Gluonic dissociation of J/ψ's in a viscous strongly-copuled quark-gluon plasma

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Introduction

Statistical QCD predicts that strongly interacting matter undergoes a deconfining transition to a new state, the quark-gluon plasma(QGP), in which the colored quarks and gluons are no longer bound to colorless hadrons. With the help of BNL RHIC and CERN LHC colliders, it makes possible to create this novel state of matter[1]. RHIC experiments have strongly suggested the existence of this new phase of matter showing a strong elliptic flow, from which a very low viscosity to entropy density ratio has been inferred. This suggests that QGP may be a strongly interacting system of quarks and gluons which is also confirmed by the lattice studies of equation of state(EOS). The main probes for QGP confirmation considered so far are real or virtual photons [2], the p_T distribution of secondary hadrons, heavy flavor mesons, quarkonia, and jets etc..The suppression of J/ψ production has been one of the most remarkable signals in this connection.

The heavy quark pair leading to the J/ψ mesons are produced in such collisions on a very short timescale. The pair then develops into the physical resonance over its formation time and traverses the plasma and (later) the hadronic matter before leaving the interacting system to decay into a dilepton. Even before the resonance is formed it may be absorbed by the nucleons streaming past it[3]. By the time the resonance is formed, the screening of the colour forces in the plasma may be sufficient to inhibit a binding of the $c\bar{c}$ [2, 4]. Or an energetic gluon[5] or a comoving hadron[6] could dissociate the resonance(s). In the present work we concentrate on the dissociation of the charmonium in quark gluon plasma due to scattering with highly energetic gluons.

Dissociation of J/ψ by gluons

In order to estimate the gluonic dissociation we recall [7] that the short range properties of the QCD can be used to derive the gluon-J/ψ cross-section as:

$$\sigma(q^0) = \frac{2\pi}{3}\left(\frac{32}{3}\right)^2 \frac{1}{m_C(\epsilon_0 m_C)^{1/2}} \frac{(q^0/\epsilon_0 - 1)^{3/2}}{(q^0/\epsilon_0)^5}, \tag{1}$$

where q^0 is the gluon energy in the rest-frame of J/ψ and ϵ_0 is the binding energy of the J/ψ. The expression for the thermal average of this cross-section $< v_{\rm rel}\sigma >$ is given by [5]

$$\langle v_{\rm rel}\sigma(k\cdot u)\rangle_k = \frac{\int d^3k v_{\rm rel}\sigma(k\cdot u) f(k^0;T)}{\int d^3k f(k^0;T)}\ , \tag{2}$$

where $f(k^0;T)$ is the gluon distribution in the rest frame of the parton gas and $v_{\rm rel}$ is the relative velocity between the J/ψ and a gluon. The temperature dependence of thermal average of gluon-J/ψ dissociation cross section at different values of the J/ψ's transverse momentum P_T has kind of peak structure, with a decreased maximum value due to the thermal average and the position of the peak shifts to smaller values of T with increase in P_T. A similar behavior is expected if one plots the thermal cross section as a function of P_T at different temperatures[9]. These features will have considerable consequences for the survival probability of a J/ψ.

Survival Probability

Using this thermal cross section, we can now calculate the survival probability of J/ψ in QGP in the central rapidity region undergoing longitudinal expansion. Suppose a J/ψ produced at point $\vec{r}$ with velocity $\vec{v}$ in the transverse direction will travel a distance $d(r,\phi) = -r\cos\phi + \sqrt{R_A^2 - r^2(1-\cos^2\phi)}$ in the time interval $t_\psi = d(r,\phi)/v$ before it escapes from a QGP of transverse extension R_A. Suppose the system evolves in a QGP state until the temperature drops below a certain value, say 170 MeV. The total

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amount of time the J/ψ remains inside a deconfined parton gas is the smaller one of the two times t_ψ and t_f, the life-time of the parton gas. Assume that the initial production rate of the J/ψ is proportional to the number of binary nucleon-nucleon interactions at impact-parameter r, $N_A(r) = A^2(1-r^2/R_A^2)/2\pi R_A^2$. The survival probability of the J/ψ averaged over its initial position and direction is given by

$$S(P_T) = \frac{\int d^2r(R_A^2 - r^2)e^{-W}}{\int d^2r(R_A^2 - r^2)} \quad \text{where} \tag{3}$$

$$W = \int_{\tau_i}^{t_{\min}} d\tau n_g(\tau)\langle v_{\rm rel}\sigma(k\cdot u)\rangle_k \tag{4}$$

where $t_{\min} = \min(t_\psi, t_f)$ and both the gluon number density $n_g(\tau)$ and the thermal cross section $\langle v_{\rm rel}\sigma(k\cdot u)\rangle_k$ depend on the temperature, which in turn is a function of time. Although deconfined partonic system formed attains thermal equilibrium but may not be in a chemical equilibrium. Therefore it approaches towards chemical equilibrium by a set of master rate equations involving quark and gluon fugacities [10] which give rise the time dependence of the temperature and fugacities, with the assumption of an ideal (nonviscous) thermal medium. To study the effect of viscous forces, the above set of master equations [10] get modified [11]

$$\frac{\dot\lambda_g + b_2/a_2(\dot\lambda_q + \dot\lambda_{\bar q})}{\lambda_g + b_2/a_2(\lambda_q + \lambda_{\bar q})} + 4\frac{\dot T}{T} + \frac{4}{3\tau}$$

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

$$\frac{\dot\lambda_g}{\lambda_g} + 3\frac{\dot T}{T} + \frac{1}{\tau} - R_3(1-\lambda_q) + 2R_2\left(1 - \frac{\lambda_q\lambda_{\bar q}}{\lambda_{g^2}}\right) = 0$$

$$\frac{\dot\lambda_q}{\lambda_q} + 3\frac{\dot T}{T} + \frac{1}{\tau} - R_2\frac{a_1}{b_1}\left(\frac{\lambda_g}{\lambda_q} - \frac{\lambda_{\bar q}}{\lambda_g}\right) = 0 \tag{5}$$

where λ_g and λ_q are the gluon and quark fugacities and the other symbols are the same as in [11].

To study the centrality (or number of participants) dependence of the survival probability, we use the initial energy density, number density and temperature from [8]

$$\begin{aligned} \epsilon_i &= 0.103 Gev fm^{-3} A^{0.504}(\sqrt{s})^{0.786} \\ n_i &= 0.370 fm^{-3} A^{0.383}(\sqrt{s})^{0.574} \\ T_i &= 0.111 Gev A^{0.126}(\sqrt{s})^{0.197} \quad , \end{aligned} \tag{6}$$

where the initial number densities for the chemically equlibrating plasma are written in terms of initial temperature and initial fugacities (λg_i and λq_i) are obtained from [10]

$$n_i = \lambda_g^i a_1 T_i^3, \epsilon_i = \lambda_g^i a_2 T_i^4 \tag{7}$$

with the symbols given in [10]. The quark fugacity is taken as $\lambda_q = \lambda_g^i/5$.

We thus have finally evaluated the survival of J/ψ's in an equilibrating strongly-coupled plasma with the number of participants which, in turn, depends on the centrality of the collision. We consider first-order dissipative corrections to the plasma equation of motion in the Bjorken boost-invariant expansion with a strongly-coupled equation of state for QGP. The J/ψ's will now take longer time to travel through medium in presence of viscous forces, the probability of scattering with gluon thus increases. This results in more suppression. The suppression will be more pronounced for low p_T J/ψ's. The effect is not large at RHIC energy but it is considerable at LHC energy. A systematic study of quarkonium suppression for systems of varying participants(dimensions) can help to identify the source of competing mechanisms: Debye screening of colour interaction and dissociation due to energetic gluons and the extent of the suppression.

Acknowledgments

Mr. Uttam Kakade is thankful to Govt.of Maharashtra for deputation under QIP scheme AICTE, New Delhi.

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