PRAMANA — journal of physics
© Indian Academy of Sciences
Vol. 60, No. 5
May 2003
pp. 1089–1093

Quarkonium suppression: Gluonic dissociation vs. colour screening

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Abstract. We evaluate the suppression of J/ψ production in an equilibrating quark gluon plasma for two competing mechanisms: Debye screening of colour interaction and dissociation due to energetic gluons. Results are obtained for S + S and Au + Au collisions at RHIC and LHC energies. At RHIC energies the gluonic dissociation of the charmonium is found to be equally important for both the systems while the screening of the interaction plays a significant role only for the larger systems. At LHC energies the Debye mechanism is found to dominate both the systems. While considering the suppression of directly produced Υ at LHC energies, we find that only the gluonic dissociation mechanism comes into play for the initial conditions taken from the self screened parton cascade model in these studies.

Keywords. Quark gluon plasma; J/ψ; suppression; dissociation; colour screening.

PACS No. 12.38.M

1. Introduction

The last two decades have seen hectic activity towards identifying unique signatures of the quark–hadron phase transition. The suppression of J/ψ production in such collisions has been one of the most hotly debated signals in this connection. The heavy quark pair leading to J/ψ mesons are produced in such collisions on a very short time-scale $\sim 1/2m_c$, where m_c is the mass of the charm quark. The pair develops into the physical resonance over a formation time τ_ψ and traverses the plasma and (later) the hadronic matter before leaving the interacting system to decay (into a dimuon) to be detected. This long 'trek' inside the interacting system is fairly 'hazardous' for J/ψ. Even before the resonance is formed it may be absorbed by the nucleons streaming past it [1]. 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 $c\bar{c}$ [2,3] or an energetic gluon [4] or a comoving hadron [5] could dissociate the resonance(s). The extent of absorption will be decided by a competition between the momentum of J/ψ and the rate of expansion and cooling of the plasma, making it sensitive to such details as the speed of sound [6,7]. Thus a study of J/ψ production is poised to provide a wealth of information about the evolution of the plasma and its properties.

In the present work we concentrate on the dissociation of the charmonium in quark gluon plasma due to colour screening and scattering with gluons and ask whether we can distinguish between the two mechanisms. We emphasize that these mechanisms are in addition to nucleonic absorption mentioned earlier.

2. Colour screening and gluon dissociation

In principle the colour screening is a collective effect, where the presence of a large number of colour quanta modifies the force between c and $\bar{c}$ so that, above the critical temperature ($T_{\rm c}$ ~200 MeV), we have

$$V(r) = -\alpha/r + \sigma r \;\;\rightarrow\;\; V(r) = -\alpha \exp(-\mu_{\rm D} r)/r, \tag{1}$$

where α and σ (the string tension) are phenomenological parameters and $\mu_{\rm D}$ is the Debye mass.

Thus, e.g., the direct production of J/ψ is inhibited once the Debye mass is more than 0.7 GeV [8]. The gluonic dissociation, on the other hand, is always possible as long as an energetic gluon can be found. They can always be present in the tail of the thermal distributions and thus given sufficient time, a J/ψ can always be dissociated in a plasma of any temperature!

Let us assume that a thermally equilibrated plasma is formed in relativistic heavy-ion collisions at some time τ_i and that the elastic scattering among the partons is sufficiently rapid to maintain thermal equilibrium. A large number of studies [9,10] have indicated that the plasma thus produced may not be in a state of chemical equilibrium and that the quark and gluon fugacities are less than unity. The evolution of the parton densities are discussed in detail by [11].

The results for the time evolution of the fugacities and the temperature for the initial conditions obtained from the self-screened parton cascade model [10] for Au+Au collisions at RHIC and LHC energies are given in [12]. For the S + S collisions we assume that while the initial fugacities are the same as those for the Au + Au system, the initial temperatures are estimated by assuming that it scales as $T_{\rm i} \sim A^{0.126}$.

We shall also introduce a energy density profile such that

$$\varepsilon(\tau_i, r) = (1+\beta)\,\langle \varepsilon_i \rangle\,(1 - r^2/R^2)^{\beta}\,\Theta(R - r), \tag{2}$$

where $\beta = 1/2$, R is the transverse dimension of the system, r is the transverse distance, and $\langle \varepsilon_i \rangle$ is the energy density obtained by taking the initial temperature as T_i and fugacities as λ_i [10].

Having obtained the density of the partons we estimate the Debye mass of the medium as

$$\mu_{\rm D}^2 = \kappa^2 4\pi\alpha_s(\lambda_g + N_f \lambda_q/6)\; T^2, \tag{3}$$

where we have arbitrarily taken κ as 1.5 to account for the corrections [13] to the lowest-order perturbative QCD which provides the above expression for $\kappa = 1$. We shall assume that J/ψ *cannot* be formed in the region where $\mu_{\rm D}$ is more than 0.7 GeV. We can then estimate the survival probability of the directly produced J/ψ as a function of its transverse momentum $p_{\rm T}$ by proceeding along the lines of refs [6–8].

In order to estimate the gluonic dissociation we recall [14] that the short range properties of the QCD can be used to derive the gluon–J/ψ cross-section as

$$\sigma(q^0) = \frac{2\pi}{3}\left(\frac{32}{3}\right)^2 \frac{1}{m_C(\varepsilon_0 m_C)^{1/2}} \frac{(q^0/\varepsilon_0 - 1)^{3/2}}{(q^0/\varepsilon_0)^5}, \tag{4}$$

where q^0 is the gluon energy in the rest-frame of J/ψ and ε_0 is the binding energy of J/ψ. The expression for the thermal average of this cross-section $\langle v_{\mathrm{rel}}\sigma\rangle$ is given in ref. [4].

We argue that the gluon–J/ψ cross-section also attains its full value only after the $c\bar{c}$ pair has evolved into the physical resonance. We assume that this evolution of the cross-section can be parametrized as

$$\sigma = \begin{cases} \sigma_0 \left(\tau/\tau_\psi\right)^2 & \text{if } \tau \le \tau_\psi \\ \sigma_0 & \text{if } \tau > \tau_\psi \end{cases}, \tag{5}$$

similarly to the case when the nuclear absorption is considered [15], where σ_0 is the cross-section estimated earlier (eq. (4)).

We can now easily estimate the time spent by J/ψ in the deconfined medium for a given p_{T} and get the survival probability following ref. [4].

3. Results and discussions

In figure 1 we show our results for RHIC energies for S+S and Au+Au collisions. We see that the combination of a finite formation time and (reasonably) large μ_{D} required to inhibit the formation of the directly produced J/ψ in the plasma ensures that the mechanism of Debye screening is not effective in suppressing its production. However the gluonic dissociation leads to a suppression of J/ψ formation even after the moderating effect of the inclusion of formation time is included.

The situation for the larger (and hotter) volume of plasma produced in Au+Au collisions is much richer in detail. We see that while J/ψs having lower transverse momenta are more

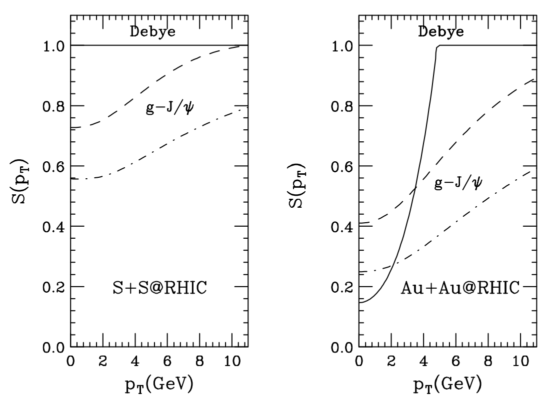

Figure 1. Survival probability of directly produced J/ψ at RHIC energies due to screening of colour interaction (solid curve) and gluonic dissociation in quark gluon plasma. The dashed curve gives the latter with inclusion of formation time of the charmonium while the dot-dashed curve gives the same with the assumption that a fully formed J/ψ is available at $\tau = \tau_i$ when the plasma is formed.

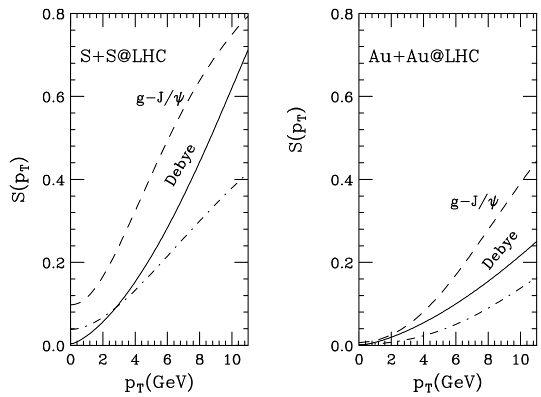

Figure 2. Same as figure 1 at LHC energies.

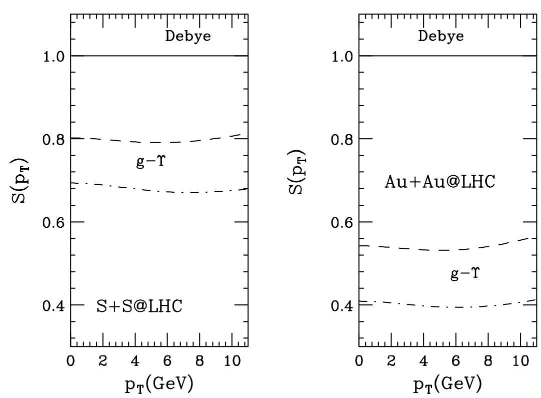

Figure 3. Same as figure 1 for ϒ at LHC energies. The Debye screening is absent for the initial conditions [10] used here.

strongly suppressed due to the Debye mechanism, those having higher transverse momenta are more suppressed by the mechanism of gluonic dissociation. In fact we see that while the Debye screening has become quite ineffective for $p_{\rm T} > 6$ GeV, the gluonic dissociation continues to be operative.

The corresponding results at LHC energies are shown in figure 2. Now we see that the Debye screening is more effective in suppressing the production of the directly produced J/ψ at all the momenta considered, provided we include the considerations of the formation time while evaluating the gluonic dissociation, for both the systems. The treatment outlined here can be extended to the case of ϒ production studied in great detail by the authors of refs [7,16], for example. We give the results only for the LHC energies, for the directly produced ϒ (figure 3).

We find that both for the light as well as the heavy systems the Debye mechanism is not at all able to inhibit the formation of the directly produced ϒs, though the gluonic dissociation leads to a considerable suppression, with the changes brought about by the inclusion of the formation time seen earlier for J/ψs. This is easily seen to be the consequence of the initial conditions used here, which have chemically non-equilibrated plasma leading to small Debye mass, even though the temperature is rather high. By the time the Υ is formed the Debye mass drops below the value of $\sim$1.6 GeV, required to inhibit its formation, causing it to escape unscathed.

While considering the suppression of Υ, we found that only the mechanism of gluonic dissociation is playing a role. This happens as the initial conditions used here involve a chemically non-equilibrated plasma. If the initial fugacities were to be larger, the Debye screening would also play a role, which will definitely be a good check on these.

In brief, we have seen that while the gluonic dissociation of J/ψ is always possible, the Debye screening is not effective in the case of small systems at RHIC energies. For larger systems, the Debye screening is more effective for lower transverse momenta, while the gluonic dissociation dominates for larger transverse momenta. At LHC energies the Debye screening is the dominant mechanism of J/ψ suppression for all the cases and momenta studied. We have also seen that the inclusion of the formation time of J/ψ plays an interesting role in reducing the role of the gluonic dissociation. As an interesting result, we find the gluonic dissociation to be substantial but the Debye screening to be ineffective for Υ suppression at the LHC energy. This may of course change if different initial conditions and screening criteria [7,16] are employed.

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