Enhancement of gluonic dissociation of $J/\psi$ in viscous QGP

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(March 25, 2022)

We have investigated the effect of viscosity on the gluonic dissociation of $J/\psi$ in an equilibrating plasma. Suppression of $J/\psi$ due to gluonic dissociation depend on the temperature and also on the chemical equilibration rate. In an equilibrating plasma, viscosity affects the temperature evolution and also the chemical equilibration rate, requiring both of them to evolve slowly compared to their ideal counter part. For Au+Au collisions at RHIC and LHC energies, gluonic dissociation of $J/\psi$ increases for a viscous plasma. Low $P_T$ $J/\psi$'s are found to be more suppressed due to viscosity than the high $P_T$ ones. Also the effect is more at LHC energy than at RHIC energy.

PACS numbers: 25.75.-q, 25.75.Dw

In relativistic heavy ion collisions $J/\psi$ suppression has been recognized as an important tool to identify the possible phase transition to quark-gluon plasma [1,2]. Because of the large mass of the charm quarks, $c\bar{c}$ pairs are produced on a short time scale. Their tight binding also make them immune to final state interactions. Their evolution probes the state of matter in the early stage of the collisions. Matsui and Satz [3] predicted that in presence of quark-gluon plasma (QGP), due to color screening, binding of $c\bar{c}$ pairs into $J/\psi$ meson will be hindered, leading to the so called $J/\psi$ suppression in heavy ion collisions. Apart from the color screening of $J/\psi$, gluonic dissociation of $J/\psi$ may be important source of $J/\psi$ suppression at RHIC and LHC energies [4,5]. Energy dependence of gluon-$J/\psi$ inelastic cross section shows a strong peak just above the breakup threshold of the gluon energy $\epsilon_0 = 2M_D - M_{J/\psi}$, where $M_{J/\psi}$ and $M_D$ are the $J/\psi$ and D meson masses [6]. In the pre equilibrium stage, the parton momenta will be high enough to break up a $J/\psi$. This break up process will continue during the equilibration process, until the temperature drops below a certain value, or the beginning of hadronisation.

Gluonic dissociation of $J/\psi$ depends on the temperature evolution and on the chemical equilibration rate [4]. It is well known that dissipative effects like viscosity affects the temperature evolution as well as chemical equilibration rate in an equilibrating plasma, requiring both of them to evolve slowly, compared to their ideal counterpart [7]. As a consequence, the pre-equilibrium stage is extended. Correspondingly gluonic dissociation of $J/\psi$ should be increased due to viscosity, $J/\psi$'s will now have more time to interact with a gluon and get suppressed. In the present brief report, we have investigated the effect of viscosity on the gluonic dissociation of $J/\psi$. As will be shown below $J/\psi$ suppression due to gluonic dissociation increases in a viscous plasma. Suppression shows strong $P_T$ dependence, low $P_T$ $J/\psi$'s being more suppressed than the high $P_T$ ones. Suppression is also energy dependent, more at LHC energy than at RHIC energy.

We assume that after a collision, a symmetric partonic system (QGP) is formed in the central rapidity region. We also assume that the partonic system quickly achieve kinetic equilibrium by time $\tau_{iso}$ when momenta of partons become locally isotropic. Beyond $\tau_{iso}$ further expansion of the partonic system can be described by hydrodynamical equations. We assume that the dominant reactions governing the chemical equilibration process are the two body reactions ($gg \leftrightarrow ggg$) and gluon multiplication and its inverse process, gluon fusion ($gg \leftrightarrow ggg$). The hot matter continues to expand and cool due to expansion and chemical equilibration, until the temperature fall below the critical value ($T_c=160$ MeV) at time $\tau_f$. We assume that the hydrodynamical expansion is purely longitudinal. As indicated in [8], at RHIC energies the transverse expansion effect is minimal. It does effect the parton equilibration rate at LHC energies, the effect showing sensitive dependence on the initial condition of the plasma. For initial conditions as obtained from HIJUNG calculations, this effect is not large [8].

A $J/\psi$ produced at point $r$ with velocity $v$ will travel a distance

$$d = -r \cos \phi + \sqrt{R_A^2 - r^2 (1 - \cos^2 \phi)}$$

in the time interval $t_\psi = M_T d/P_T$, before it escapes from the partonic system of transverse extension $R_A$, $\phi$ being the angle between the vectors $r$ and $v$. The total amount of time the $J/\psi$ remains in the plasma and interact with a gluon is the smaller one of $\tau_\psi$ and $\tau_f$, the life time of the plasma.

The survival probability of the $J/\psi$ averaged over its initial position and direction in an equilibrating parton gas can be written as [8],

$$S(P_T) = \frac{\int d^2 r (R_A^2 - r^2) \exp[-\int_{\tau_{iso}}^{\min(\tau_\psi, \tau_f)} d\tau n_g(\tau) <v_{rel} >]}{\int d^2 r (R_A^2 - r^2)}$$

(2)
where \( n_g(\tau) \) is the gluon density at time \( \tau \), \( \langle v_{rel}\sigma \rangle \) is the thermal averaged gluon-\( J/\psi \) cross section, expression for which can be found in [4].

Details of the calculation of \( n_g \) can be found in ref. [7]. In brief, if the dominant reactions leading to chemical equilibration process are \( gg \leftrightarrow ggg \) and \( gg \leftrightarrow q\bar{q} \), following coupled equations determine the evolution of temperature and gluon and quarks fugacities,

\[
\frac{\lambda_g + b_2/a_2(\lambda_q + \lambda_{\bar{q}})}{\lambda_g + b_2/a_2(\lambda_q + \lambda_{\bar{q}})} + \frac{\dot{T}}{T} + \frac{4T}{3\tau} - \frac{4\eta}{3\tau^2} \frac{1}{T^4} = 0 \tag{3a}
\]

\[
\frac{\lambda_q}{\lambda_g} + 3\frac{\dot{T}}{T} + \frac{1}{\tau} - R_3(1 - \lambda_g) + 2R_2(1 - \frac{\lambda_q}{\lambda_g}) = 0 \tag{3b}
\]

\[
\frac{\dot{\lambda}_q}{\lambda_g} + 3\frac{\dot{T}}{T} + \frac{1}{\tau} - R_2 a_1 b_1(\frac{\lambda_q}{\lambda_g} - \frac{\lambda_{\bar{q}}}{\lambda_g}) = 0 \tag{3c}
\]

In eqs.3, \( \lambda_g \) and \( \lambda_q \) are the gluon and quark fugacities, defined as

\[
n_g(\tau) = \tilde{n}_g \lambda_g \tag{4a}
\]

\[
n_q(\tau) = \tilde{n}_q \lambda_q \tag{4b}
\]

where \( \tilde{n}_i \) is the equilibrium density for parton species \( i \),

\[
\tilde{n}_g = \frac{16}{\pi^2} \zeta(3) T^3 = a_1 T^3 \tag{5a}
\]

\[
\tilde{n}_q = \frac{9}{2\pi^2} \zeta(3) N_f T^3 = b_1 T^3 \tag{5b}
\]

\( a_2, b_2 \) are parameters of the equation of state. For a partially equilibrating plasma, the equation of state was written as [7,9],

\[
\varepsilon = 3P = [a_2 \lambda_g + b_2(\lambda_q + \lambda_{\bar{q}})] T^4 \tag{6}
\]

which implies a speed of sound \( c_s = 1/\sqrt{3} \). In eq.(8), \( a_2 = 8\pi^2/15, b_2 = 7\pi^2 N_f / 40, N_f \approx 2.5 \) is the dynamical quark flavors. \( R_2 \) and \( R_3 \) are the density and velocity weighted reaction rates

\[
R_2 = 1/2 < \sigma_{gg\rightarrow q\bar{q}} > n_g, \quad R_3 = 1/2 < \sigma_{gg\rightarrow ggg} > n_g \tag{7}
\]

can be found in [7]. \( \eta \) is the viscosity coefficient. As it was done in our earlier study [7], to demonstrate the effect of viscosity, we have considered two viscosity coefficients,

\[
\eta_1 = \lambda_g \eta_g + \lambda_q \eta_q \tag{8a}
\]

\[
\eta_2 = \frac{12.8}{30} \frac{a_1 T^3}{R_3/T + R_2/T} \tag{8b}
\]

The parameters \( \eta_{g,q} \) are given in ref. [7]. It was seen that while the temperature evolution and the chemical equilibration rate differ considerably for viscosity coefficients \( \eta_{1,2} \), time integrated signals e.g. photon and dilepton emission rates from the equilibrating plasma are nearly same for \( \eta_1 \) and \( \eta_2 \).

Initial conditions for hydrodynamical evolution are listed in table 1. They are the result of the HIJING model calculation for \( \text{Au+Au} \) collision. HIJING is a QCD motivated phenomenological model, as only initial direct parton scatterings are taken into account. Thus there are some uncertainties in these parameters. However, they suffice our purpose of demonstrating the effect of viscosity on gluonic dissociation of \( J/\psi \).

In fig.1, we have shown the \( J/\psi \) survival probability from gluonic dissociation at RHIC and LHC energy for \( \text{Au+Au} \) collisions. Survival probability for the ideal plasma and for the viscous plasma, for the two viscosity coefficients (appropriately labeled) are shown. As expected, survival probability at RHIC energy is large compared to LHC energy [7]. Results confirms our expectation that gluonic dissociation of \( J/\psi \) increases in a viscous plasma. Low \( p_T \) \( J/\psi \)'s are more suppressed than the high \( p_T \) ones. The effect of viscosity is not large at RHIC energy. Due to viscosity survival probability decreases by 7-9% for low \( p_T \) \( J/\psi \)'s. For high \( p_T \) \( J/\psi \), the effect is still lower. Viscosity affects the survival probability of low \( p_T \) \( J/\psi \)'s considerably at LHC energy. For low \( p_T \) \( J/\psi \)'s suppression is increased by 20-27%. As for RHIC energy, effect is minimal for high \( p_T \) \( J/\psi \)'s. \( p_T \) dependence of the survival probability is easily understood. With viscosity, pre-equilibrium stage is increased, thus low \( p_T \) \( J/\psi \) gets more time to interact and get
lost. Larger effect of viscosity at LHC energy is also understood. At LHC energy, initial parton density is high due to high initial temperature. Pre-equilibrium stage is also longer. These leads to more suppression at LHC energy. We also note that the survival probability is nearly same for both the viscosity coefficients. Even at LHC, where the effect is most prominent, the difference between the two survival probabilities is less than 10%. This is in accordance with our earlier findings on photon and dilepton emission from equilibrating plasma [7].

\[
\begin{align*}
S(PT) &
\begin{array}{c}
0.2 \\
0.4 \\
0.6 \\
0.8 \\
1.0
\end{array}
\end{align*}
\]

\begin{align*}
\begin{array}{c}
0 \\
2 \\
4 \\
6 \\
8 \\
10
\end{array}
\end{align*}

\begin{align*}
\begin{array}{c}
\text{RHIC} \\
\text{LHC}
\end{array}
\end{align*}

\begin{align*}
\begin{array}{c}
\text{ideal} \\
\text{vis. (n1)} \\
\text{vis. (n2)}
\end{array}
\end{align*}

FIG. 1. Survival probability of \( J/\psi \) in an equilibrating parton plasma at RHIC and LHC energy.

To summarise, we have studied the effect of viscosity on the gluonic dissociation of \( J/\psi \). Using HIJING inspired initial conditions, it was shown that at RHIC and LHC energies, suppression of \( J/\psi \) due to gluonic dissociation increases with viscosity. Low \( p_T \) \( J/\psi \)'s are now more suppressed. The effect of viscosity is not large at RHIC energy but it is considerable (20-30%) at LHC energy. It is hoped that results will help to have a better understanding of \( J/\psi \) suppression.

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Initial conditions characterising the parton plasma at the onset of hydrodynamic evolution

|          | RHIC | LHC |
|----------|------|-----|
| \( \tau_{iso}(\text{fm/c}) \) | 0.31 | 0.23 |
| \( T_0(\text{GeV}) \)     | 0.57 | 0.83 |
| \( \lambda_0^g \)        | 0.09 | 0.14 |
| \( \lambda_0^q \)        | 0.02 | 0.03 |