Re-visiting the J/Ψ suppression for quark-gluon plasma formation in small systems

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Outline of Talk:

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Introduction

- Initially QGP (a thermally equilibrated phase) was hardly expected in $p - p$ collision.
- However, to the contrary the data from $p - Pb$ collisions at $\sqrt{s_{NN}} = 5.02 TeV$ **(Phys.Lett.B 742 (2015) 200-224)**, and the same for $p - p$ collisions at $\sqrt{s} = 5 TeV$, $7 TeV$ and $13 TeV$ at the LHC **(Phys.Lett.B 765 (2017) 193-220)** indicated the observation of non-zero elliptic flow co-efficients-which is regarded a hallmark for collectivity of a medium.
- Thus observation of the closest possible example of matter in nature with the shear viscosity co-efficient near the quantum mechanical bound, dubbed as the most perfect fluid, might have formed even in $p - p$ collisions.
- Quarkonia suppression has been among a few clean signals put forward for the confirmation of the formation of a deconfined phase of matter of quarks and gluons in Heavy Ion Collisions.

Introduction

- In some of the recent studies, there have also been calculations for quarkonia suppression even in small systems such as those produced in $p - A$ and $p - p$ collisions. In these studies, however, the the evolution of the quarkonia state has been taken as adiabatic. To the contrary, in the case of systems produced in $p - p/p - A$ collisions, it is expected that the system cools down very fast.
- In the present study, we investigate the scenario of non-adiabatic evolution of the state in QGP medium for systems produced in $p - p/p - A$ collisions along with ideal as well as viscous evolution of temperature within a (2+1)D expansion model.
- We find the probability of transition from initial quarkonium states to the continuum states is rather small.

Basic Picture

- For the system created in heavy ion collision, the pressure gradient in the transverse direction is quite small compared to the longitudinal pressure gradient. Hence the Bjorken $(1+1)$D expansion is quite reasonable to use.
- For Bjorken $(1+1)$D expansion of perfect fluid, the temperature evolves as $T = T_0 * (\tau_0/\tau)^{1/3}$. The viscous effect slows down the cooling rate.
- Whereas for a small system of collisions, the energy density gradient in the transverse direction is quite large (at least 5 times larger than that in the $Pb - Pb$ or $Au - Au$ collision).
- Hence the expansion of matter in the transverse space will also be comparable to that the longitudinal direction.

Basic Picture

Continued

- A better description for the system produced in $p-p$ collision should incorporate the hydrodynamic expansion as a $(2+1)$D expansion, with the simplistic assumption of an isitropic transverse energy density gradient.
- As a result, the temperature is expected to decrease faster in time than the case of Bjorken $(1+1)$D expansion.
- Hence the QGP phase (if produced) will remain for a shorter time than its expected lifetime for Heavy Ion Collisions.
- So the produced J/ψs may not get sufficient time for dissociation, or dissociation may get suppressed in this rapid evolution.

Mechanism

- Initially, before thermalization J/ψ potential was not screened.
- The Hamiltonian can be considered as zero temperature Hamiltonian ($H_0 = \frac{p^2}{2m} + \sigma r - \frac{4}{3}\alpha_s/r$)
- Now as medium thermalizes, Hamiltonian also evolves and becomes Hamiltonian with finite temperature ($H(t) = \frac{p^2}{2m} + \frac{\sigma}{\mu}(1 - exp^{-\mu r} - \frac{4}{3}\alpha_s exp^{-\mu r}/r$)
- α_s is strong coupling constant, σ is string tension, μ is screening mass, depends on temperature as $\mu = \sqrt{6\pi\alpha_s}T(t)$

Mechanism

- After some time the temperature becomes less than the critical temperature and effectively the Hamiltonian becomes zero temperature Hamiltonian.
- The whole process is quite fast $\Rightarrow$ the initial quarkonia states may not evolve adiabatically and they make the transition to other states, orthogonal to the initial state.
- When Hamiltonian evolves with time, states also change.
- Effectively the Hamiltonian starts evolving from zero temperature Hamiltonian to a finite temperature and then again comes to zero temperature$\Rightarrow$ initial and final eigen states remain the same.

Mechanism

- Consider the initial state $|i\rangle$ to be an eigen state of H_0 and evolves due to the perturbation $H'(t) = H(t) - H_0$.
- The projection operator orthogonal to that initial state and a few stable eigen states say $|m\rangle$ is $Q = 1 - \sum_m |m\rangle\langle m|$.
- $|i\rangle \in |m\rangle$. $|\psi\rangle$ is the evolved state after the action of the perturbation.
- Transition probability ζ can be written as

$$\zeta = \langle\psi|Q|\psi\rangle \tag{1}$$

- One can expand $|\psi\rangle$ in terms of the eigenstates $|n\rangle$ of initial Hamiltonian H_0.

$$|\psi\rangle = \sum_n c_n|n\rangle \tag{2}$$

- From first-order perturbation theory one can write,

$$c_n = \delta_{ni} - i\int_0^{\tau} \langle n|H'(t)|i\rangle dt \tag{3}$$

Mechanism

- $|i\rangle$ & $|n\rangle$ are comparatively slowly varying functions than $H' \Rightarrow$

$$c_n = \delta_{ni} - i\tau\langle n| \left(\frac{1}{\tau}\int_0^\tau H'(t)dt\right)|i\rangle$$
$$= \delta_{ni} - i\tau\langle n|\bar{H}'|i\rangle \quad (4)$$

$$\bar{H}' = \frac{1}{\tau}\int_0^\tau H'(t)dt \quad (5)$$

Using equations (1, 2, 4 & 5) and after simplification we have

$$\zeta = \tau^2(\langle i|\bar{H}'^2|i\rangle - \sum_m \langle m|\bar{H}'|m\rangle^2) \quad (6)$$

- In QGP only J/Ψ, χ and Ψ' states are stable. So effectively ζ shows the transition from bound states to unbound states, which is the dissociation probability.

Gubser Flow

- The Evolution of QGP in $(2+1)$D has been considered in **(Nucl.Phys.B 846 (2011) 469-511)** by Gubser and Yarom.
- Here the longitudinal flow has been taken to be boost invarient like the Bjorken flow, along with that there is also consideration of flow in transverse direction with isotropic transverse expansion.
- The evolution of energy density of QGP with Gubser flow symmetry including third order viscous correction can be found in **(PhysRevC.97.064909)** by Chandrodoy Chattopadhyay et al.

$$\frac{d\hat{\epsilon}}{d\rho} = -\left(\frac{8}{3}\hat{\epsilon} - \pi\right) tanh(\rho) \tag{7}$$

$$\frac{d\hat{\pi}}{d\rho} = -\frac{\hat{\pi}}{\hat{\tau}_\pi} + tanh(\rho)\left(\frac{4}{3}\hat{\beta}_\pi - \hat{\lambda}\hat{\pi} - \hat{\chi}\frac{\pi^2}{\hat{\beta}_\pi}\right) \tag{8}$$

Gubser Flow

- Here $\hat{\epsilon} = \epsilon\tau^4$, $\hat{\pi} = \pi\tau^4$ and so on.
  $\hat{\beta}_\pi = \frac{4}{5}\hat{P}$, $\hat{\lambda} = \frac{46}{21}$ and third order correction parameter $\hat{\chi} = \frac{72}{245}$
- $sinh(\rho) = -\frac{1-q^2\tau^2+q^2{x_T}^2}{2q\tau}$
- x_T is the position in transverse plane.
- $q \sim \frac{1}{r_t}$, r_t is the system size.
- $r_t \to \infty$ or $q \to 0 \Rightarrow$ Gubser flow $\to$ Bjorken Flow

Results

Here we have solved the evolution equations with initial condition as $\hat{T} = \hat{T}_0$ at $\tau = \tau_0$ and initial $\hat{\pi} = \frac{4}{3}\hat{\beta}_\pi \hat{\tau}_\pi$. Below we show the evolution of temperature of QGP.

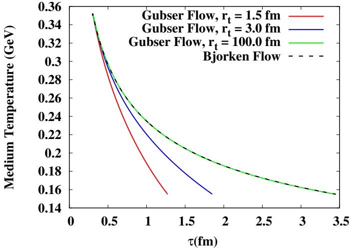

Figure : Temperature as a function of time. (Left panel)- Inviscid. (Right panel)- Viscous (Navier-Stokes Theory).

Results

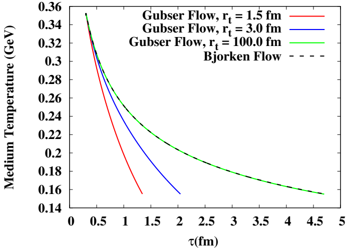

Figure : Temperature as a function of time. (Left panel)- Dissipative Muller Israel Stwart theory. (Right panel)-Dissipative hydrodynamics with 3rd order viscous correction terms.

Results

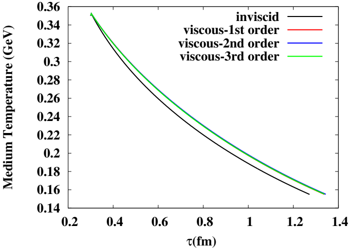

Figure : Here we have calculated temperature evolution for different orders of theories of viscous correction.

Results

Corresponding with all above temperature evolution scenarios considered, we have calculated the dissociation probability in our framework.

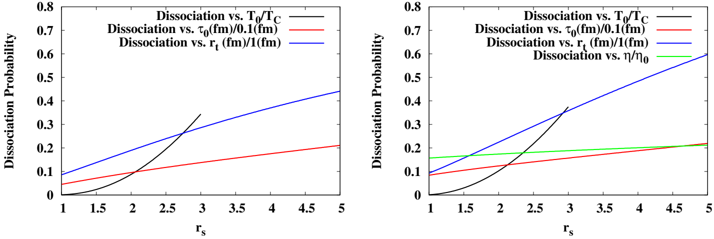

Figure : The probability of dissociation has been calculated for the inviscid case (Left panel) and for 3rd order viscous correction (Right panel)

Summary

- The dissociation probability of J/ψ always remains less than 40% with the initial temperature $\sim 3T_c$
- This probability is the maximum probability of dissociation where we have considered that the J/ψ once formed does not leave the medium before the system hadronizes.
- The overall dissociation probability of J/Ψ will be further smaller with a consideration of transverse energy density profile and/or moving J/Ψ.
- In this study with our present scenarios, the J/ψ hardly dissociates in medium created in $p-p$ collisions in contrast to the traditional age-old mechanism if the temperature remains less than $3T_c$.

Thank You !