J/ψ suppression in the presence of dissipative forces in a sQGP

Vineet Kumar Agotiya and Binoy K. Patra

Department of Physics, Indian Institute of Technology Roorkee, Roorkee-247667, India

Abstract

We have considerd first-order dissipative corrections to the plasma equation of motion in the Bjorken boost-invariant expansion with a strongly-coupled QGP equation of state which is quite close to the lattice equation of state. We study the survival of $c\bar{c}$ states in a strongly coupled quark-gluon plasma. We consider the dissipative corrections which are coming from the shear viscosity, η only. We further explore the sensitivity of prompt and sequential suppression of these states to the shear viscosity to entropy density ratio,η/s. We consider perturbative QCD as well as AdS/CFT predictions for η/s. Our results show excellent agreement with the recent experimental results at RHIC.

Key words: Sequential melting, Survival probability, Heavy-ion collisions
PACS:

1. Introduction

Charmonium (J/ψ) suppression has long been proposed as a signature of QGP formation[1] and has indeed been seen at SPS[2] and RHIC experiments[3]. The heavy quark pair leading to the J/ψ mesons are produced in nucleus-nucleus 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 dilepton) to be detected. If the plasma has cooled to a energy density less than ϵ_s, the $c\bar{c}$ pair would escape and quarkonium would be formed. If however, the energy density is still larger than ϵ_s, the resonance will not form and we shall have a quarkonium suppression. It is easy to see that the p_T dependence of the survival probability will depend on how rapidly the plasma cools. If the initial energy density is sufficiently high, the plasma will take longer to cool and only the pairs with very high p_T will escape. If however the plasma cools rapidly, then even pairs with moderate p_T will escape.

The main motivation of this article is: i) First we use an appropriate equation of state (EoS) which should reproduce the lattice results verifying the strongly-interacting nature of QGP. ii) Then we study hydrodynamic boost-invariant Bjorken expansion in $(1+1)$ dimension with the EoS discussed in i) as an input. In addition we explore the effects of dissipative terms on the hydrodynamic expansion by considering the shear viscosity η up to first-order in the stress-tensor.

2. Longitudinal expansion of QGP

In the presence of viscous forces the energy-momentum tensor is written as [6,7],

$$T^{\mu\nu} = (\epsilon + p)u^\mu u^\nu + g^{\mu\nu}p + \pi^{\mu\nu}, \tag{1}$$

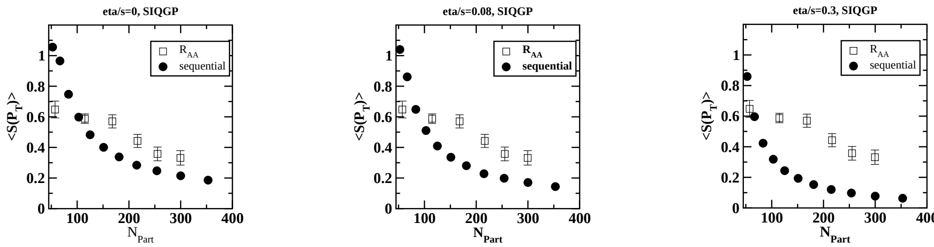

Fig. 1. The variation of p_T integrated survival probability (in the range allowed by invariant p_T spectrum of J/ψ by the Phenix experiment [3]) versus number of participants at mid-rapidity. The experimental data (the nuclear-modification factor R_{AA}) are shown by the squares with error bars whereas solid circles represent the sequential melting using the values of T_D's [10] and related parameters from Table I using SIQGP equation of state.

where $\pi^{\mu\nu}$ is the stress-energy tensor. Dissipative corrections to the first-order in the gradient expansion are recovered by setting the relaxation time to zero. This leads to: $\pi^{\mu\nu} = \eta\langle\nabla^\mu u^\nu\rangle$, where η is the co-efficient of the shear viscosity and $\langle\nabla^\mu u^\nu\rangle$ is the symmetrized velocity gradient. In (1+1) dimensional Bjorken expansion in the first-order dissipative hydrodynamics, only one component $\pi^{\eta\eta}$ of the viscous stress tensor is non-zero. In this case the equation of motion reads,

$$\partial_\tau \epsilon = -\frac{\epsilon + p}{\tau} + \frac{4\eta}{3\tau^2} \,. \tag{2}$$

The solution of above equation is obtained as,

$$\epsilon(\tau)\tau^{(1+c_s^2)} + \frac{4a}{3\tilde{\tau}^2}\tau^{(1+c_s^2)} = \epsilon(\tau_i)\tau_i^{(1+c_s^2)} + \frac{4a}{3\tilde{\tau_i}^2} = \text{const} \,, \tag{3}$$

where $a = \left(\frac{\eta}{s}\right) T_i^3 \tau_i$ and $\tilde{\tau}^2$ and $\tilde{\tau}_i^2$ are given by $(1-c_s^2)\tau^2$ and $(1-c_s^2)\tau_i^2$, respectively. The first term in both LHS and RHS accounts for the contributions coming from the zeroth-order expansion and the second term is the first-order viscous corrections

In our work we consider three values of the shear viscosity-to-entropy density ratio to see the effects of nonzero values of the shear viscosity on the expansion. The first one is from perturbative QCD [4] calculations where η/s is =0.3 near $T \sim T_c - 2T_c$. The second one is from AdS/CFT studies [5] where $\eta/s = 1/4\pi$ ($\sim$ 0.08). Finally we consider η/s=0 (for the ideal fluid) for the sake of comparison. We shall employ Eq.(3) to study the charmonium suppression in a strongly interacting QCD medium formed in a ultra-relativistic heavy-ion collisions in the next section.

2.1. *Survival probability*

Let us take a simple parametrization for the initial energy-density profile on any transverse plane :

$$\epsilon(\tau_i, r) = \epsilon_i A_T(r); A_T(r) = \left(1 - \frac{r^2}{R_T^2}\right)^\beta \theta(R_T - r) \tag{4}$$

where r is the transverse co-ordinate and R_T is the transverse radius of the nucleus.The average energy-density is obtained from the Bjorken formula. The time τ_s when the energy density drops to the screening energy density ϵ_s is estimated from Eq.(3) as

$$\tau_s(r) = \tau_i \left[\frac{\epsilon_i(r) - \frac{4a}{3\tilde{\tau}_i^2}}{\epsilon_s - \frac{4a}{3\tilde{\tau}_s^2}}\right]^{1/1+c_s^2} \tag{5}$$

where $\epsilon_i(r) = \epsilon(\tau_i, r)$ and $\tilde{\tau}_s^2$ is $(1-c_s^2)\tau_s^2$. The critical radius r_s, is seen to mark the boundary of the region where the quarkonium formation is suppressed, can be obtained by equating the duration of screening $\tau_s(r)$ to the formation time $t_F = \gamma\tau_F$ for the quarkonium in the plasma frame and is given by: $r_s = R_T(1-A)^{\frac{1}{2}}\theta\,(1-A)$, where A is given by

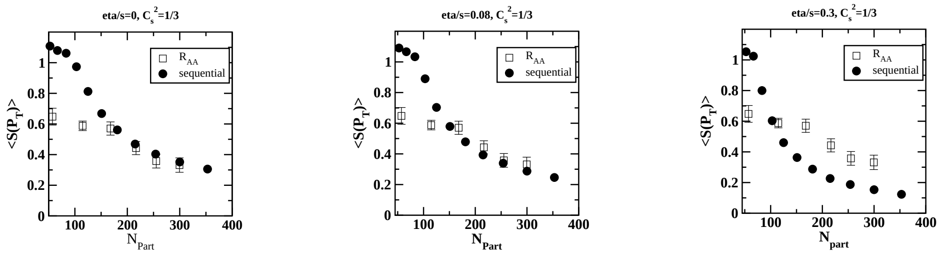

Fig. 2. Same as Fig. 1 but the related parameters from the ideal EoS.

$$A = \left[\left(\frac{\epsilon_s}{\epsilon_i}\right)\left(\frac{t_F}{\tau_i}\right)^{1+c_s^2} + \frac{1}{\epsilon_i}\left(\frac{t_F}{\tau_i}\right)^{(1+c_s^2)} \frac{4a}{3\tilde{t}_F^2} + \frac{1}{\epsilon_i}\frac{4a}{3\tilde{\tau}_i^2} \right]^{1/\beta} \tag{6}$$

with $\tilde{t}_F^2 = (1-c_s^2)t_F^2$. The quark-pair will escape the screening region (and form quarkonium) if its position $\mathbf{r}$ and transverse momentum $\mathbf{p}_T$ are such that

$$|\mathbf{r} + \tau_F \mathbf{p}_T/M| \geq r_s. \tag{7}$$

Thus, if ϕ is the angle between the vectors $\mathbf{r}$ and $\mathbf{p}_T$, then

$$\cos\phi \;\geq\; \left[(r_s^2 - r^2)\, M - \tau_F^2\, p_T^2/M\right] / \left[2\, r\, \tau_F\, p_T\right], \tag{8}$$

which leads to a range of values of ϕ when the quarkonium would escape. Now we can write for the survival probability of the quarkonium:

$$S(p_T) = \left[\int_0^{R_T} r\, dr \int_{-\phi\mathrm{max}}^{+\phi\mathrm{max}} d\phi\, P(\mathbf{r}, \mathbf{p}_T) \right] / \left[2\pi \int_0^{R_T} r\, dr\, P(\mathbf{r}, \mathbf{p}_T) \right], \tag{9}$$

where ϕ_{max} is the maximum positive angle $(0 \leq \phi \leq \pi)$ allowed by Eq.(8) and P is the probability for the quark-pair production at ($\mathbf{r}$, $\mathbf{p}_T$), in a hard collision. The production of J/ψ mesons in hadronic reactions occurs in-part through production of higher excited $c\bar{c}$ states and their decay into quarkonia ground state. Since the lifetime of different sub-threshold quarkonium states is much larger than the typical life-time of the medium which may be produced in nucleus-nucleus collisions so their decay occurs almost completely outside the produced medium. This means that the produced medium can be probed not only by the ground state quarkonium but also by different excited quarkonium states. Since, different quarkonium states have different sizes (binding energies), one expects that higher excited states will dissolve at smaller temperature as compared to the smaller and more tightly bound ground states. These facts may lead to a sequential suppression pattern in J/ψ yield in nucleus-nucleus collision as the function of the energy density or number of participants in the collision.

In nucleus-nucleus collisions, it is known 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 decay of ψ'. Hence, the p_T-integrated inclusive survival probability of J/ψ in the QGP becomes [8,9].

$$\langle S^{\mathrm{incl}} \rangle = 0.6 \langle S^{\mathrm{dir}} \rangle_{\psi} + 0.3 \langle S^{\mathrm{dir}} \rangle_{\chi_c} + 0.1 \langle S^{\mathrm{dir}} \rangle_{\psi'} \tag{10}$$

3. Results and discussions

The screening scenario of J/ψ suppression in an expanding plasma involved three time-scales: The screening time, τ_s,the formation time of J/ψ in the plasma frame ($t_F = \gamma\tau_F$)and the cooling rate which depends on the speed of sound. More precisely, the screening time depends upon (i) the difference between the initial energy density ϵ_i and the screening energy density ϵ_s: the more will be the difference the more will be the suppression, (ii) the speed of sound: the values of c_s^2 which are less than 1/3, the rate of cooling will be slower which, in turn, makes the screening time large for a fixed difference in (ϵ_i- ϵ_s) leading to more suppression, and (iii) the η/s ratio: if the ratio is larger then the cooling will be slower, so the system will take longer to reach ϵ_s resulting the higher

Table 1
Formation time (fm), dissociation temperature T_D (in units of T_c=197 MeV for a 3-flavor QGP) with the Debye mass in the leading-order [10,11], the speed of sound c_s^2 and the screening energy density ϵ_s (GeV/fm^3) calculated in SIQGP and ideal EoS for J/ψ, ψ', χ_c states [10,11], respectively.

State	τ_F	T_D	c_s^2(SIQGP)	c_s^2(Id)	ϵ_s (SIQGP)	ϵ_s(Id)
J/ψ	0.89	1.61	0.26	1/3	17.65	21.77
ψ'	1.50	1.16	0.24	1/3	04.51	06.53
χ_c	2.00	1.25	0.24	1/3	06.15	08.47

value of screening time and hence more suppression compared to $\eta/s = 0$. With this physical understanding we analyze $\langle S(p_T)\rangle$ as a function of the number of participants $N_{\rm Part}$ in an expanding QGP. In Fig. 1, we find that the survival probability of $\langle S^{\rm incl}\rangle$ is closer to the the experimental results [3].For the lower value of η/s our predictions are closer to the experimental ones. In Fig.2, we used the same values of dissociation temperatures as in Table I but the thermodynamic variables *viz.* ϵ_s, c_s^2 etc. have been calculated in the ideal EoS to see the sensitivity of the EoS to the plasma dynamics. The matching is almost perfect for η/s=0. This can be understood in terms of the sensitivity of $\langle S(p_T)\rangle$ on the speed of sound for a fixed difference in (ϵ_i-ϵ_s) because cooling of the system with ideal EoS is much faster compared to the strongly-interacting EoS so the system will spend less time in the screening region results in less suppression.

Another interesting observation, which is common to both Fig.1 and 2 is that as the ratio η/s is increased from 0 to 0.3, $\langle S(p_T)\rangle$ for sequential J/ψ's become smaller. As the ratio η/s is increased from zero, cooling becomes slower so that χ_c and ψ' show more suppression due to their smaller value of ϵ_s (smaller T_D) compared to J/ψ making the difference between ϵ_i and ϵ_s larger. This leads to more suppression for χ and ψ''s.

4. Conclusions

In conclusion, we have studied the charmonium suppression in a longitudinally expanding QGP in the presence of dissipative forces. We find that presence of dissipative terms in the fluid equation of motion slower the expansion rate and eventually lead to the enhanced suppression of J/ψ. In this work, we have exploited a recent understanding of dissociation of quarkonia in the QGP medium which rely on the fact that the transition from the hadronic matter to QGP is a crossover not a phase transition in the true sense. We have employed the results of [10,11] on dissociation temperatures of various charmonium states. We have employed the SIQGP equation of state to estimate the screening energy density and the speed of sound to study the J/ψ yield. We find that the results on J/ψ survival probability agree with the Phenix Au-Au data[3] with the set of dissociation temperatures (Table I) obtained with the perturbative result of the Debye mass.

References

[1] T. Matsui and H. Satz, Phys. Lett. B **178**, 416 (1986)
[2] G. Borges, NA50 Collaboration, J. Phys. G **32**, S 381 (2006)
[3] J. Adams, *et al*,Phys. Rev. Lett. **9e2**, 112301 (2004); A. Adare *et al.*, (PHENIX Collaboration), Phys. Rev. Lett. **98**, 232301 (2007)
[4] P. Arnold, G. D. Moore, and L. G. Yaffe, JHEP **11**,001 (2000); *ibid* **05**, 051 (2003)
[5] P. Kovtun, D.T. Son, A. O. Starinets, Phys. Rev. Lett. **94**, 111601 (2005)
[6] H. Kouno, M. Maruyama, F. Takagi, and K. Saito, Phys. Rev. D **41**, 2903 (1990)
[7] A. Muronga, Phys. Rev. Lett. **88**, 062302 (2002)
[8] H. Satz, Nucl. Phys. A **783**, 249 (2007)
[9] D. Pal, B. K. Patra and D. K. Srivastava, Euro. Phys. J. **C 17**, 179 (2000)
[10] V. Agotiya, V. Chandra and B. K. Patra, Phys. Rev. C **80**, 025210 (2009)
[11] V. Agotiya, V. Chandra and B. K. Patra, arXiv:Nucl-th/0910.0586