Abstract

We calculate the rapidity dependence of \(J/\psi\) nuclear modification factor and averaged transverse momentum square in heavy ion collisions at RHIC in a 3-dimensional transport approach with regeneration mechanism.

Key words: \(J/\psi\) production, regeneration, heavy ion collisions, quark-gluon plasma

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\(J/\psi\) suppression \([1]\) is widely accepted as a probe of quark-gluon plasma (QGP) formed in relativistic heavy ion collisions and was first observed at SPS \([2]\) more than ten years ago. At RHIC and LHC energy, a significant number of charm quarks are generated in central heavy ion collisions, and the recombination of these uncorrelated charm quarks offers another source for \(J/\psi\) production \([3]\). There are different ways to describe the \(J/\psi\) regeneration. In the statistical model \([4]\), all the \(J/\psi\)s are produced at hadronization of the system through thermal distributions and charm conservation. In some other models, \(J/\psi\)s come from both the continuous regeneration inside the hot medium and primordial production through initial nucleon-nucleon collisions \([3, 5]\). The regeneration is used to describe \([6]\) the \(J/\psi\) nuclear modification factor \(R_{AA}\) and averaged transverse momentum square \(\langle p_t^2 \rangle\). From the experimental data \([7]\) at RHIC, the \(R_{AA}\) is almost the same as that at SPS, which seems difficult to explain in models with only primordial production mechanism.

The rapidity dependence of \(J/\psi\) production was also measured at RHIC \([7, 8]\) and discussed in models \([9, 10, 11]\). The surprising finding of the experimental result is that the apparent suppression at forward rapidity is stronger than that at midrapidity, i.e. \(R_{AA}^{\text{mid}} > R_{AA}^{\text{forward}}\). This is again difficult to explain in models with only initial production mechanism, since the suppression at midrapidity should be stronger than that at forward rapidity. Not only \(R_{AA}\) but also \(\langle p_t^2 \rangle\) depends on the rapidity \([7]\). In semi-central and central Au+Au collisions the value of \(\langle p_t^2 \rangle\) at midrapidity is lower than that at forward rapidity, i.e. \(\langle p_t^2 \rangle^{\text{mid}} < \langle p_t^2 \rangle^{\text{forward}}\). In this paper, we will discuss the rapidity dependence of \(R_{AA}\) and \(\langle p_t^2 \rangle\) in a 3-dimensional transport model with both initial production and continuous regeneration mechanisms.

At RHIC \(J/\psi\)s are detected at midrapidity \(|y| < 0.35\) and forward rapidity \(1.2 < y < 2.2\), both are located in the plateau of the rapidity distribution of light hadrons \([12]\). Therefore, the space-time evolution of the QGP can be approximately described by the transverse hydrodynamic equations at midrapidity \([13]\), and the \(J/\psi\) motion is controlled by a 3-dimensional transport equation in an explicitly boost invariant form

\[
\left[\cosh(y_{\Psi} - \eta) \frac{\partial}{\partial \tau} + \sinh(y_{\Psi} - \eta) \frac{\partial}{\partial \eta} + v_t^\Psi \cdot \nabla_t\right] f_{\Psi} = -\alpha_{\Psi} f_{\Psi} + \beta_{\Psi},
\]
where \( f_W = f_W(p, y, x, \eta, \tau|\mathbf{b}) \) is the charmonium distribution function in phase space at fixed impact parameter \( \mathbf{b} \), and we have used transverse energy \( E_t = \sqrt{E_{W}^2 - p_{z}^2} \), rapidity \( y_W = 1/2 \ln(E_{W} + p_{z})/(E_{W} - p_{z}) \), proper time \( \tau = \sqrt{t^2 - z^2} \) and space-time rapidity \( \eta = 1/2 \ln([t + z]/[t - z]) \) to replace the charmonium energy \( E_{\Psi} = \sqrt{p_{z}^2 + m_{W}^2} \), longitudinal momentum \( p_{z} \), time \( t \) and longitudinal coordinate \( z \). The term with transverse velocity \( v_{t}^W = p_{t}/E_{t} \) reflects the leakage effect in charmonium motion. To take into account the decay of the charmonium excitation states into \( J/\psi \), the symbol \( \Psi \) here stands for \( J/\psi, \chi_c \) and \( \psi' \) and the ratio of their contributions in the initial condition is taken as 6:3:1. The suppression and regeneration in the QGP are described by the loss and gain terms on the right hand side of the transport equation. Considering the gluon dissociation process, \( \alpha \) can be explicitly written as [14]

\[
\alpha_W(p, x, t, \mathbf{b}) = \int d^3\mathbf{q}/ \left( (2\pi)^3 \right) \frac{E_{\Psi}^c}{\psi_{\Psi}(s)} W_{c\Psi}^c(s) f_{\Psi}(q, T, u) \Theta(T - T_{c})/\Theta(T_{c} - T),
\]

where \( W_{c\Psi}^c \) is the transition probability [13] as a function of the colliding energy \( \sqrt{s} \) of the dissociation process, \( E_{\Psi} \) and \( f_{\Psi} \) are the gluon energy and gluon thermal distribution, and \( T_{c} \) and \( T_{c}^q \) are the critical temperature of the deconfinement phase transition and dissociation temperature of \( \Psi \), taken as \( T_{c} = 165 \text{ MeV} \) and \( T_{c}^q = 1.9 \). The two step functions \( \Theta \) in \( \alpha \) indicate that the suppression is finite in the QGP phase at temperature \( T < T_{c}^q \) and becomes infinite at \( T > T_{c}^q \). We have here neglected the suppression process in hadron phase [13, 6].

The gain term \( \beta_{W} \) can be obtained from the loss term \( \alpha \) by considering detailed balance [3]. We assume local thermalization of charm quarks in the QGP and take the charm quark distribution as

\[
f_{c}(k, x, t) = \rho_{c}(x, t)f_{Q}(k)
\]

with \( \rho_{c} \) being the density of charm quarks in coordinate space,

\[
\rho_{c}(x, t) = T_{A}(x_0)T_{B}(x_t - \mathbf{b}) \cosh \eta/\tau \frac{d\sigma_{W}^{c\Psi}}{d\eta}
\]

and \( f_{Q} \) the normalized Fermi distribution in momentum space, where \( T_{A} \) and \( T_{B} \) are the thickness functions for the two colliding nuclei determined by nuclear geometry. Since the large uncertainty of charm quark production cross section in pp collisions for both experimental and theoretical studies, we assume the rapidity dependence of charm production as a Gauss distribution \( d\sigma_{W}^{c\Psi}/d\eta = d\sigma_{W}^{c\Psi}/d\eta\big|_{\eta=0} e^{-\eta^2/2\eta_0^2} \) with \( d\sigma_{W}^{c\Psi}/d\eta\big|_{\eta=0} = 120 \mu b \) which agrees with the experimental data [16] and \( (d\sigma_{W}^{c\Psi}/d\eta)\big|_{\eta=1.7}/(d\sigma_{W}^{c\Psi}/d\eta)\big|_{\eta=0} = 1/3 \) to determine the parameter \( \eta_0 \) which is in between the smallest and largest theoretical estimation [16].

The contribution from the primordial charmonium production is reflected in the initial condition of the transport equation at the starting time \( \tau_0 \). By fitting the experimental data [17] for pp collisions at RHIC, the initial charmonium momentum distribution is extracted as

\[
f_{pp}(p, y) = 5g(y)/\left[ 4\pi(p_{T}^c(y)) \right] \left( 1 + p_{T}^c/\left( 4(p_{T}^c(y)) \right) \right)^{-6},
\]

where the rapidity distribution \( g(y) \) is a double Gauss function [17], and the rapidity dependence of the averaged transverse momentum square is taken as \( \langle p_{T}^c(y) \rangle \). We add an extra term to \( \langle p_{T}^c \rangle \) which comes from the gluon multi-scattering with nucleons [6, 11].


The charmonium production, including initial production and regeneration, is related to the QGP evolution through the local temperature $T$ and fluid velocity $u$, appearing in the thermal gluon and charm quark distributions, they are determined by the ideal hydrodynamics [13].

Figure 1: The nuclear modification factor $R_{AA}$ (left panel) and averaged transverse momentum square $\langle p_t^2 \rangle$ (right panel) at mid and forward rapidity as functions of number of participants $N_p$. The theoretical calculations with only initial production (dot-dashed lines), only regeneration (dashed lines) and both (solid lines) are compared with the experimental data [7, 8].

With the known distribution $f_{J/\psi}(p_t, y, x_t, \eta, \tau|b)$, one can calculate the $J/\psi$ yield and momentum spectra. The nuclear modification factor $R_{AA}$ and averaged transverse momentum square $\langle p_t^2 \rangle$ at mid and forward rapidity are shown in Fig.1 as functions of centrality. Since $R_{AA}$ is normalized to the pp collisions, the assumption of the same medium at mid and forward rapidity leads to similar $R_{AA}$ in the two rapidity regions, when we consider only initial production, as shown in the left panel. The regeneration at forward rapidity is, however, much less than that at mid rapidity. As a result of the competition, the total $R_{AA}$ at forward rapidity is less than that at mid rapidity, consistent with the experimental observation.

While the population is dominated by low momentum $J/\psi$s, the averaged transverse momentum carries more information on high momentum $J/\psi$s and can tell us more about the dynamics of charmonium production and suppression. The initially produced $J/\psi$s are from the hard nucleon-nucleon process at the very beginning of the collision and their $p_t$ spectrum is harder. From the gluon multi-scattering with nucleons before the two gluons fuse into a $J/\psi$, there is a $p_t$ broadening for the initially produced $J/\psi$s. Considering further the leakage effect which enables the high momentum $J/\psi$s escape from the anomalous suppression in the hot medium, the initially produced $\langle p_t^2 \rangle$ increases smoothly with centrality and becomes saturated at large $N_p$. Since the regenerated $J/\psi$s are from the thermalized charm quarks inside the QGP, their averaged
momentum is small and almost independent of the centrality. Both the initially produced and regenerated \( \langle p_T^2 \rangle \) is not sensitive to the rapidity region. While the difference between the initially produced and regenerated \( R_{AA} \) decreases with increasing \( N_p \), the difference between the values of \( \langle p_T^2 \rangle \) from the two rapidity regions increases smoothly with centrality! The total \( \langle p_T^2 \rangle \) depends strongly on the fraction of the regeneration. At mid rapidity, the regeneration and initial production are equally important in central collisions, see the left panel of Fig. The large contribution from the regeneration leads to a remarkable decrease of the value of \( \langle p_T^2 \rangle \) at mid rapidity. At forward rapidity, the regeneration contribution is, however, very small even for central collisions, see the left panel again. In this case, the total \( \langle p_T^2 \rangle \) is dominated by the initial production in the whole \( N_p \) region.

In summary, we calculated the \( J/\psi \) nuclear modification factor and averaged transverse momentum square at mid and forward rapidity in a three dimensional transport approach. The experimentally observed rapidity dependence of \( R_{AA} \) and \( \langle p_T^2 \rangle \) in Au+Au collisions at \( \sqrt{s}=200 \) GeV can well be explained by our model calculation where the continuous regeneration of \( J/\psi \) from thermalized charm quarks in QGP is an important ingredient. We predict that at higher colliding energies, for example at LHC, the regeneration will become the dominant ingredient.

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