quarkonium production in an opposite way. When Debye screening is important, initially produced quarkonia are destroyed and the finally observed quarkonium production in RHIC and LHC energies is similar to that for $\Upsilon_{1S}$ at RHIC (LHC), see the comparison between Fig.1 and the upper panel of Fig.3. For the excited state $\Upsilon_{2S}$, its dissociation temperature is much lower than the fireball temperature at LHC, therefore, the initial production is significantly suppressed and the dominant regeneration leads to a very small $p_t$ $r_{AA}$. These predictions will be checked by the future experimental data from RHIC and LHC.

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