\(J/\psi\) in a hot baryonic plasma

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We calculate the bound state properties of \(J/\psi\) in a hot and dense QCD plasma using phenomenological potentials augmented by inputs from perturbative QCD. The temperature and density region of study will be relevant in future heavy ion collision experiments at FAIR. We find that the effect of baryon density on the dissociation of \(J/\psi\) is small in this regime. However we indicate that if there is a critical end point in the QCD phase diagram then strong density fluctuation will dissociate charmonia near hadronization. The measurement of \(J/\psi\) suppression can therefore signify the existence of the critical point unambiguously.

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The aim of the ongoing relativistic heavy ion collision experiments is to create a deconfined phase of strongly interacting matter dubbed as quark gluon plasma (QGP). Almost 30 years ago, Matsui and Satz argued that the screening of the confining potential at high temperature will lead to the dissolution of heavy quark bound states in the plasma and their depleted production may be used for a forensic study of the hot and dense medium created in such collisions \[1\]. One of the significant results of SPS heavy ion program was the observation of anomalous \(J/\psi\) suppression. For \(\sqrt{s_{NN}} = 17.3\) GeV Pb+p and In+In collisions, the relative yield of \(J/\psi\) was found to be suppressed compared to estimates based on cold nuclear matter (CNM) effects alone beyond a centrality threshold \[2\]. High statistics data for quarkonia suppression in Au+Au collisions at \(\sqrt{s_{NN}} = 200\) GeV at RHIC \[3\] and in Pb+Pb collisions at \(\sqrt{s_{NN}} = 2.76\) TeV at LHC \[4\] have been checked against screening based models and it lends strong support for the creation of a deconfined partonic phase \[5\].

The bulk matter created at RHIC and LHC have low baryon densities, \(\mu_B \simeq 0\). Upcoming Facility for Antiproton and Ion Research (FAIR) at GSI will collide heavy ions in the energy range \(\sqrt{s_{NN}} \sim 6 - 10\) GeV. Numerical simulations employing different dynamical models show that a medium with high baryon density and relatively low temperature is likely to be created at such collision energies \[6\]. CBM collaboration at FAIR, in particular, has a dedicated heavy flavor program and is expected to throw light on the possible in-medium modifications of open and hidden charm spectra. At zero baryon density, the excited states of charmonium family - \(\chi_c\) and \(\psi\) melt just above \(T_{pc}^0\), where \(T_{pc}^0 \approx 170\) MeV is the pseudo-critical temperature of QCD in a baryon symmetric medium. The ground state may survive upto \(\sim 1.5 T_{pc}^0\) and the maximum temperature achievable at FAIR will be below it whereas the chemical potential \(\mu_q\) could be as high as \(\sim 2 T_{pc}^0\). Should we expect to see a density driven melting of \(J/\psi\) at low energy collisions then? The purport of the present paper is to find an answer.

Heavy quark spectroscopy is well described by non-relativistic potential models \[7\] at zero temperature. In statistical QCD, the choice of the potential is debated and it is unclear whether free energy, internal energy or a linear combination thereof is the right candidate for it. Nevertheless, potential models have been extensively used at finite temperature to calculate various in-medium properties of quarkonia, see \[8,9\] for recent reviews. Apart from simplicity, the advantage of the potential model is that a slew of information can be extracted from it at no cost. Such studies complements first principle calculation from lattice gauge theory and seems indispensable now for baryon rich phase of QCD where progress in lattice computation is hindered by hitherto unsolved sign problem.

As alluded earlier, our aim here is to understand the in-medium modification of charmonia in a hot baryonic plasma which might be produced at low energy heavy ion collisions. We scan the region of phase diagram where \(T/T_{pc}^0 \sim (1 - 1.5)\), and \(\mu_q/T_{pc}^0 \sim (1 - 2)\) where \(T\) and \(\mu_q\) are equilibrium temperature and chemical potential of the system respectively. It is assumed that \(\mu_u = \mu_d = \mu_q\). How does the finite baryon chemical potential influence the charmonium dissociation? A large chemical potential implies increased screening or weak binding of charmonia in the medium. A substantial background temperature is responsible for, apart from decrease in binding, rupture of resonances through partonic breakup processes. In the extreme case of cold and dense quark matter \(\mu_q/T \rightarrow \infty\), partonic dissociation shuts off and sharp nature of Fermi surfaces may lead to nontrivial modification of heavy quark bound states \[10\]. We relegate this issue for discussion elsewhere.

First quantitative assessment of quarkonia dissociation within potential model in a hot QCD plasma was made by Karsch, Mehr and Satz \[11\]. For the \(Q\bar{Q}\) free energy, following choice was adopted,

\[
\mathcal{F} = \frac{\sigma}{m_D} \left(1 - e^{-m_D r}\right) - \alpha e^{-m_D r}/r. \tag{1}
\]
Here $\sigma$ is the string tension and $\alpha = C_F \alpha_s$. $C_F = (N_c^2 - 1)/(2N_c)$ and $\alpha_s$ is the coupling constant of QCD. $N_c = 3$ is the number of color. $m_D$ is the electric screening mass. The long range part of the free energy can be realized in Gribov-Zwanziger-Sringl scenario of confinement [12] involving a $D = 2$ gluon condensate [13].

Since the free energy contains an entropy contribution at finite temperature, $F = U - TS$, it is not the potential per se. So it was suggested to use the internal energy instead [14]. Lattice based internal energy were employed in several [14] investigations. Soon it was realized that since the entropy changes rapidly across the transition temperature, internal energy computed on lattice provides more binding than the vacuum potential. In [16] the authors constructed a model for “maximally binding” potential by fitting the lattice data for free energy at short and long distances. Since a first principle approach suggested in [17]. The internal energy is obtained here by subtracting entropy (and number density) contribution at all distances from the free energy in Eq. (1),

\[
U = F - T \frac{\partial F}{\partial T} - \mu_q \frac{\partial F}{\partial \mu_q} = \frac{2\sigma}{m_D} \left(1 - e^{-m_D \sigma} \right) - e^{-m_D} \left(\sigma T + m_D + \frac{\alpha}{r}\right).
\]

Running of $\alpha_s$ is neglected in arriving at (2). The problem of overshooting the vacuum potential is not eliminated in (2) but it is minimal near $T_{pc}$ where most of the bound states are supposed to melt [17].

Recently, Laine and collaborators [18] have shown that the real time static $\bar{Q}Q$ potential has an imaginary part and describes dissociation of quarkonium through scattering via exchange of a spacelike gluon (see also [19]). We equate the real part of potential to the internal energy instead [14]. Lattice based internal energy were extracted using a "fuzzy bag" equation of state [24] as parameterized in [25]. The fuzziness here merely represent the $T^2$ correction in pressure and could be understood in terms of $D = 2$ gluon condensate akin to the potential in Eq. (1) [20]. We assume that the system equilibrates at time $\tau_0 = 3.5$ fm/c which corresponds to little more than the passing time of two nuclei $\tau = 2R_A/\sqrt{\gamma^2 - 1}$. The evolution is followed until $\tau_f = 6.5$ fm/c when the temperature falls below hadronization temperature $T_{pc}^0 = 170$ MeV. For brevity, we take here the same hadronization temperature as in zero baryon density case. The resulting evolution of temperature and quark chemical potential is shown in Fig. 1.

\[
\int [V] = -2i\alpha T \int_0^\infty \frac{dss}{(s^2 + 1)^2} \left(1 - \frac{\sin m_D rs}{m_D rs}\right).
\]

For the parameters in the potential, we take $\sigma = 0.223$ GeV$^2$ and $\alpha = 0.385$. The electric screening mass is written as, $m_D^2 = 4\pi\alpha\kappa^2 \left(1 + N_f/6\right) T_s^2$ where,

\[
T_s^2 = T^2 \left(1 + 2\kappa^2 \frac{3N_f}{\pi^2 \left(6 + N_f\right)} \frac{\mu_q^2}{T^2}\right).
\]

We call $T_s$ an effective screening temperature. It can be thought of as the equilibrium temperature of a plasma without a net baryon excess that produces the same amount of electric screening as the plasma with temperature $T$ and chemical potential $\mu_q$. The encapsulation of the combined effect of temperature and density in $T_s$ makes comparison with corresponding result at zero density easier. $\kappa_1$ and $\kappa_2$ are parameters to take care of nonperturbative effects in the transition region. We take $\kappa_1 = 1.4$ as follows from comparing leading order result of screening mass with that from a fit to long distance part of lattice $Q\bar{Q}$ free energy [21]. Determination of $\kappa_2$ is little subtle. On general ground, it is expected that $\kappa_2 \sim 1$ [22]. This is also consistent with lattice result in [23] for $T \geq 1.5T_{pc}$. Curiously enough the lattice simulations seem to suggest a divergent behavior of $\kappa_2$ and hence a diverging screening mass close to $T_{pc}$. Later we shall argue that this divergence in the screening mass is a reflection of the proximity to a critical end point and discuss the correlated consequences. For the moment being, however, we neglect this divergence and set $\kappa_2 = 1$ in what follows.

FIG. 1. (color online) Evolution of temperature and chemical potential in the central hotspot for most central ($b = 0$) Au + Au collision at $\sqrt{s_{NN}} = 7.62$ GeV.
by the background temperature and the density has little role to play except in extreme conditions. This is transpired in Fig. 1 wherein it is shown that $T_\gamma$ remains close to $T$ for the entire evolution of the system.

The potential embodied in (2) and (3) is now fed into Schrödinger equation and complex energy eigenvalue $E = M - i\Gamma$ is solved for. The binding energy of the resonance is obtained as $\epsilon = 2m_c + \Re \{V(r \to \infty)\} - M$, where $m_c = 1.3$ GeV is the charm quark mass. A resonance is effectively dissociated when binding energy and decay width come at par $\epsilon = \Gamma$.

The evolution of binding energy and decay width of $J/\psi$ in the central hotspot are shown in Fig. 2. The decay width remains lower than the binding energy even at earliest time of evolution when most extreme condition of temperature and density are met. As the system cools and dilutes, the screening and decay width become weaker and correlation between $QQ$ pair grows until the system hadronizes.

We delineate in Fig. 3 the evolution of $J/\psi$ spectral function in the central hotspot. Close to threshold, the spectral function $\rho_\gamma(\omega)$ is related to the forward correlator,

$$\rho_\gamma(\omega) = \lim_{\vec{r},\vec{r}' \to 0} C^\gamma_\gamma(\omega, \vec{r}, \vec{r}') + \mathcal{O}\left(e^{-\frac{2m_c}{\tau}}\right). \quad (5)$$

A nice algorithm has been presented in [18] for the numerical evaluation of the spectral function which we followed here.

The dissolution of a resonance is signaled by the disappearance of the corresponding peak from the spectral function. As seen from the figure, the $J/\psi$ peak is not smeared out even at the initial time. The ground state remains strongly correlated throughout the evolution.

The strong correlation between quark-antiquark pair does not imply the survival of the resonance in the medium. Scattering with the particles in the heatbath will destroy this correlation and put the quark and antiquark in separate trajectories. The pertinent observable here is the survival probability, $S = \exp\left(-\int_0^{\tau_\infty} d\tau \Gamma\right)$ which measures the fraction of charmonium surviving the trek in the medium. Since the density effect on the screening properties of the medium is rather small the survival probability is essentially determined by the time of exposure of $J/\psi$ to the medium and the background temperature. For the energy range covered by FAIR, the changes in the local temperature and plasma life time with respect to collision energy do not change much so we do not expect appreciable change in the observed suppression when collision energy is varied. At higher collision energies, competing effect from the regeneration of charmonium in the medium becomes important [27]. In fact, the regeneration of charmonium is arguably the reason for similar $J/\psi$ suppression at RHIC and SPS. Combined together, the direct dissociation of primordial charmonium and the regeneration in the medium is expected to result in a rather flat suppression pattern of $J/\psi$ from low to moderate collision energy where baryon density could have had any effect. If an appreciable deviation of in-medium charmonium suppression from the baseline measurement at SPS is observed here then it is possibly a hint for a new physics.

What this new physics could be? Theoretically it has been argued that there is a critical end point (CEP) in the QCD phase diagram where the line of first order phase transition terminates at a second order point [28]. The conjectured critical point belongs to the universality class of 3D Ising model. The exact coordinate of the CEP on the phase diagram is currently unknown but lattice calculations have provided some hazy clue about its location [29]. If such a critical point exists it will lead to enhanced susceptibilities which can be measured through event-by-event analysis of fluctuation of conserved charges. Since the fermionic contribution to the electric screening mass is proportional to the quark number susceptibility $m_{D,Q}^2 \propto \chi_q$ [30], an enhancement in susceptibility is also expected to lead to an increased screening mass. Precisely this behavior is observed in lattice simulation at finite chemical potential

![FIG. 2. (color online) variation of binding energy and decay width of $J/\psi$ in the central hotspot (left) as a function of time (right) as a function $T_\gamma/T_{pc}$. For clarity, effect of baryon density is not shown separately.](image)

![FIG. 3. (color online) evolution of $J/\psi$ spectral density](image)
near $T_{\psi}^c$. We assume that the critical behavior of susceptibility is also shared by the screening mass and write $(m^{1/2}_q)^2 = 2\pi\alpha_s \chi_q^i/3$, where $m^1_{D}$ and $\chi^i_q$ are irregular part of the electric screening masses and quark number susceptibility respectively. The divergent part of the quark number susceptibility is gleaned from $[32]$

$$\chi_q = \frac{9n_c^2}{(\delta + 1) P_c} \left[ \frac{1}{3} \frac{3m^1_{D} + 5\delta |\eta|^\delta - 1}{(2 - \gamma)} \right].$$

Here, $t = (T - T_c)/T_c$ and $\eta = (n - n_c)/n_c$, $n$ is the quark number density and $P$ is the pressure. $T_c$, $P_c$ and $n_c$ are the critical values of the respective variables. The critical exponents are $\gamma = 1.24$ and $\delta = 4.815$. The regular part of the screening mass has been mentioned in $[3]$. So we can now see how the presence of a critical point inflict upon the survival of $J/\psi$ in the deconfined medium.

In Fig. 4, we display the spectral function of $J/\psi$ near the critical point. As the critical point is approached, the spectral strength of the $J/\psi$ is significantly reduced.

The loss of quark-antiquark correlation in this case is brought about by the increase of screening mass near the critical point. This should be contrasted with high $T$ behavior in Fig. 3 where disappearance of the spectral peak is caused both by increased screening (reduction in strength) as well as increase in decay width (smearing of peak). This leads to an interesting picture of charmonium survival in a baryonic plasma depending on whether or not the critical point is hit or missed during the course of evolution. If the evolution of the system cross the phase boundary away from the critical point then the singlet quark-antiquark correlation goes on increasing till hadronization. On the other hand, the critical point will be hit if the evolution of the system proceeds in proximity since CEP acts as attractor of hydrodynamical trajectories $[33]$. As the critical point is approached, the $Q\bar{Q}$ correlation goes on dwindling due to increased screening and thermal excitation can easily break it off. The divergence of the susceptibilities imply that the trajectories in the $(T, \mu_q)$ plane linger near the CEP. More the bound state stays close to the CEP more likely it is to be broken by scattering in the background medium. It should be emphasized that the critical point presents a difficult condition for the hidden charm states to be realized close to hadronization. By the time the hadronization is complete, the signature of the CEP is imprinted in the near absence of charmonia in the medium and it is unlikely that subsequent hadronic evolution will mask it. The sudden drop of $J/\psi$ yield at the critical point will therefore provide a clean and robust signal for its existence.

Summarizing, we have discussed in detail the bound state properties of $J/\psi$ in a hot baryonic medium. This provides the requisite input for an all embracing investigation of charmonium production at low collision energy. Work along this direction is under progress and will be reported elsewhere. Furthermore, we have argued that if the evolution of the medium proceeds through a critical point then strong density fluctuation will remove the charmonium states from the spectrum before hadronization. This opens up an interesting possibility to locate the critical end point through the measurement of charmonium suppression.

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