Bottomonium suppression: A probe to the pre-equilibrium era of hydrodynamics

U.S. Kakade[1], Binoy Krishna Patra[1], and A.K. Chaudhuri[2]
[1] *Physics Department, Indian Institute of Technology, Roorkee-247 667, INDIA and*
[2] *Variable Energy Cyclotron Center, Kolkata-700 064, INDIA*

1. Introduction

The experimental programs of heavy-ion collisions at RHIC and LHC open an interesting window onto the properties of QCD at high temperatures in the guise of quark-gluon plasma(QGP). At high temperature such deconfined state exhibits the screening of static chromo-electric fields which leads to heavy quarkonium suppression [1]. Nowadays the bottomonium is looked as better probe over J/ψ at LHC because the competition between suppression and enhancement is unlikely, in contrast to charmonium states due to the smaller charm quark mass ($m_c < m_b$).

In view of absence of theoretical proof of early thermalization of plasma it is hard to assume the hydrodynamical behavior of the system from the beginning, implies that there is a possibility of the pre-equilibrium phase before thermalization of plasma and thus introduces momentum-space anisotropy via the longitudinal expansion along beam line and imprints its impact on quarkonium suppression before the system is isotropized [2]. In the present work, we focus on bottomonium suppression and estimated the inclusive suppression of Υ states for both the pre-equilibrium evolution as well as ideal hydrodynamical evolution which are significant before and after the isotropization time, respectively. Our estimation shows a good matching with CMS data [3]. The dynamical evolution of plasma is discussed in section 2, section 3 deals with in medium behavior and suppression of bottomonium. Finally the results and conclusions are discussed in section 4 .

2. Dynamical evolution of plasma

Recently there have been significant advances in the dynamical models for the plasma evolution to incorporate momentum anisotropy at the very early stage of collision, in addition to the equilibrium hydrodynamics.
A. Pre-equilibrium era: The partonic system generated in heavy-ion collisions cannot be isotropic from the beginning because of the substantial longitudinal expansion due to asymptotic weak-coupling compared to the transverse expansion. As a result, an anisotropy in momentum space sets in [4] and can be envisaged through the distribution function, in the small anisotropic limit

$$f_{\rm aniso}(\mathbf{p},\xi,p_{\rm hard}) = f^{\rm iso}(\sqrt{\mathbf{p^2}+\xi(\mathbf{p}.\hat{\mathbf{n}})^2},p_{\rm hard})\,. \quad (1)$$

where $p_{\rm hard}$ and ξ are the hard momentum scale and the anisotropy parameter, respectively which characterize the pre-equilibrium era, equivalent to the two-temperature system. With this anisotropic distribution, the proper time-dependence of energy density ($\mathcal{E}$), anisotropy (ξ), etc. can be written as [2]

$$\xi(\tau,\delta) = \left(\frac{\tau}{\tau_0}\right)^{\delta(1-\lambda(\tau))} \quad (2)$$

$$\mathcal{E}(\tau) = \mathcal{E}_0(p_{\rm hard})\,\mathcal{R}(\xi)\,\bar{\mathcal{U}}^{4/3}, \quad (3)$$

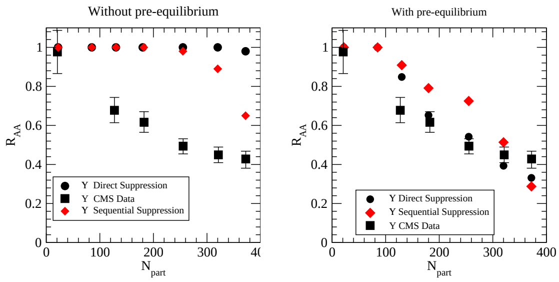
$$p_{\rm hard}(\tau) = T_0\ \bar{\mathcal{U}}^{1/3}\ ;\ \bar{\mathcal{U}} = \mathcal{U}(\tau)/\mathcal{U}(\tau_i) \quad (4)$$

$$\mathcal{U} = \left[\mathcal{R}\left((\frac{\tau_{iso}}{\tau_0})^{\delta}-1\right)\right]^a\left[\frac{\tau_{\rm iso}}{\tau}\right]^b$$

where, $\mathcal{R}(\xi) = \frac{1}{2}\left[\frac{1}{\xi+1}+\frac{arctan\sqrt{\xi}}{\sqrt{\xi}}\right]$, $\mathcal{E}_0(p_{\rm hard})$ is the initial energy density, the parameters- a= $3\lambda(\tau)/4$, b=1-$\delta(1-\lambda(\tau))/2$, δ is interpolating coefficient, and $\lambda(\tau) \equiv (\tanh(\gamma(\tau-\tau_{\rm iso})/\tau_0)+1)/2$ is a smeared step function to govern the smoothness of transition from pre-equilibrium to equilibrium, namely, for $\tau \ll \tau_{\rm iso}$, $\lambda \to 0$, the system is expanding like free-streaming partons and for $\tau \gg \tau_{\rm iso}$, $\lambda \to 1$, the system is expanding hydro dynamically. Thus the pre-equilibrium era is significant for the time duration: $\tau_0 \le \tau \le \tau_{iso}$.
B. Equilibrium era: When the rate of expansion overcomes the parton interaction rate the system attains local thermodynamic equilibrium for times $\tau \ge \tau_{iso}$. For a simple relativistic fluid in local equilibrium, conservation of the energy-momentum tensor ($T^{\mu\nu}$) gives the hydrodynamic evolution of the plasma: $\partial_\mu T^{\mu\nu} = 0$ with $T^{\mu\nu} = (\epsilon+P)u^\mu u^\nu - Pg^{\mu\nu}$ where ϵ, P and u^μ are the energy density, the pressure and fluid four-velocity, respectively. The viscous hydrodynamics [5] can be also studied with the addition of stress-tensor to $T^{\mu\nu}$.

3. Bottomonium Suppression

A. Bottomonium in anisotropic medium: Recently we have studied the properties of quarkonium states [6] in the presence of small momentum anisotropy (ξ) by considering both perturbative as well as the non-perturbative effects and found that in-medium modification to the heavy-quark potential causes less screening and hence they are more bound, compared to their



(a) (b)

FIG. 1: Bottomonium Suppression at LHC

isotropic counterpart :

$$E_{\rm bin} = -\frac{m_Q \sigma^2}{m_d^4 n^2}\left[1+\frac{\xi}{3}\right]^2 - \alpha m_d, \qquad (5)$$

where m_Q is the bottomonium mass, σ is the string tension m_d is the Debye screening mass and α is the coupling constant. Hence the dissociation temperatures are increased with the anisotropy [6] like - $T^D_{\rm aniso} = T^D_{\rm iso}\left[1+\frac{\xi}{7}\right]$. Thus the properties of quarkonia has been refined with the dynamical evolution of the plasma through the pre-equilibrium and equilibrium phases differently. Recent developments have shown that the potential is always accompanied by an imaginary part due to Landau damping which causes the early dissociation of the states.

B. Bottomonium Suppression: Relativistic heavy-ion collision results in the formation of partons at τ_0 and there exists a region of energy density, $\epsilon \geq \epsilon_s$ (screening energy density) where a particular $Q\bar{Q}$ state is melted. Initially the partons undergo the pre-equilibrium era and thereafter it attains local equilibrium and evolves according to the hydrodynamics. Let a pair is created at $\mathbf{r}$ with the momentum $\mathbf{p}_T$ on the transverse plane, it would thus take time $\gamma\tau_F$ to form a resonance in the plasma. In between the pair moves to a position $(\mathbf{r}+\tau_F\mathbf{p}_T/M)$. If, at this instant, the plasma has been cooled below ϵ_s, the pair may escape and the quarkonium would be formed. On the other hand it will be suppressed if $\epsilon > \epsilon_s$. The survival of quarkonium state depends on how rapidly the plasma expands, how the properties of quarkonia change in (an)isotropic medium, the equation of state etc. For high initial energy density it takes longer time to cool and only the $Q\bar{Q}$ pairs with very high p_T will escape, while in case of rapid cooling, $Q\bar{Q}$ pairs with moderate p_T may also escape, enriches the P_T dependence of quarkonia.To estimate quarkonium suppression one need to construct constant energy density contour for both the pre-equilibrium and equilibrium phases. The same can be obtained by searching the time availed to screen the potential i.e, the screening time (τ_s) profile is obtained when $\epsilon(\tau, r)$ is equal to ϵ_s. Then the critical radius r_s (boundary of quarkonium suppression) is obtained by $\tau_s(r) = \tau_F$. Thus the condition of survival is recasted as: $|\mathbf{r}+\tau_F\mathbf{p}_T/M| \geq r_s$ i.e., the cosine of the angle becomes: $\cos\phi \geq \left[(r_s^2 - r^2)\, M - \tau_F^2\, p_T^2/M\right] / \left[2\, r\, \tau_F\, p_T\right]$. The suppression factor of the quarkonium is obtained as [7]

$$R_{AA} = \frac{\int_0^R d^2r \int_{-\phi_m}^{+\phi_m} d\phi\, P(\mathbf{r}, \mathbf{p}_T) dp_T}{\int_0^R d^2r P(\mathbf{r}, \mathbf{p}_T) dp_T} \qquad (6)$$

where ϕ_m is the maximum positive angle ($0 \leq \phi \leq \pi$) and $P(\mathbf{r}, p_T)$ is the probability for the heavy quark-(anti) quark pair production in a hard collision.

4. Results and Conclusions

We have estimated the suppression factor for both prompt Υ's and Υ's coming from the decays (feed-down) with or without pre-equilibrium phase, in addition to the equilibrium phase alone and is presented in Fig.1 along with the CMS data. The left and right panel of the figure represent the suppression of bottomonium without and with the pre-equilibrium era, respectively. The suppression factor with the local equilibrium hydrodynamics regime alone is much higher than the experimental data and indicates that only the equilibrium evolution may not be sufficient to probe the bottomonium suppression. Some additional time zone of plasma evolution is to be searched for more suppression. The inclusion of pre-equilibrium era, in addition to the local equilibrium evolution shows reasonable matching with the data. Hence, it can be inferred that *the amalgamation of anisotropy dependent binding energy with the high initial energy density in pre-equilibrium phase* may be responsible for the additional suppression for Υ state. Thus we conclude that the bottomonium suppression is more sensitive to probe pre-equilibrium era of the QGP.

References

[1] T. Matsui and H. Satz, Phys. Lett. B **178**, 416(1986).
[2] Martinez M and Strickland M Nucl Phys.**A848**, 183(2010)
[3] S. Chatrchyan *et al.*, Phys. Rev. Lett. **109**, 222301(2012).
[4] Dumitru A, Guo Y and Strickland M Phys.Rev. **D79**, 114003(2009)
[5] V. Roy, A.K. Chaudhuri, PRC**85**, 024909(2011)
[6] Lata Thakur, N. Haque, Uttam Kakade and B.K. Patra PRD **in press** (2013)
[7] D Pal, B K Patra and D K Srivastava, Eur J Phys C B **507**, 113(2001)