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J/Ψ suppressions in a thermally equilibrating quark-gluon plasma at RHIC

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Abstract: We estimate the survival probability of J/ψ in relativistic heavy-ion collisions, using both short-distance QCD and nuclear absorption mechanism. The suppression is found to be almost 100 percent for a thermally equilibrating quark-gluon plasma. The measurement of such a huge suppression of J/ψ may suggest the existence of a deconfined partonic medium, possibly a thermalised quark-gluon plasma, at RHIC.

Keywords: QCD, Hadronic Colliders.

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Contents

1 Introduction

Recently a lot of effort is being made to detect a new phase of matter, namely quark-gluon-plasma(QGP). It is known from lattice quantum chromodynamics [1] that hadronic matter at sufficiently high temperatures ($\sim 200MeV$) and densities undergoes a transition to this quark-gluon plasma phase. While such a phase surely did exist in the early universe, it is interesting if we can recreate the early universe and experimentally verify this QCD phase in the laboratory *i.e.* in ultra relativistic heavy ion collisions (URHIC). In the near future, the relativistic heavy ion colliders(RHIC) at BNL and large Hadron Colliders(LHC) at CERN [2, 3] will be able to study such a phase. However this deconfined phase is not accesible directly at these collider experiments. The signatures are therefore necessarily indirect, and the prominent ones are : 1) J/ψ suppression [4], 2) electromagnetic probes such as dilepton and direct photon production [5, 6, 7], and 3) strangeness enhancement [8].

Dileptons and single photons have long been proposed as useful probes of the plasma [7], as once produced, they hardly interact with the strongly interacting matter and thus carry the details of the circumstances of their production. However, as they are also produced via hadronic decays in the later stages of evolution, where plasma expands and cools, it becomes difficult to distinguish between them. In that sense the production of $c\bar{c}$ is a clean process, as it is not produced in the later stages due to its heavy mass. The production of $c\bar{c}$ takes place mainly at the hard vertex. Once produced, $c\bar{c}$ will evolve in to open D mesons and charmonium states, such as J/ψ, χ, etc., while travelling through this dense phase of matter. Unlike hadronic collisions, where an enhancement of J/ψ is found at tevatron energy [9], both $c\bar{c}$ and J/ψ get suppressed while traveling through different stages of quark-gluon plasma. There might be thermal charm productions in the very early stage of the plasma, where the temperature is very high, but no production of $c\bar{c}$ can occur in the later stages due to decrease in the temperature.

The various stages by which the complete evolution of quark-gluon plasma is described in URHIC are, i) pre-equilibrium, ii) equilibrium, where one actually studies the thermalised quark-gluon plasma, iii) cooling and iv) hadronisation. The production of an equilibrated quark-gluon plasma in stage (ii) crucially depends on the pre-equilibrium evolution, *i.e.* on stage (i). Matsui and Satz [4] has suggested the suppression of J/ψ in the equilibrium phase. In their study, the debye screening length which is calculated from lattice QCD, is found to be less than the J/ψ radius. This forbids the binding of $c\bar{c}$ to J/ψ in the equilibrated quark-gluon plasma. However, such a study is not available for an equilibrating quark-gluon plasma. There could be any interesting effects in the pre-equilibrium stage, when $c\bar{c}$ or J/ψ travel before reaching the equilibrium stage. As high energy deconfined partons are also present in the pre-equilibrium stage, J/ψ is suppressed due to its interaction with these deconfined partons. Since the J/ψ dissociation cross section inside a deconfined partons is very different from that inside a hadronic gas (see section 2), the study of J/ψ suppression can then provide us with evidence for color deconfinement in the parton plasma and possibly with information on the QCD phase transition.

Another outcome of the pre-equilibrium study is the prediction of the equilibration time, the time at which quark-gluon plasma equilibrates. A detail knowledge of equilibration time and J/ψ formation time is very crucial in determining the J/ψ suppressions in URHIC. This is because, a large equilibration time may permit a J/ψ formation from $c\bar{c}$ pairs before plasma equilibrates. Then the interaction of a fully formed J/ψ with deconfined partons is prefered than screening. If the J/ψ formation time is greater than the equilibration time or comparable to it, then $c\bar{c}$ interacts with the deconfined partons before screening starts operating in the equilibrium stage. The interaction of a $c\bar{c}$ with the partons before plasma equilibriates is not studied yet, and such a calculation is beyond the scope of this paper.

In any case, a careful study of pre-equilibrium evolution of quark-gluon plasma is the consistent way to study production and equilibration of quark-gluon plasma in URHIC. From this point of view it is necessary to study what happens actually to the J/ψ suppressions at different stages of evolution of QGP, rather than estimating it in an equilibrated quark-gluon plasma. We study here the suppression of a fully formed J/ψ in equilibrating quark-gluon plasma using short distance QCD and suppression of a nascent J/ψ by nuclear absorption. The J/ψ may also be suppressed in later stages due to inelastic collisions with hadrons, but we do not consider it here. This suppressions will be less due to lesser value of the hadron-J/ψ inelastic cross section (described in section 2).

However, J/ψ suppression is also measured in p-A collisions where there is no existence of quark-gluon plasma [10, 11]. At these experiments the suppression of J/ψ is due to the presence of a nuclear medium. The prominent mechanism by which these datas are explained at SPS is via nuclear absorption, the suppression of a nascent J/ψ before it forms a physical resonance [12, 13]. Within this mechanism, one does not as-

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sume the existence of a quark-gluon plasma phase or a highly densed deconfined partonic medium. This is the case with some light nuclei collisions at SPS [10, 11]. However the recent measurements of J/ψ suppression by NA50 collaboration [14] (Pb-Pb collisions at $\sqrt{s} = 17GeV$) yeild an excess suppression of J/ψ, which is not explained by the above conventional approach. Presence of a nuclear medium may not be enough to explain this data. There are speculations that this suppression is due to the existence of a deconfined partonic medium [15] or a high energy density matter [16].

Whether an equlibrated plasma has formed in Pb-Pb collisons at SPS($\sqrt{s} = 17GeV$) or not, is debatable, but at RHIC(Au-Au collisions at $\sqrt{s} = 200GeV$) we may go closer to the equilibrated quark-gluon plasma. In this paper we estimate the J/ψ suppressions at RHIC and its possible implication on deconfinement.

However before studying charmonium suppressions in quark-gluon plasma it is essential to study the corresponding situations in hadronic collisions. The experimental analysis of quarkonia production in high energy hadronic collisions at tevatron energy [9] revealed a drastic disagreement with the predictions from color singlet model [17]. A substantial fraction of quarkonium production at very high energy arises from intermediate color octet fluctuation during the evolution into final state color singlet Q$\bar{Q}$ pair. Now a rigorous theoretical foundation has been achived by Bodwin, Braaten, and Leepage [18], who devloped a QCD formalism by marrying pQCD and an effective field theory within non-relativistic QCD(NRQCD). This formalism accounts for the production of both color singlet and color octet $c\bar{c}$ states, that evolve in to final color singlet quarkonium. Within NRQCD, the production amplitude is expanded in powers of both the strong coupling α_s and the velocity of heavy quark($v^2 = .23$ for $c\bar{c}$ system), which includes higher fock-state components. The long distance non-pertubative matrix element is either fitted from experiments or taken, in principle, from lattice QCD [19]. This technique has been used to study many heavy quarkonium production processes in hadronic collisons. However a space time evolution of quarkonium using this technique has not been achived. This is crucial for studying the evolution of J/ψ in nuclear collisions. The existence of background chromoelectric field [20] and high dense partonic medium complicates the study of the evolution of $c\bar{c}$ to J/ψ, both at RHIC and LHC. As $c\bar{c}$ takes $\simeq$ 1.0 fm (time in $c\bar{c}$ rest frame) to form a J/ψ bound state, it interacts with the nearby light partons and with the background chromoelectric field during this period. No attempts is made on this line to study J/ψ production and its subsequent evolution in nucleus-nucleus collisions. This might be the consistent way to study J/ψ suppression in URHIC.

Since we study the suppression of J/ψ in equilibrating quark-gluon plasma, it is relevant to discuss the process of equilibration of QGP in URHIC. The equilibration of QGP in heavy-ion collisions is not completely studied yet. The rate of equilibration is different for diiferent models. Some relevant models that describe the equilibration of QGP are parton cascade model(PCM) [21], heavy-ion jet interaction generator(HIJING) [22] and color flux-tube model [20]. PCM and HIJING are both perturbative QCD based models, and color flux-tube model is a field theoritical model. The former models describe the evolution of hard and semihard partons and the later describes the production of soft partons via non-perturbative Schwinger mechanism. For a complete study of production and equilibration of quark-gluon plasma, color flux-tube model may be combined with the pQCD based models. As an initial attempt, we use here the distribution of partons from parton cascade model to study J/ψ suppressions in a thermally equilibrating quark-gluon plasma at RHIC. Within parton cascade model, a relativistic transport equation is solved to study the distribution of partons by considering the direct collision processes $2->2$, the inelastic collision processes $2->1$, and the decay processes $1->2$ [21]. More explicitly, this is written as

$$p^\mu \partial_\mu f_i(x,p) = C_i(x,p) \tag{1.1}$$

where $f_i(x,p)$ is the distribution of a particular type of parton i in the usual phase space. The collisions term $C_i(x,p)$ is derived from pQCD taking all the processes mentioned above. The initial condition on $f_i(x,p)$ is the distribution of partons inside the nucleus before the two nuclei collide with each other [24]. However for a complete study, the addition of soft partons and the effect of background field has to be taken into account. This background electric field may not exist in the very early stage where pQCD is applicable [25], but in later times it will have an important role in the equilibration of the plasma [25, 26]. Such calculations will be available once the color flux-tube model is combined to the pQCD based models [23]. The addition of soft partons to hard and semi hard partons within color flux-tube model will enhance the J/ψ suppression (see below). This will be taken up separately.

In section 2 we describe the short-distance QCD and the dissociation of J/ψ. Section 3 contains a brief discussion of nuclear absorpton mechanism. Results and discussions are presented in section 4, for RHIC energy. We summarise and conclude the main results in section 5.

2 J/ψ dissociation by deconfined gluons

In the framework developed by Bhanot and Peskin [27, 28], interactions between light hadrons and deeply bound, heavy quarkonium states, such as the J/ψ, are mediated by short-range color dipole interactions. For sufficiently heavy quarks, the dissociation of quarkonium states by interaction with light hadrons is fully accounted for by short-distance QCD [27, 28]. Because of its small size, a heavy quarkonium can probe the short distance properties of light hadron. A parton based calculation of the J/ψ-hadron cross section is thus possible via an operator product expansion method, simillar to that used in deeply inelastic lepton-hadron scatterings [27, 28, 29, 30]. These pertubative calculations become valid when the space and time scale associated with the quarkonium state, r_Q and t_Q, are small in comparison to the nonperturbative scale λ_{QCD}^{-1}, which is the characteristic size of the light hadrons, *i.e.* $r_Q <<< \lambda_{QCD}^{-1}$, and $t_Q <<< \lambda_{QCD}^{-1}$. For J/ψ ground state $r_{J/\psi} \simeq 0.2fm = (1GeV)^{-1}$ and $E_{J/\psi}(2M_D - M_{\psi'}) \simeq 0.64$ GeV. With $\lambda_{QCD} = 0.2GeV$, the above inequalities seem to be well satisfied [31] and one expect that the dissociation of J/ψ by hadron will be governed by the J/ψ-hadron break-up cross section as calculated in short distance QCD. The operator product expansion allows one to express the hadron-J/ψ inelastic cross section in terms of the convolution of the gluon-J/ψ dissociation cross section with the gluon distribution inside the hadron. The gluon-J/ψ cross section is given by [27, 28, 30]:

$$\sigma(q^0) = \frac{2\pi}{3}(32/3)^2(\frac{16\pi}{3g_s^2})(1/m_Q^2)\frac{(q^0/\epsilon_0 - 1)^{3/2}}{(q^0/\epsilon_0)^5}. \tag{2.1}$$

Here g_s is the coupling between gluon and charm quark, m_Q the charm quark mass, and q^0 the gluon energy in the J/ψ rest frame. The heavy quarkonium is coulomb like, and one writes, $\epsilon_0 = (\frac{3g_s^2}{16\pi})^2 m_Q$ [27, 30].

The gluons which are soft inside a pion are not capable of dissociating a charmonium. Hence they give a low π-J/ψ cross section. However, deconfined gluons, which carry enough energies, are sufficient to break a charmonium [31]. These high energy partons are present in URHIC, as observed in several calculations, such as [20, 21]. These deconfined gluons can break a fully formed J/ψ that exit inside QGP. This conclusion does not seem to be affected substantially by nonperturbative effects [32].

We use the above g-J/ψ dissociation cross section to study the J/ψ suppressions in a thermally equilibrating quark-gluon plasma at RHIC. For the central collisions, the J/ψ survival probability is:

$$S_{g-J/\psi}(P_T) = \exp[-\int d\tau n_g(\tau) < v_{rel}\sigma(k\cdot v) >_k]. \tag{2.2}$$

Here $n_g(\tau)$ is the gluon number density which evolves as system expands longitudinally. According to Bjorken scenerio [33], this number density is a function of the boost invariant parameter τ ($\tau = \sqrt{(t^2 - z^2)}$). The thermal average g-J/ψ cross section, $< v_{rel}\sigma(k\cdot v) >_k$, is

$$< v_{rel}\sigma(k\cdot v) >_k = \frac{\int d^3k v_{rel}\sigma(k\cdot v) f(k^0, T(\tau))}{\int d^3k f(k^0, T(\tau))}. \tag{2.3}$$

Here $v (\equiv (M_T, \vec{P_T}, 0)/M_{J/\psi})$ is the four-velocity of J/ψ in central rapidity region and k is the four-momentum of gluon in the parton gas. In the thermal average cross section we use the distribution function, $f(k^0, T(\tau)) = \frac{a(\tau)}{\exp(k^0/T(\tau))-1}$ for gluon. Here $a(\tau)$ captures the deviation from equilibrium, which in principle, is determined from the relation, $n_g(\tau) = \int d\Gamma(p^\mu u_\mu) f(p, T(\tau))$, by knowing the evolution of temperature and n_g, for an equilibrating quark-gluon plasma. Here $d\Gamma = \frac{\gamma d^3p}{(2\pi)^3 p_0}$ with $\gamma = 2\times 8$(the product of spin and color degeneracy), and u ($= (t/\tau, 0, 0, z/\tau)$) is the flow velocity. However, as $a(\tau)$ cancels both from numerator and denominator of equation (2.3), we need not know its form. What matters is $n_g(\tau)$ and T(τ) whose evolutions are taken from PCM [21]. Within PCM, $n_g(\tau) \simeq 0.72 n(\tau)$, with $n(\tau) = 565 fm^{-3}(\frac{\tau}{\tau_0})^{-0.90}$ and $T(\tau) = 950 MeV(\frac{\tau}{\tau_0})^{-0.30}$, for a thermally equilibrating quark-gluon plasma at RHIC. Here $\tau_0 = .05 fm$. Using this distributions the integration in equation (2.2) is performed numerically to study the J/ψ survival probability.

3 J/ψ suppression by nuclear absorption

Consider p-A collisions: unlike hadronic collisions, where an enhancement of J/ψ is measured at very high energy [9], J/ψ suppression is measured in p-A collisions. A number of explanations have been given [12, 13, 34, 35] for this suppression, among which nuclear absorpton is the prominent. This nuclear absorption is well described according to Glauber theory [12]. Within this theory a J/ψ survival probability is written as

$$S_{pA} = \frac{1}{A}\int d^2b dz \rho_A(\mathbf{b}, z)\exp(-\int_z^\infty dz'\rho_A(\mathbf{b}, z')\sigma_{abs}(1-1/A)). \tag{3.1}$$

Here $\mathbf{b}$ is the impact parameter where the proton collides with the nucleus and z is the longitudinal distance at which a $c\bar{c}$ pair is created. After the $c\bar{c}$ is produced, it travels in the forward direction colliding inelastically with the surrounding nucleons. The inelastic $c\bar{c}$-N absorption cross section, σ_{abs}, is determined from the experiment. The nuclear density, ρ_A at a point $\mathbf{r}(\mathbf{b}, z)$ is normalised such that: $\int d^3r\rho_A(\mathbf{r}) =$ A. After integrating over z, we get

$$S_{pA} = (\frac{1}{A'\sigma_{abs}})\int d^2b[1-\exp(-\sigma_{abs}(1-1/A)T_A(\mathbf{b}))], \tag{3.2}$$

where $T_A(\mathbf{s}) = \int_{-\infty}^{+\infty}\rho_A(\mathbf{s}, z)dz$, is the nucleon density per unit area in the transverse plane(transverse to the collision axis), and $A' = A(1-1/A)$. Extending to nucleus-nucleus collisions [12] we write the survival probability as,

$$S_{AB} = \frac{1}{A'B'\sigma_a^2}\int d^2b\int d^2s\,[1-\exp(-\sigma_{abs}(1-1/A)T_A(\mathbf{s}))] \times [1-\exp(-\sigma_{abs}(1-1/B)T_B(\mathbf{s}-\mathbf{b}))]\,. \tag{3.3}$$

Here $\mathbf{b}$ is the impact parameter of collision and $\mathbf{s}$ describes the transverse coordinates of the interacting nucleons which produce $c\bar{c}$. This equation can be written in a more simpler form,

$$S_{AB} = \exp(-\sigma_{abs}\rho(L_A + L_B)), \tag{3.4}$$

where L_A+L_B is the effective length a $c\bar{c}$ travels inside two nuclei. Except for the case of Pb-Pb collision, where an anomaluos J/ψ suppression is observed by NA50 [14, 36], this method explains almost all datas upto $S-U$ collisions, using a common absorption cross section $\simeq 6.2mb$.

For a fixed impact parameter $\mathbf{b}$, this survival probability is;

$$S_{c\bar{c}-N}(b) = \frac{1}{T_{A'B'}(b)\sigma_{abs}{}^2}\int d^2s\,[1-\exp(-\sigma_{abs}(1-1/A)T_A(\mathbf{s}))] \times [1-\exp(-\sigma_{abs}(1-1/B)T_B(\mathbf{s}-\mathbf{b}))]\,, \tag{3.5}$$

where $T_{AB}(b) = \int d^2sT_A(\mathbf{s})T_B(\mathbf{s}-\mathbf{b})$.

In our calculation we use a uniform density($R_A = r_0A^{1/3}$, with $r_0 = 1.2fm$), which is applicable for heavy nuclei and have adopted a absorption cross section of 6.2mb(used by the NA50 collaboration [36]). For central Au-Au collisions($b = 0$), we obtain from the above equation, $S_{c\bar{c}-N} \simeq 0.42$.

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4 Results and discussions

In figure 1 we present the thermal averaged gluon-J/ψ cross section as a function of J/ψ transverse momentum P_T, for different values of temperature. It can be seen that this value is decreased as the temperature of the plasma is increased. Also for J/ψ with high P_T this thermal cross section becomes less. This has a direct impact on J/ψ suppression. As P_T becomes large the survival probability must increase. However, due to large initial parton density formed in the initial stage of the plasma, these smaller thermal cross sections do not have a large effects on the total survival probability. This is shown in figure 2 where we have plotted the survival probability $S_{g-J/\psi}$ as a function of P_T for a thermally equilibrating QGP at RHIC within PCM. As can be seen, the suppression is almost 100 percent for J/ψ with low transverse momentum. Even for J/ψ with high $P_T(\simeq 10GeV)$ the suppression is about 95 percent. This huge suppression is due to the presence of a highly densed deconfined partonic medium at RHIC. As can be seen from equation (2.2) and figure 1 this suppression will be more for a plasma with larger number density and lower temperature. A denser and cooler plasma is obtained once the soft partons are added to the hard and semi hard partons [23]. The measurement of such huge suppression will reveal the existence of such a deconfined partonic medium, possibly a thermalised quark-gluon plasma, at RHIC.

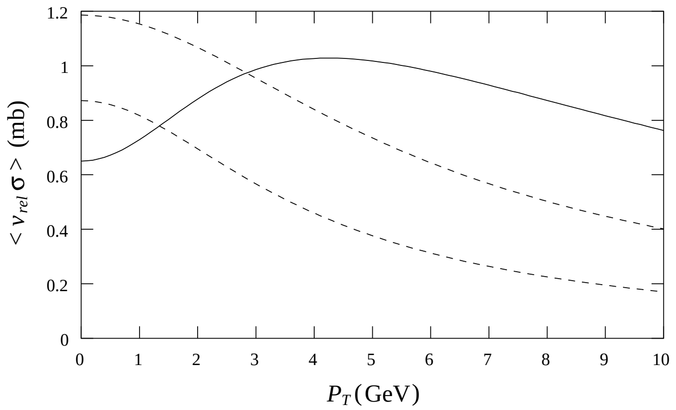

Figure 1: The thermal averaged gluon-J/ψ cross section $< v_{rel}\sigma >$ as a function of transverse momentum P_T at different temperatures. Solid line refers to T= 0.2 GeV, upper broken line corresponds to T= 0.4 GeV and lower broken line refers to T=0.8 GeV.

However, what one actually measures experimentally is the total survival probability. This implies that other sources of J/ψ suppression, without the existence of a QGP phase, have to be singled out from the total survival probability in order to see the suppressions only from this deconfined partonic medium. In section 3, we have estimated a large suppression (about 60 percent) due to the nuclear abosorption before a J/ψ is formed. If the estimated suppression due to all sources without QGP phase is much less than the experimental findings,

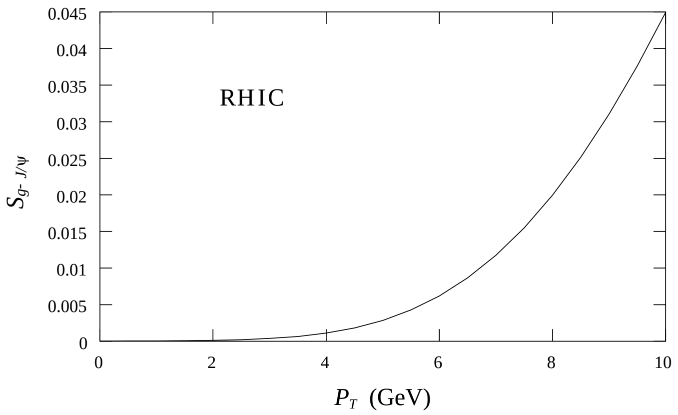

Figure 2: The survival probability of J/ψ in a thermally equilibrating plasma at RHIC.

one may then hope that the rest of the suppressions is due to the existence of a highly densed deconfined partons. The experimental measurement of J/ψ at RHIC will be able to reveal all the possibilities and may explain the existence of such a deconfined partonic medium, possibly a thermalised quark-gluon plasma.

On the other hand J/ψ enhancement can occur due to an increase in the (thermal)charms produced at a very high temperature, especially in the initial stage of the evolution of the system [37, 38]. We recall that screening of J/ψ was originally [4] proposed without taking production of thermal charms into account, which was argued to be negligible at $T \simeq$ 200 - 300 MeV. However, the system may approach a temperature which is as large as 900 MeV initially, and can therefore produce a large number of thermal charms at RHIC. So to make resonable estimates at RHIC and LHC, one has to take into account both thermal and hard J/ψ. For simplicity, we have not considered here those J/ψ which are created from thermal charms.

5 Conclusion

We have found a reasonable suppression(around 60 percent) before a J/ψ is fully formed, due to the nuclear absorptoin alone and an additional suppression of about 95-100 percent due to a deconfined phase. These two mechanisms give a huge suppression, almost 100 percent, to those J/ψ which are produced from primary charm quarks. In principle, the total survival probability is written as

$$S_T = S_{c\bar{c}-N} S_{g-J/\psi} S_{other} \,, \tag{5.1}$$

where first two suppressions ($S_{c\bar{c}-N}$, $S_{g-J/\psi}$) are due to pre-resonance nuclear absorption and g-J/ψ dissociation, and the last one(S_{other}) is due to any other possible sources of suppression [39, 40, 41] such as final state comover scatterings. As the hadron-J/ψ cross section is smaller than g-J/ψ cross section [31], we expect a lesser suppression of J/ψ in the hadronisation stage. The prominent suppression seems to be due to the nuclear absorption and J/ψ dissociation in the deconfined partonic system. Hence the measurement of a huge J/ψ suppression at RHIC may suggest the existence of a partonic plasma. However, many refinements, such as space time evolution of quarkonium production in nucleus-nucleus collision using NRQCD has to be worked out, before unambigous conclusions can be drawn for the pre-resonance suppression of J/ψ. In any case the contribution from thermal J/ψ, which may not be neglible at RHIC and LHC, has to be taken into account. It is only after incorporating the above features the certainty of screening can be justified.

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