Transverse Momentum Distribution as a Probe of $J/\psi$ Production Mechanism in Heavy Ion Collisions

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We investigate $J/\psi$ transverse momentum distribution in a transport approach. While the nuclear modification factor $R_{AA}(N_p)$ at RHIC is almost the same as at SPS, the averaged transverse momentum square $\langle p_t^2 \rangle$ and $R_{AA}(p_t)$ are very different at SPS, RHIC and LHC and can be used to differentiate from the $J/\psi$ production mechanisms in high energy nuclear collisions.

1. Introduction

From lattice Quantum Chromodynamics (QCD) calculations, there exists a phase transition from ordinary hadronic matter to a new state of matter, the so-called Quark Gluon Plasma (QGP), at finite temperature. The $J/\Psi$ suppression has long been considered as a probe of the new state produced in high energy heavy ion collisions [1]. The primordially produced charmonia via hard nucleon-nucleon (NN) collisions are subject to subsequent nuclear absorption in the initial stage and anomalous suppression in the hot and dense medium. The normal and anomalous suppression are indeed observed in heavy ion collisions at the CERN Super Proton Synchrotron (SPS) [2] and investigated in many theoretical models [3].

Different from the $J/\psi$ production at SPS, there are a remarkable number of charm quarks in the QGP phase produced in higher energy nuclear collisions at the BNL Relativistic Heavy Ion Collider (RHIC) and the CERN Large Hadron Collider (LHC), and the regeneration, namely the recombination of those uncorrelated charm quarks offers another source for $J/\psi$ production [4]. Obviously, the regeneration will enhance the $J/\psi$ yield and alter its momentum spectrum.

From recently observed $J/\psi$ production at RHIC [5], the nuclear modification factor $R_{AA}(N_p)$ as a function of the number of participant nucleons $N_p$ at RHIC is almost the same as at SPS, see Fig[1]. The same suppression at SPS and RHIC looks difficult to be understood in models with only initial production mechanism, because the temperature at RHIC is higher and then the anomalous suppression is predicted to be stronger at RHIC, in comparison with SPS. The puzzle of the same suppression was theoretically studied by many models. With the idea of sequential suppression [6], if the temperatures at RHIC and SPS are both in between the $J/\psi$ dissociation temperature and $\psi'$ and $\chi_c$ dissociation
temperature, the value $R_{AA} \sim 0.6$ will not change from SPS to RHIC energy. Considering three gluon fusion as the main $J/\psi$ production mechanism \cite{7}, the cold nuclear matter effect which is medium independent can explain the same suppression too. In the frame of regeneration, the competition between the initial production and regeneration can explain well the same suppression \cite{8,9}.

The transverse momentum distribution contains more dynamic information on the charmonium production and suppression mechanism. The regenerated $J/\psi$s are mainly distributed in low $p_t$ and central rapidity region \cite{9}, but the high $p_t$ region is closely related to the Cronin effect \cite{10} and leakage effect \cite{11} for the initially produced $J/\psi$s. While the $J/\psi$ yield which is a global quantity is not sensitive to the detailed dynamics, the transverse momentum distribution at RHIC is very different from SPS, see Fig.2 and may be used to differentiate from the production and suppression mechanisms at different energies. In this paper, we investigate the $J/\psi$ transverse momentum moments and the $p_t$ dependence of $R_{AA}$ from SPS to LHC energy.

2. Transport Model and Numerical Results

We start with a transport equation \cite{12} for the distribution function $f_\Psi(p_t, x_t, \tau|b)$ in central rapidity region and transverse phase space $(p_t, x_t)$ at time $\tau$ and fixed impact parameter $b$,

$$ \frac{\partial f_\Psi}{\partial \tau} + v_\Psi \cdot \nabla f_\Psi = -\alpha_\Psi f_\Psi + \beta_\Psi, \quad (1) $$

where $\Psi$ stands for $J/\psi$, $\psi'$ and $\chi_c$, $v_\Psi = p_t/\sqrt{p_t^2 + m_\Psi^2}$ is the transverse velocity, and $\alpha_\Psi(p_t, x_t, \tau|b)$ and $\beta_\Psi(p_t, x_t, \tau|b)$ are the loss and gain terms representing the anomalous suppression and regeneration in the hot medium. Considering the gluon dissociation process $g + \Psi \rightarrow c + \bar{c}$, $\alpha$ is the momentum integration of the dissociation cross section \cite{13} multiplied by thermal gluon distribution, and $\beta$ can be obtained from detailed balance between the suppression and regeneration. The distribution $f_\Psi(p_t, x_t, \tau_0|b)$ at initial time $\tau_0$ is determined by the geometrical superposition of NN collisions, including the Cronin effect \cite{10} and nuclear absorption \cite{3}. The local temperature, baryon chemical potential and collective flow appeared in the thermal gluon and charm quark distribution functions are determined by the ideal hydrodynamic equations \cite{12}.

In comparison with the QGP phase, the particle density in the hadronic phase which appears in the later period of the system evolution is much lower. To simplify the numerical calculation, we neglect the hadron contribution to the $J/\psi$ production. Solving the coupled transport equation for the charmonium motion and the hydrodynamic equations for the QGP evolution, one can obtain the $J/\psi$ distribution function at the hadronization time and then get the final state $J/\psi$ yield and transverse momentum distribution.

We now calculate the nuclear modification factor $R_{AA}$ and averaged transverse momentum square $\langle p_t^2 \rangle$ as functions of the number of participant nucleons $N_p$ for $J/\psi$s produced in Pb+Pb collisions at SPS and LHC energy and Au+Au collisions at RHIC. All the calculations are in mid rapidity. The corresponding parameters for the initial charmonium and charm quark distributions in NN collisions and for the hot medium can be found in Ref.\cite{9}. At RHIC, both the suppression and regeneration in the medium are stronger than at SPS, the competition between the suppression and regeneration leads to almost the same.
\(R_{AA}\) at RHIC and SPS, especially for semi-central and central collisions with \(N_p > 150\), see Fig. 1. However, the case is very different at LHC. The initially produced \(J/\psi\)s are almost all eaten up by the very hot, long lived and large fireball, and the regeneration becomes dominant in a wide region of \(N_p\). Only for peripheral collisions with \(N_p < 50\), the initial production is important. Due to the increasing suppression and regeneration with centrality, the \(R_{AA}\) decreases with \(N_p\) in the initial production dominant region and increases with \(N_p\) in the regeneration dominant region, see Fig. 1.

![Figure 1](image-url)

Figure 1. The nuclear modification factor \(R_{AA}\) as a function of \(N_p\) for Pb+Pb collisions at SPS and LHC and Au+Au collisions at RHIC at mid rapidity. The SPS and RHIC data are from [2] and [5], and the lines are our theoretical calculations.

Now we come to the \(p_t\) distribution. Fig. 2 shows the averaged transverse momentum square normalized by the corresponding value in NN collisions, \(\langle p_t^2 \rangle_{AA}/\langle p_t^2 \rangle_{pp}\), as a function of centrality (left panel) and the \(R_{AA}\) as a function of \(p_t\) (right panel). While the \(R_{AA}(N_p)\) is almost the same at SPS and RHIC, the transverse momentum distribution is really sensitive to the production mechanism. The dominant initial production, Cronin effect and leakage effect at SPS lead to an increasing \(\langle p_t^2 \rangle_{AA}/\langle p_t^2 \rangle_{pp}\) with \(N_p\) and an increasing \(R_{AA}(p_t)\) with \(p_t\). In contrast to SPS, the regeneration is the dominant production mechanism at LHC which results in decreasing \(\langle p_t^2 \rangle_{AA}/\langle p_t^2 \rangle_{pp}\) and \(R_{AA}(p_t)\). Since we assumed charm quark thermalization in the medium, \(\langle p_t^2 \rangle_{AA}/\langle p_t^2 \rangle_{pp}\) becomes saturated when the contribution from the initial production disappears. Considering the fact that the regenerated \(J/\psi\)s carry low momentum, the \(R_{AA}(p_t)\) is larger than 1 at low \(p_t\) but vanishes at high \(p_t\). The case at RHIC is in between SPS and LHC where both the initial production and regeneration are important and the competition between them controls the \(J/\psi\) production. It is the contribution from the regeneration that separates clearly the \(J/\psi\) transverse momentum distribution at RHIC from that at SPS.

In summary, we studied the contribution from the primordial production in the initial stage and the regeneration in the medium to the \(J/\psi\) production. We found that with increasing fraction of the regeneration from SPS to LHC, the transverse momentum distribution behaves very differently and can be used to differentiate from the \(J/\psi\) production mechanism in high energy nuclear collisions.
Figure 2. The normalized averaged transverse momentum square $\langle p_t^2 \rangle_{AA}/\langle p_t^2 \rangle_{pp}$ as a function of $N_p$ (left panel) and $R_{AA}$ at $b = 0$ as a function of $p_t$ (right panel) for Pb+Pb collisions at SPS and LHC and Au+Au collisions at RHIC at mid rapidity. The SPS and RHIC data are from [14] and [15], and the lines are our theoretical calculations.

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