

\textbf{J/ψ suppression: gluonic dissociation vs. colour screening}

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(October 28, 2018)

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 for both the systems. While considering the suppression of directly produced \( T \) 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. Thus we find that a systematic study of quarkonium suppression for systems of varying dimensions can help identify the source and the extent of the suppression.

PACS numbers: 12.38M

Relativistic heavy ion collision experiments at the CERN SPS are believed \( \mathbb{1} \) to have led to a production of quark gluon plasma - which existed in the early universe and which may be present in the core of neutron stars. The last two decades have seen a 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 the \( J/ψ \) 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 \( \tau_c \) 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 the \( J/ψ \). Even before the resonance is formed it may be absorbed by the nucleons streaming past it \( \mathbb{3} \). 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 \( c\bar{c} \). Or an energetic gluon \( \mathbb{2} \) or a comoving hadron \( \mathbb{4} \) could dissociate the resonance(s). The extent of absorption will be decided by a competition between the momentum of the \( J/ψ \) and the rate of expansion and cooling of the plasma, making it sensitive to such details as the speed of sound \( \mathbb{5} \). Thus a study of \( J/ψ \) production is poised to provide a wealth of information about the evolution of the plasma and its properties.

It has been shown \( \mathbb{6} \) that the nucleonic absorption (the “normal absorption”), operating on the pre-resonance- which is yet to evolve into a physical particle- is identical for \( J/ψ, ψ', \) and \( χ_c \). This absorption is always present and is brought about by the nucleons (or the Lorentz-contracted partonic clouds) streaming past the pre-resonances, as mentioned earlier. A reliable quantitative estimate within Glauber model is available \( \mathbb{3} \) for this.

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.

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 (\( T_c \sim 200 \text{ MeV} \)), we have:

\[ V(r) = -\alpha/r + \sigma r \quad \rightarrow \quad V(r) = -\alpha \exp(-\mu_D r)/r \quad (1) \]

where \( \alpha \) and \( \sigma \) (the string tension) are phenomenological parameters and \( \mu_D \) is the Debye mass.

Thus, e.g., the direct production of the \( J/ψ \) is inhibited once the Debye mass is more than 0.7 GeV \( \mathbb{11} \). 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!

Of course in actual practice the QGP will expand and cool and undergo hadronization below the critical temperature \( T_c \), and thus the hot medium will have only a finite life-time. This enriches the competition between the mechanisms of the gluonic dissociation and the Debye screening for the charmonium suppression. In the present work we show that this also provides us with a handle to decipher the extent to which each mechanism contributes to the suppression of \( J/ψ \).

Let us assume that a thermally equilibrated plasma is formed in relativistic heavy ion collisions at some time \( \tau_i \) and that the elastic scattering among the partons is sufficiently fast to maintain thermal equilibrium. A large number of studies \( \mathbb{12} \mathbb{13} \) 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. We assume that the chemical equilibration proceeds dominantly via

\[ gg \leftrightarrow ggg, \quad gg \leftrightarrow q\bar{q}. \quad (2) \]

Assuming the evolution to proceed according to Bjorken hydrodynamics, the evolution of the parton densities are given by \( \mathbb{13} \):
\[ \frac{\dot{\lambda}_q}{\lambda_q} + 3\frac{\dot{T}}{T} + \frac{1}{\tau} = R_3(1 - \lambda_g) - 2R_2 \left( 1 - \frac{\lambda_q}{\lambda^2_q} \right), \]  
\( (3) \)

\[ \frac{\dot{\lambda}_q}{\lambda_q} + 3\frac{\dot{T}}{T} + \frac{1}{\tau} = R_2 \frac{a_1}{b_1} \left( \frac{\lambda_q}{\lambda_q} - \frac{\lambda_q}{\lambda_q} \right), \]  
(4)

\[ \left( \frac{\lambda_q}{a_2^2} \right)^{3/4} T^3\tau = \text{const}, \]  
(5)

where \( a_1 = 16\zeta(3)/\pi^2 \approx 1.95 \), \( a_2 = 8\pi^2/15 \approx 5.26 \), \( b_1 = 9\zeta(3)N_f/\pi^2 \approx 2.20 \), and \( b_2 = 7\pi^2N_f/20 \approx 6.9 \). The expressions for the density and velocity weighted reaction rates,

\[ R_3 = \frac{1}{2} < \sigma_{gg \to gg} v > n_g, \quad R_2 = \frac{1}{2} < \sigma_{gg \to q\bar{q}} v > n_g \]  
(6)

can be found in Ref. [13].

The results for the time evolution of the fugacities and the temperature for the initial conditions obtained from the self screened parton cascade model [12] for \( Au + Au \) collisions at RHIC and LHC energies are given in Ref. [14]. For the \( S + S \) collisions we assume that while the initial fugacities are same as those for the \( Au + Au \) system, the initial temperatures are estimated by assuming that it scales as \( T_i \sim A^{0.126} \). This is motivated by a recent study on the basis of parton saturation [13] which also suggests that the initial number density divided by \( T_i^3 \) is nearly independent of the mass-number of the nuclei. This, we believe, provides a useful initial guess, even though the conditions envisaged for self screening are not strictly met for \( S + S \) at RHIC. For the sake of completeness, we have given the initial conditions in Table 1. It may be noted that these are different from those used in Ref. [13], which were ‘inspired’ by the HIJING model and which had, for example, much smaller fugacities. (We have verified that our computer program fully reproduced the results of Ref. [13], with the initial conditions given there.)

We shall also introduce a energy density profile such that,

\[ \epsilon(\tau, r) = (1 + \beta) < \epsilon_i > (1 - r^2/R^2)^\beta \Theta(R - r) \]  
(7)

where \( \beta = 1/2 \), \( R \) is the transverse dimension of the system and \( r \) is the transverse distance, and \( < \epsilon_i > \) is the energy density obtained by taking the initial temperature as \( T_i \) and fugacities as \( \lambda_i \) [14]. The profile plays an important role in defining the boundary of the hot and dense deconfined matter.

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

\[ \mu_D^2 = \kappa^2 \times 4\pi\alpha_s(\lambda_g + N_f\lambda_q/6) T^2 \]  
(8)

where we have arbitrarily taken \( \kappa \) as 1.5 to account for the corrections [14] to the lowest order perturbative QCD which provides the above expression for \( \kappa = 1 \). Results for other values of \( \kappa \) are easily obtained. We shall assume that the \( J/\psi \) can not be formed in the region where \( \mu_D \) is more than 0.7 GeV. We can then estimate the survival probability of the directly produced \( J/\psi \) as a function of its transverse momentum \( p_T \) by proceeding along the lines of Ref. [13].

In order to estimate the gluonic dissociation we recall [17] that the short range properties of the QCD can be used to derive the gluon-\( J/\psi \) cross-section as:

\[ \sigma(q^0) = \frac{2\pi}{3} \left( \frac{32}{3} \right)^2 \frac{1}{m_C(\epsilon_0)mc)^{1/2}} \left( q^0/\epsilon_0 - 1 \right)^{3/2}/(q^0/\epsilon_0)^5, \]  
(9)

where \( q^0 \) is the gluon energy in the rest-frame of \( J/\psi \) and \( \epsilon_0 \) is the binding energy of the \( J/\psi \). The expression for the thermal average of this cross-section \( < v_{\text{rel}}^1 > \) is given in Ref. [11]. (See, also Ref. [13] for an interesting alternative approach.)

We wish to have a quantitative comparison of these two processes and therefore it is imperative that we compare their results for similar conditions. Thus, exactly as while dealing with Debye screening, we assume that the \( \sigma \) produced initially takes a finite amount of time \( \sim 0.89 \text{ fm}/c \) in its rest frame to evolve into the physical resonance. This can get large due to time dilation, in the frame of the plasma, leading to the characteristic \( p_T \) dependence of the survival probability for the \( J/\psi \) discussed in the literature.

We argue that the gluon-\( J/\psi \) cross-section also attains its full value only after the \( \sigma \) pair has evolved into the physical resonance. We assume that this evolution of the cross-section can be parametrized as

\[ \sigma = \begin{cases} \sigma_0 & \text{if } \tau \leq \tau_\psi \\ \sigma_0(\tau/\tau_\psi)^\nu & \text{if } \tau > \tau_\psi \end{cases} \]  
(10)

similarly to the case when the nuclear absorption is considered [19], where \( \sigma_0 \) is the cross-section estimated earlier (Eq. 1). A similar assumption was invoked by Farrar et al. [21] when the \( Q\bar{Q} \)-system evolves as it moves away from the point of hard interaction. One may imagine that this amounts to assuming that the effective cross-section scales as the transverse area of the system relative to the size it attains when it is fully formed. In the present work we follow, Blaizot and Ollitrault [13] who have used \( \nu = 2 \). Farrar et al. [21] have suggested that \( \nu = 1 \) corresponds to a quantum diffusion of the quarks while \( \nu = 2 \) would correspond to maximal rapid (classical) expansion. Legrand et al. [22] have used \( \nu = 1 \) in a recent study.

This aspect is in contrast to the work of Xu et al. [13] where a fully formed \( J/\psi \) is assumed to exist right at the initial time in the plasma. We shall see that ignoring the formation time leads to an enhanced suppression of the charmonium.

We can now easily estimate the time spent by the \( J/\psi \) in the deconfined medium for a given \( p_T \) and get the survival probability following Ref. [13].
In Fig. 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 $\mu_D$ required to inhibit the formation of the directly produced $J/\psi$ 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 the $J/\psi$ 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 the $J/\psi$s having lower transverse momenta are more 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 $p_T > 6$ GeV, the gluonic dissociation continues to be operative. The different results obtained here compared to authors of Ref. [8,23] (when the formation time considerations are ignored) are solely due to the SSPC initial conditions (Table 1) used here.

The corresponding results at LHC energies are shown in Fig. 2. Now we see that the Debye screening is more effective in suppressing the production of the directly produced $J/\psi$ at all the momenta considered, provided we include the considerations of the formation time while evaluating the gluonic dissociation, for both the systems.

Of-course in a model calculation one can arbitrarily enhance the impact of Debye screening by taking a larger value for the coefficient $\kappa$ (Eq.8). This sensitivity would be useful for determining its precise value [23].

The treatment outlined here can be extended to the case of $\Upsilon$ production studied in great detail by the authors of Ref. [1] (when the formation time considerations are ignored) are solely due to the SSPC initial conditions (Table 1) used here.

Of-course a full study will additionally include the effect of the nuclear and the co-mover absorption, before these interesting details are investigated.

The incorporation of the formation time is interesting for one more reason. The pre-equilibrium stage (before the time $\tau_1$) may be marked by presence of gluons of high transverse momenta, as a result of first hard collisions, and one may imagine that they play an important role in suppression of charmonium formation. This is unlikely for two reasons. Firstly, the gluon-charmonium cross-section drops rapidly as the gluon momentum increases after reaching a peak around $p \sim 1$ GeV. Secondly we expect these cross-sections to be further suppressed during the formation era due to the considerations of the formation time.

While considering the suppression of $\Upsilon$, 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 the $J/\psi$ is always possible, the Debye screening is not effective in the case of small systems at RHIC energies. For the 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 $J/\psi$ suppression for all the cases and momenta studied. We have also seen that the inclusion of the formation time of the $J/\psi$ 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 $\Upsilon$ suppression at the LHC energy. This may of-course change if different initial conditions and screening criteria [23] are employed.
ACKNOWLEDGEMENTS

We thank Dr. Dipali Pal for collaboration during the early phases of this work and Prof. Helmut Satz for useful comments. We also thank Prof. Joseph Kapusta for useful correspondence.

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| Table I. Initial values for the time, temperature, fugacities etc. for Au+Au and S+S at RHIC and LHC. | RHIC | LHC |
|---|---|---|
| $\epsilon_i$ (GeV/fm$^3$) | 61.40 | 425 |
| $T$ (GeV) | 0.668 | 1.02 |
| $\tau_0$ (fm) | 0.25 | 0.25 |
| $\lambda_g$ | 0.34 | 0.43 |
| $\lambda_q$ | 0.068 | 0.086 |

| | RHIC | LHC |
|---|---|---|
| $\epsilon_i$ (GeV/fm$^3$) | 24.3 | 170 |
| $T$ (GeV) | 0.531 | 0.811 |
| $\tau_0$ (fm) | 0.25 | 0.25 |
| $\lambda_g$ | 0.34 | 0.43 |
| $\lambda_q$ | 0.068 | 0.086 |
FIG. 1. Survival probability of directly produced $J/\psi$ 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 $J/\psi$ is available at $\tau = \tau_i$ when the plasma is formed.

FIG. 2. Same as Fig. 1 at LHC energies.

FIG. 3. Same as Fig. 1 for $\Upsilon$ at LHC energies. The Debye screening is absent for the initial conditions used here.