Space-time Evolution of $J/\psi$ Production in High Energy Nuclear Collisions

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Abstract. The space-time evolution of $J/\psi$ production in central Au+Au collisions at RHIC energy is investigated in a transport model. Both gluon dissociation and continuous regeneration of $J/\psi$s inside the deconfined state are considered.

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$J/\psi$ suppression [1] is widely accepted as an essential signal of the quark-gluon plasma (QGP) formed in relativistic heavy ion collisions. However, the mechanism of $J/\psi$ production in hot and dense medium is still an open question. Different from the $J/\psi$ suppression observed at SPS [2] where almost all the charmonia are produced in the initial stage via hard processes and then suffer from the anomalous suppression in the QGP, there is a remarkable number of charm quarks in the QGP produced at RHIC energy and the recombination of those uncorrelated charm quarks offers another origin of $J/\psi$ production [3]. Both sudden generation on the hadronization surface in grand canonical ensemble [4] or canonical ensemble [5] and continuous regeneration [6, 7] inside the QGP are discussed to describe the charmonium production.

Since the charmonia are so heavy, they are difficult to be fully thermalized in the QGP with light quarks and gluons as constitutes, and a natural way to describe the charmonium motion in hot and dense medium is through a transport approach. In this paper, we investigate the space-time evolution of charmonium production and calculate the nuclear modification factor $R_{AA}$ and averaged transverse momentum square $\langle p_t^2 \rangle$ for $J/\psi$s at RHIC energy in a transport model [8], where the QGP is characterized by hydrodynamic equations and the charmonium motion is controlled by a classical transport equation. Both initial production and regeneration of charmonia and both nuclear absorption and anomalous suppression can be self-consistently considered in the model. The leakage effect [1, 9, 10], which is especially important for describing the transverse momentum saturation at SPS energy [11], is reflected in the free streaming term of the transport equation.

Since a charmonium mass is much larger than the typical temperature of the fireball created at RHIC, it is a good approximation to describe the charmonium distribution...
function \( f_\Psi(p_t, x_t, \tau | b) \) for \( \Psi = J/\psi, \psi', \chi_c \) in the transverse phase space \((p_t, x_t)\) at time \( \tau \) and fixed impact parameter \( b \) by a Boltzmann equation \([8]\),

\[
\frac{\partial f_\Psi}{\partial \tau} + v_\Psi \cdot \nabla f_\Psi = -\alpha_\Psi f_\Psi + \beta_\Psi. \tag{1}
\]

The second term on the left hand side arises from the free-streaming of \( \Psi \) with transverse velocity \( v_\Psi = p_t / \sqrt{p_t^2 + m_\Psi^2} \), which leads to the leakage effect and is important to high momentum charmonia \([11]\). The first and second terms on the right hand side are respectively the suppression and regeneration rates of charmonia. The former is usually taken from the gluon dissociation process \( J/\psi + g \to c + \bar{c} \tag{12} \). For \( J/\psi \) the cross section reads

\[
\sigma_{J/\psi}(\omega) = A_0 \frac{(\omega/\epsilon_{J/\psi} - 1)^{3/2}}{(\omega/\epsilon_{J/\psi})^5}, \tag{2}
\]

where \( \omega \) is the gluon energy relative to \( J/\psi \), and \( \epsilon_{J/\psi} \) is the \( J/\psi \) binding energy. Such a cross section leads to a flat tail of \( R_{AA} \), and can not explain the plateau structure in semi-central collisions and the strong suppression in central collisions observed at RHIC \([13, 14]\). Generally, the charmonium binding energy decreases with temperature, and the cross section \((2)\) is no longer valid above some dissociation temperature \( T_d \), at which the binding energy becomes zero. In order to take such an effect into account, we modify the loss term \( \alpha(p_t, x_t, \tau | b) \tag{8} \) by a step function \( \Theta(T_d - T) \),

\[
\alpha_\Psi = \frac{1}{2E_\Psi} \int \frac{d^3 p_g}{(2\pi)^3 2E_g} W^{\text{ce}}_{g\Psi}(s) f_g \Theta(T - T_c) / \Theta \left( T_d^\Psi - T \right), \tag{3}
\]

where \( E_\Psi \) and \( E_g \) are the charmonium and gluon energies, \( W^{\text{ce}}_{g\Psi}(s) \) is the transition probability of the gluon dissociation process as a function of \( s = (p_\Psi + p_g)^2 \), \( f_g(p_g, T, u) \) is the gluon thermal distribution, and \( T(x_t, \tau | b) \) and \( u(x_t, \tau | b) \) are the local temperature and velocity of the hot medium. The gain term \( \beta \) can be obtained by the detailed balance \([8]\).

The local temperature \( T \) and fluid velocity \( u \), which govern the thermal gluon distribution in \( \alpha \) and charm quark distribution in \( \beta \) and the suppression and regeneration region controlled by the two step functions in \((3)\), are determined by hydrodynamic equations. We assume that the produced partonic plasma reaches local equilibrium at time \( \tau_0 = 0.6 \text{ fm} \). After that, the plasma evolves according to the 2+1 dimensional Bjorken’s hydrodynamic equations,

\[
\begin{align*}
\partial_\tau E + \nabla \cdot \mathbf{M} &= -(E+p)/\tau, \\
\partial_\tau M_x + \nabla \cdot (M_x v) &= -M_x/\tau - \partial_x p, \\
\partial_\tau M_y + \nabla \cdot (M_y v) &= -M_y/\tau - \partial_y p, \\
\partial_\tau R + \nabla \cdot (Rv) &= -R/\tau
\end{align*}
\tag{4}
\]

with the definitions of \( E = (\epsilon + p)\gamma^2 - p \), \( \mathbf{M} = (\epsilon + p)\gamma^2 \mathbf{v} \) and \( R = \gamma n \), where \( \gamma \) is the Lorentz factor, and \( \epsilon, p \) and \( \mathbf{v} \) are the energy density, pressure and transverse velocity of the QGP. To close the equations, we take the equation of state of ideal gases of partons and hadrons with a first order phase transition at \( T_c \). The initial condition for the
hydrodynamics at RHIC is the same as in Ref [8]. Both the $J/\psi$ direct production and the feed-down from $\chi_c$ and $\psi'$ are considered in our calculation, and the ratio of them in the initial collision is taken as $6 : 3 : 1$ [15].

In following numerical calculations, we take the dissociation temperature for $\chi_c$ and $\psi'$ as the critical temperature of the deconfinement phase transition, $T_{\chi_c} \approx T_{\psi'} \approx T_c$. Since the binding energy of $J/\psi$ in hot and dense medium is estimated to be less than 220 MeV [16, 17], we take $\epsilon_{J/\psi} = 150$ MeV and the dissociation temperature $T_{dJ/\psi} = 1.92T_c$ to fit the experimental data. From the lattice simulations, the critical temperature is taken as $T_c=165$ MeV. Extracted from the experimental data at RHIC energy [18, 19], the charm quark and charmonium production cross sections at central rapidity region in nucleon-nucleon collisions are $d\sigma_{NN}/dy|y=0 = 120 \mu b$ and $B_{NN}d\sigma_N^\Psi/\sqrt{y}|y=0=26.4, 4.4$ and 13.2 nb for $\Psi = J/\psi, \psi'$ and $\chi_c$.

Figure 1. The $J/\psi$ nuclear modification factor as a function of time for central Au+Au collisions at RHIC energy.

With the known $J/\psi$ distribution $f_{J/\psi}$ as a function of time and transverse coordinate and momentum, one can easily extract the space-time evolution of $J/\psi$ production and the final state distributions determined at the hadronization hypersurface. The time evolution of the nuclear modification factor $R_{AA}$ for central Au+Au collisions at RHIC energy is shown in Fig.1. The evolution starts at the thermalization time $\tau_0$. At the beginning, the system is very hot and both the suppression and regeneration are significant. The initially produced charmonia, which are treated as initial condition $f_{\Psi}(p_t,x_t,\tau_0|b)$ [8] of the transport equation (1), suffer from the strong gluon dissociation and the number drops fast. Since the regeneration is proportional to the square of charm quark number but the suppression is linear in gluon number, the number of the survived regenerated $J/\psi$'s increases with time fast in the beginning. With the expansion of the system, the temperature decreases, and the suppression and regeneration become smooth and finally get saturated at the phase transition temperature $T_c$ which corresponds to the time $\tau \sim 4$ fm/c. Since we did not
consider the suppression and regeneration in hadronic phase, the initial production and regeneration are time independent after the phase transition. Due to the competition between the initial production and regeneration, the total $J/\psi$ production is almost a constant in the whole evolution.

Where are the finally observed $J/\psi$s from, from the central part of the fireball or the surrounded region? We calculated the source distribution of the observed $J/\psi$s from the function $f_{J/\psi}$ in the limit of $\tau \to \infty$. The $J/\psi$ number density as a function of the fireball radius in the transverse plane is shown in Fig. 2. The initially produced charmonia in the central region are fully eaten up by the extremely hot QGP in the initial stage when the temperature is larger than $T_d$. Since regeneration happens continuously in the whole QGP region, those regenerated $J/\psi$s in the later stage with temperature $T < T_d$ have the probability to survive, and therefore the finally observed $J/\psi$s coming from the center of the fireball are mostly regenerated. In the periphery of the fireball where the temperature is low, both the suppression and regeneration are weak, and the observed $J/\psi$s from this region are dominated by the initial production. For those $J/\psi$s coming from the middle part of the fireball, both the initially produced and regenerated $J/\psi$s are important.

![Figure 2](image.png)

**Figure 2.** The observed $J/\psi$ number density as a function of the fireball radius in the transverse plane for central Au+Au collisions at RHIC energy.

We now turn to discuss the centrality dependence of the nuclear modification factor $R_{AA}$ and the averaged transverse momentum square $\langle p_t^2 \rangle$ for $J/\psi$s. The calculated $R_{AA}$ as a function of the participant nucleon number $N_p$ for Au+Au collisions at RHIC energy and the comparison with the experimental data [13, 14] are shown in the left panel of Fig. 3. Since both the suppression and regeneration increase with centrality, the yield of the initially produced $J/\psi$s drops monotonously and the yield of the regenerated $J/\psi$s goes up monotonously. For peripheral and semi-central collisions where the temperature of the system is low, the $J/\psi$ production is controlled by the initial production, while for central collisions where the charm quark density is high, both the initial production
and regeneration are important. From the data, there exists a flat structure in between $N_p = 60$ and 170, and then the $R_{AA}$ decreases further for $N_p > 170$. The plateau can be explained by the competition between the initial production and regeneration, and the further decrease in large $N_p$ region is due to the fact that the maximum temperature of the fireball created in central collisions is higher than the dissociation temperature $T_d$. For extremely central collisions around $N_p = 350$, the difference between the data and the theory is probably due to the geometry fluctuations which are proved to be important at SPS energy [11] [20].

![Graph](image)

**Figure 3.** The nuclear modification factor $R_{AA}$ (left panel) and averaged transverse momentum square $\langle p_t^2 \rangle$ (right panel) as functions of participant nucleon number $N_p$ in mid-rapidity region for Au+Au collisions at RHIC energy. The data are from PHENIX collaboration [13] [14].

Different from the global yield, the momentum distribution is more sensitive to the mechanism of $J/\psi$ production and suppression. Our theoretical calculation of $J/\psi$ $\langle p_t^2 \rangle$ as a function of centrality for Au+Au collisions at RHIC energy and the comparison with the experimental data [13] are given in the right panel of Fig.3. Similar to the calculation at SPS energy [11], the $\langle p_t^2 \rangle$ of the initially produced $J/\psi$s increases with centrality and gets saturated in central collisions, due to the gluon multi-scattering [21] with nucleons in the initial state and the leakage effect which is especially important for high momentum $J/\psi$s. Since we have assumed kinetic equilibration of charm quarks in the QGP, the transverse momentum distribution of the regenerated $J/\psi$s is controlled by the charm quark thermal distribution, and the corresponding $\langle p_t^2 \rangle$ is only about half of that for initially produced ones. The total $\langle p_t^2 \rangle$ is dominated by the competition between the two production mechanisms. At high $N_p$ the contribution from the regeneration becomes important, and the competition leads to a transverse momentum suppression in central collisions which agrees well with the data.

We calculated also the $R_{AA}$ and $\langle p_t^2 \rangle$ for Cu-Cu collisions at RHIC energy. Since the colliding energy for Au+Au and Cu+Cu collisions are the same, and the nuclear geometry is mainly reflected in the participant nucleon number, the $R_{AA}$ and $\langle p_t^2 \rangle$ for the
two kinds of nuclear collisions are almost the same in the centrality region of \( N_p < 110 \) where 110 is the maximum \( N_p \) for Cu+Cu collisions. Our calculation agrees with the experimental data [22].

In summary, we have calculated the space-time evolution and the observed nuclear modification factor and averaged transverse momentum square of \( J/\psi \)s produced in relativistic heavy ion collisions at RHIC energy. While the initial production dominates the peripheral and semi-central collisions, the initial production and regeneration are almost equally important for central collisions.

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