Charmonium suppression in a baryon rich quark-gluon plasma

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Abstract. We have investigated the survival probability of different charmonium states, in a high baryon density parton plasma, expected to be produced in nuclear collisions at FAIR. Charmonia are assumed undergo complete dissociation by color screening, if the in-medium Debye radius becomes comparable to the spatial size of the corresponding bound state. Results indicate a non-trivial dependence of the suppression pattern on the plasma evolution dynamics.

1. Introduction

Bound states of charm (c) and anti-charm ($\bar{c}$) quark, which are stable under strong decay are collectively known as charmonia. Among different charmonium resonances, the most extensively studied state is J/ψ meson. In relativistic nuclear collisions, J/ψ suppression has long been predicted as an unambiguous and experimentally viable signature to indicate the possible occurrence of phase transition to quark-gluon plasma (QGP) [1]. Till date no measurement exists on charmonium production in heavy-ion collisions below the top SPS energy ($E_b = 158$ A GeV), primarily due to the extremely low production cross sections. This in turn demands accelerators delivering extremely high intensitiy heavy-ion beams and detectors with high rate handling capability. The upcoming Compressed Baryonic Matter (CBM) experiment at FAIR [2], in GSI, Germany, for the first time, is aiming at the measurement of charmonium production in low energy nuclear collisions, over a range E_b=10-40 A GeV. In this energy domain, highest possible baryon densities are expected to be produced at the center of the collision zone [3]. This might lead to a density driven QCD phase transition of the nuclear matter to a baryon rich QGP. In a baryonic plasma, as expected to be produced in the FAIR energy collisions, different charmonium states might get suppressed due to Debye screening. In this present paper, we aim to calculate the survival probability of different charmonium states, suffering dissociation due to plasma screening, at FAIR energy domain. For this purpose we have developed a variant of the threshold model, where Debye screening mass as a function of temperature and baryon chemical potential $m_D(T, \mu_B)$, in a dynamically evolving plasma is used to decide the fate of different charmonium states implanted in the medium.

2. Theoretical formulation

In literature, quarkonium suppression in nuclear collisions, due to color screening inside the plasma, are generally treated within threshold model scenario [4, 5, 6, 7]. The basic assumption is the existence of a characteristic threshold/critical dissociation temperature (T_d) or equivalent
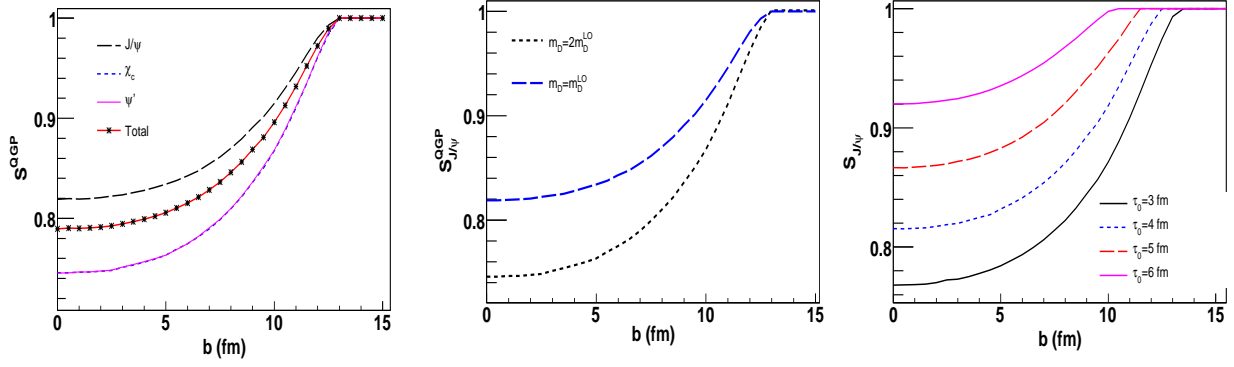
Figure 1. (Left) Centrality dependence of the inclusive survival probability of different charmonium states, in 30 A GeV Au+Au collisions. Suppression is induced by Debye screening mechanism only. (Middle) Sensitivity of the inclusive suppression pattern on non-perturbative effcets in screening mass. (Right) Sensitivity of the inclusive suppression pattern on the plasma formation time.

threshold/critical dissociation energy density ($\epsilon_d \simeq T_d^4$),that encloses the plasma volume where the screening length is shorter than the characteristic Bohr radius of a particular resonance state. This prevents the formation of the bound state for all $c\bar{c}$ pairs inside the region at the corresponding resonance formation time (t_F) in the plasma frame. At mid-rapidity, competition between t_F, the finite volume and life time of the plasma, leads to the characteristic p_T dependent survival probability. Finite lifetime of the plasma sets an upper limit on the p_T at which charmonia are suppressed. The deconfined medium produced in the collisions, is believed to reach thermalization within a time comparable to the formation time of the primordial $c\bar{c}$ pairs in the collision frame. However the situation might be different at FAIR owing to different kinematic conditions. Due to much smaller collision energies, much longer time will be required for the medium to attain thermalization compared to that at higher energies. It might thus be reasonable to consider that at FAIR, different charmonium states will be formed in the pre-equilibrium stage and the plasma would encounter the already formed physical bound states rather than their precursors (see [8] for details). If the local temperature $T(x)$ and chemical potential $\mu(x)$ inside the plasma are such that the screening radius $r_D(T(x), \mu(x)) \leq r_i$, the ith state will melt, where r_i denotes the separation radius of the ith charmonium state. At an impact parameter **b**, the instantaneous survival probability for the ith state, at a transverse position **s**, can be expressed as

$$S_{QGP}^i(\mathbf{b}, \mathbf{s}, \tau) = \Theta(r_i - r_D(\mathbf{b}, \mathbf{s}, \tau)) \tag{1}$$

Determination of survival probability thus boils down to the estimation of Debye screening mass m_D (note that m_D is inverse of r_D) at finite T and μ_B. In leading order perturbation theory, the μ_B dependence of the screening mass reads as, $m_D(T, \mu_q) = gT\sqrt{\frac{N_c}{3} + \frac{N_f}{6} + \frac{N_f}{2\pi^2}(\frac{\mu_q}{T})^2}$, where $\mu_q = \mu_B/3$ is the quark chemical potential and the other symbols have their usual meaning [9]. The NLO level estimates of Debye mass suffer from large uncertainties as well as the presently available lattice estimates are still at their infancy [10]. In our present phenomenological study, we thus refrain from using lattice estimates and make use of the LO pQCD estimations only. The model now demands the determination of local T and μ_B of the fluid, as a function of collision energy and collision centrality. Central collisions of gold nuclei have been simulated using various dynamical models, based on transport or hydrodynamical equations, in the FAIR energy regime [3]. For each case, central values of net baryon density (ρ_B) and the total energy density (ϵ) are extracted as a function of time, which exhibit a large degree of mutual agreement.

For our present calculations we make use of the results from UrQMD model to get $\rho_B(t)$ and $\epsilon(t)$, extracted for a central cell of unit thickness ($\Delta z = 1$). To account for the spatial inhomogenity of the medium we set the initial profiles of ρ_B and ϵ in the transverse plane of the collision, in proportion to the participant density ($n_{part}(\mathbf{b}, \mathbf{s})$), a quantity calculable using Glauber model. Space time dependent density values (ρ_B, ϵ) are then simultaneously plugged in phenomenological QGP equations of state (EOS) proposed by Kapusta [11] to solve for the corresponding values of local T and μ_B, as a function of collision energy and centrality. One input parameter of the EOS, T_0, can be identified with T_c the pseudo-critical temperature at $\mu_B \approx 0$. The critical energy density (ϵ_c), required for deconfinement can then be estimated at $\mu_B \approx 0$. Since T_c as a function of μ_B is believed to follow a nearly constant density curve, we assume ϵ_c, to remain constant with increase in μ_B. Incorporation of ϵ_c endows the plasma with finite space-time extent. Debye screening remains operational on a bound state, over the time it spends inside the plasma. The lower limit of the duration of screening can be taken as the same as the thermalization time (t_{th}) of the medium, which we assume to coincide with the passing time of the two colliding nuclei. For beam kinetic energy $E_b = 30$ A GeV, and for a central cell of longitudinal width 1 fm, as used in our present analysis, $t_{th} \simeq 3.7$ fm/c. Again a particle of mass m, inserted at a point $\mathbf{r}$, in the transverse plane ($z = 0$) of the fireball, with velocity $\mathbf{v}$ will travel a distance d ($d = -r\cos\phi + \sqrt{R^2 - r^2(1 - \cos^2\phi)}$), in the time interval $t_b = M_T d/p_T$, before it escapes from the system of transverse extension R, ϕ being the angle between the vectors $\mathbf{r}$ and $\mathbf{v}$ and $M_T = \sqrt{m^2 + p_T^2}$ denotes the transverse mass. Thus minimum between the two time values t_I and t_b should fix the upper limit of duration, a bound state suffers dissociation due to screening, where t_I denotes the plasma extinction time. Since the chramonia produced in the central rapidity region would have very small p_T, they remain inside the system till the plasma is alive.

3. Numerical Results

We now have all the ingredients to calculate the anomalous J/ψ suppression pattern due to plasma screening in a deconfined medium. Our aim is the estimation of the inclusive J/ψ survival probability as a function of collision centrality. Since J/ψ mesons are produced in the initial hard collisions, we distribute the J/ψs in the transverse plane, following the transverse density of binary collisions $n_{coll}(\mathbf{b}, \mathbf{s})$, as obtained in Glauber model. At a given impact parameter, the total inclusive survival probability suffering dissociation inside a QGP is then obtained by integrating Eq. 1. Results are shown in the left panel of Fig. 1, for different resonance states. As inputs to the EOS, we have chosen $N_f = 2$ and $T_0 = 154$ MeV guided by the current state-of-the-art lattice simulations of T_c [12]. Excited states suffer larger suppression. Magnitude of suppression for ψ' and χ_c are visibly indistinguishable. In practice, it has been found that only about 60% of the observed J/ψ originate directly in hard collisions while 30% of them come from the decay of χ_c and 10% from the ψ'. Hence, the total survival probability of J/ψ becomes, $S_{tot} = 0.6 S_{J/\psi} + 0.3 S_{\chi_c} + 0.1 S_{\psi'}$. As evident from the figure, at FAIR energies, color screening effect alone leads to a maximum $15 - 20\%$ suppression in most central collisions. It might now be interesting to test the sensitivity of suppression pattern on various model inputs. Let us first check how S_{tot} quantitatively depends on the enumeration of screening mass. In finite temperature lattice guage theory, at $\mu_B = 0$, the screening behavior is found to be in good agreement with leading order perturbation theory for $T \geq 1.5 T_c$. However for lower temperature values, large non-perturbative corrections are found to arise in the estimation of Debye mass. They are quantified through a multiplicative constant A ($A = 1$, for LO pQCD), with $A = 1.39$. Such non-perturbative effects might also be prevalent at finite baryon density regime accessible at FAIR. To find out its effect on the inclusive survival probability, we have calculated $S_{J/\psi}$ with $m_D(T, \mu_B) = 2 m_D^0(T, \mu_B)$, where m_D^0 denotes the LO pQCD estimate. Results are depicted in
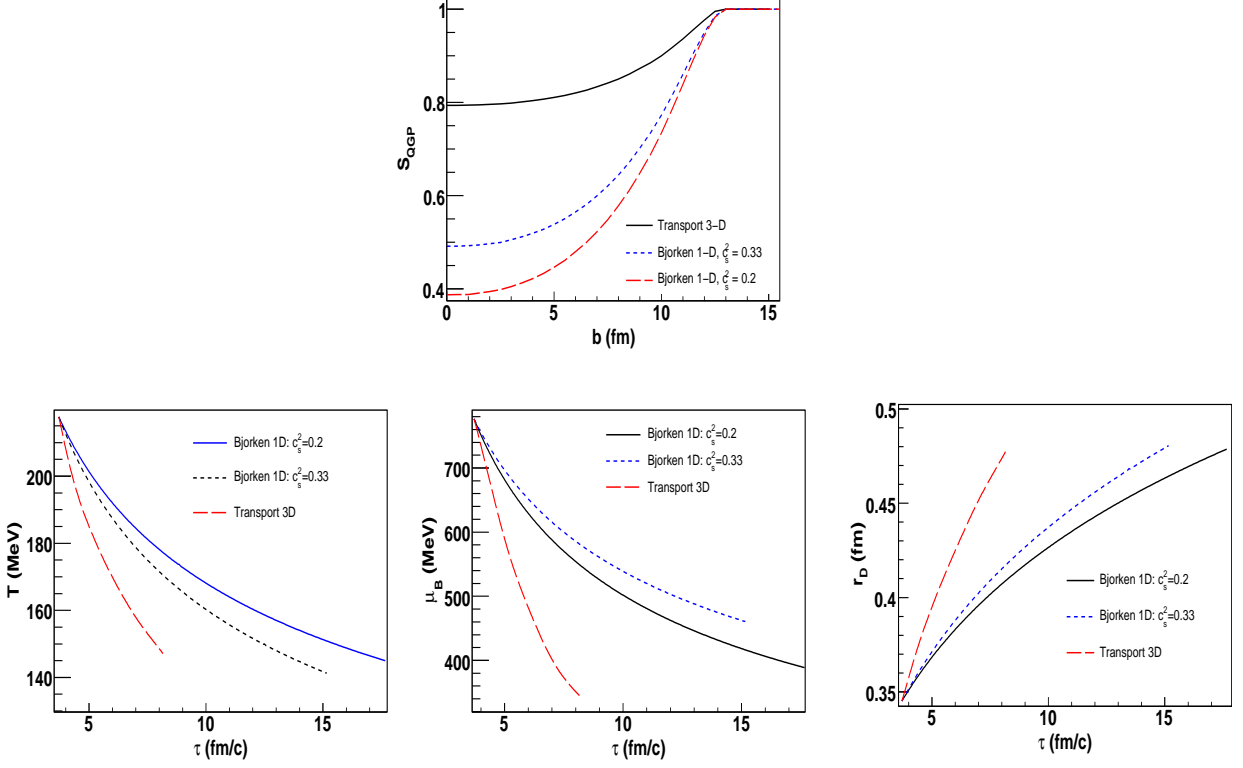
Figure 2. (Top) Sensitivity of the inclusive survival probability on the medium expansion dynamics. (Bottom) Time evolution of local temperature (T), baryon chemical potential (μ_B) and screening radius (r_D) under different expansion scenarios.

the middle panel of Fig. 1. Even for a non-perturbative correction factor as large as $K = 2$, difference in $S_{J/\psi}$ appears to be less than 10%. Perturbation theory might thus do a reasonable job so far as the estimation of the inclusive survival probability is concerned. It might also be useful to test the sensitivity of the suppression pattern on the choice of medium thermalization time. As discussed earlier, we assume thermalization time to be equal to the passing time of the two colliding nuclei, which is commonly believed to set the lower bound of t_{th}. In right panel of Fig. 1, we have calculated the survival probability of the directly produced J/ψs for different values of t_{th} between 3 to 6 fm/c. In case of late thermalization of the deconfined matter, all the J/ψ would possibly escape the suppression due to plasma screening. Our calculations indicate that for $t_{th} \geq 7$ fm, there is no suppression at all.

Finally, let us explore the sensitivity of the suppression pattern on the medium expansion dynamics. Most of the calculations, performed so far, generally assume the plasma to expand following Bjorken 1-D boost invariant scaling solutions. It is basically driven by the expectation that the suppression occurs before the transverse expansion could set in. For a quantitative comparison it might be useful to find the effect of the transverse expansion on the observed suppression pattern. In our present calculations, we have followed the time evolution of the densities from UrQMD which includes the full 3-D expansion of the fireball. Thus in order to find the effect of transverse dynamics, we have also calculated the suppression for a case where the fluid dynamics is governed by Bjorken 1-D hydrodynamical expansion. For such cases the net baryon and the energy densities would evolve as $\rho_b \tau = constant$ and $\epsilon \tau^{1+c_s^2} = constant$, where c_s denotes the speed of sound in the plasma. For ideal massless relativistic gas $c_s^2 = 0.33$. For a massive interacting system c_s^2 would be less than that. We have chosen here two illustrative

values of $c_s^2 = 0.33, 0.2$, in accord with [5]. In Figure 2, we have shown comparative suppressions of directly produced J/ψ, between 3-D and 1-D expansion of the partonic fluid. Suppression strongly depends on the medium expansion dynamics. In absence of transverse expansion, plasma would expand slowly and hence screening would operate for a longer time. The rate of expansion, in case of longitudinal dynamics, would be governed by the value of c_s^2. Among the three cases considered, slowest possible expansion occurs for $c_s^2 = 0.2$, giving largest suppression effects. On the other hand presence of the transverse expansion accelerates the rate of expansion thereby shortening the duration of the screening which would increase the chances of J/ψ survival. It can be understood on a more quantitative basis if we look the the evolution of the medium. Hence in Fig. 2, we have also plotted the time evolution of local T, μ_B and r_D, for the central fluid cell in central Au+Au collisions. Fluid is allowed to expand till the energy density drops down to ϵ_c, the critical energy density for deconfinement to occur. Clearly the fluid gets diluted and cold much faster if it follows UrQMD 3-D expansion dynamics. For 1-D expansion, rate of dilution and cooling is controlled by the value of c_s, leading minimum survival for slowest expansion. A static medium would thus generate maximum amount of suppression.

4. Summary

In summary, we have demonstrated the possible charmonium suppression due to color screening, inside a hot baryonic plasma, anticipated to be produced at FAIR energy domain. Screening effects alone are found to generate a maximum of about 20% suppression in most central Au+Au collisions. Centrality dependence of the inclusive survival probability is found to be sensitive on the different parameters of the plasma EOS. Debye mass as a function of T and μ_B, is used to fix the deconfining zone. In the deconfined QGP, quark contribution to the screening mass is dominant and the gluonic contribution is small at low temperature. At high temperature, both quarks and gluon contribute to the screening. In our present work, we have assumed that the deconfinement sets in the nuclear collisions which eventually leads to the formation of a partonic medium in thermal and chemical equilibrium. Chemical equilibration is assumed to occur simultaneously with thermal equilibrium which allows us to estimate the screening mass in terms of T and μ_B. Debye screening could also set in inside a thermally equilibrated but chemically equilibrating plasma. Moreover color screening seems not to be the sole source of charmonium suppression in a deconfined medium. Suppression can also result from collisional dissociation of the charmonia in the pre-resonance or resonance stage with the quarks and gluons co-moving with the evolving charmonium states. Such microscopic dissociation mechanisms do not require equilibration to set in and can be operational in the pre-equilibrium stage as well, as along as the medium remains in deconfined state. Work is under progress for a quantitative estimation of these effects.

[1] T. Matsui and H. Satz, Phys. Lett. B **178**, 416 (1986).
[2] P. Senger, Nucl. Phys. A **862-863**, 139 (2011).
[3] I. C. Arsene *et al.*, Phys. Rev. C **75**, 034902 (2007).
[4] J. P. Blaizot and J. Y. Ollitrault, Phys. Lett. B **199** 499 (1987); M. C. Chu and T. Matsui, Phys. Rev. D. **37**, 1851 (1988); F. Karsch and R. Petronzio, Phys. Lett. B **193** 105 (1987); R. Vogt, Phys. Lett. B **430**,15 (1998).
[5] D. Pal, B. K. Patra and D. K. Srivastava, Eur. Phys. J. C **17**,179 (2000); B. K. Patra and D. K. Srivastava, Phys. Lett. **B 505**, 113 (2001).
[6] O. Linnyk, E. L. Bratkovskaya, W. Cassing and H. Stocker, Nucl. Phys. A **786**, 183 (2007).
[7] M. Mishra, C. P. Singh, V. J. Menon and Ritesh Kumar Dubey, Phys. Lett. **B 656**, 45 (2007); P.K.Srivastava, M. Mishra and C. P. Singh, Phys. Rev. C. **87**, 034903 (2013); T. Gunji, H. Hamagaki, T. Hatsuda and T. Hirano, Phys. Rev. **C 76**, 051901(R) (2007); A. K. Chaudhuri, Phys. Rev. **C 80**, 047901 (2009);
[8] P. P. Bhaduri, A.K. Chaudhuri and S. Chattopadhyay, Phys. Rev. **C 88**, 061902 (2013) .
[9] T. Toimela, Phys. Lett. **B 124**, 407 (1983).
[10] M. Doring, S. Ejiri,O. Kaczmarek,F. Karsch and E. Laermann, Eur. Phys. J. C **46** (2006) 179.
[11] J. I. Kapusta, Phys. Rev. C **81**, 055201 (2010).
[12] A. Bazavov *et al.*, HotQCD Collaboration, Phys. Rev. D **85**,(2012) 054503.