How Does Relativistic Doppler Shift Influence Υ(1S) & J/ψ Yields in the Anisotropic QGP Medium?

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Introduction

Quarkonia production plays a crucial role in probing the very existence of quark-gluon plasma (QGP) in high-energy heavy-ion collisions at facilities like RHIC BNL and LHC CERN. The suppression of quarkonia depends on its melting temperature and the temperature of the medium. In this work, we observed that quarkonia traversing through the medium does not carry the same temperature as the medium due to the relativistic Doppler shift effect. The implicit temperature of the particle depends on its velocity, and here we showed how quarkonia velocity (v_Q) or transverse momentum (p_T) influences the dissociation and regeneration of the particle in the medium. In this study, we consider an anisotropic deconfined hot QCD medium and obtain the modification on the quarkonia potential imposed by the medium. This modification of the potential induces the collisional damping for quarkonia. Besides that, the gluons surrounding the quarkonia make it transit from singlet to octet state. These two mechanisms cause quarkonia to decay in the medium. Apart from this, we calculate the regeneration of quarkonia within the QCD medium using the detailed balance approach. Further, we observe the influence of medium anisotropy and relativistic Doppler shift on the particle's net decay width ($\Gamma_{\rm D}$) and reaction reactivity ($\Gamma_{\rm F}$) responsible for quarkonia regeneration. The $v_{\rm Q}$ and T_{eff} dependent $\Gamma_{\rm D}$ and $\Gamma_{\rm F}$ are obtained for J/ψ and Υ(1S) for the for the strength of medium anisotropy, $\zeta = 0.2, 0.4$ at T = 300 MeV. The present study is an extension of our previous work to incorporate an anisotropic correction to the UMQS model, which is used to estimate the net quarkonia suppression in ultra-relativistic collisions at the RHIC and LHC energies [1].

Formalism

The relativistic Doppler shift induced due to the relative velocity (v_r) between the heavy meson and the medium causes an angle-dependent effective temperature (T_{eff}). Thus, the Doppler effect results in a blue-shifted T_{eff} in the forward direction and a red-shift in the backward direction. In the region where $T_{eff} > T$, which experiences the blue-shift, this shift only occurs at very small angles. On the other hand, the red-shifted region is more dominant than the blue-shifted region at all relative velocities $v_r > 0$, causing $T_{eff} < T$. With higher velocities, the red-shift increases, leading to a decrease in the effective temperature for particles with high p_T values. The angle averaged T_{eff} is given as [2]:

$$T_{eff}(\tau, b, p_T) = T(\tau, b)\, \frac{\sqrt{1-|v_r|^2}}{2\,|v_r|}\, \ln\left[\frac{1+|v_r|}{1-|v_r|}\right]$$

Moreover, to obtain the medium-modified potential for quarkonia, we employed anisotropic distribution functions for partons derived from isotropic ones through rescaling in one direction in momentum space [2]:

$$f(\mathbf{p}) \rightarrow f_\zeta(\mathbf{p}) = C_\zeta\, f(\sqrt{\mathbf{p}^2 + \zeta(\mathbf{p}\cdot\hat{\mathbf{n}})^2})$$

Here, $\hat{\mathbf{n}}$ is a unit vector ($\hat{\mathbf{n}}^2 = 1$) representing the direction of anisotropy, and ζ quantifies the anisotropic strength in the medium. It describes the degree of squeezing ($\zeta > 0$, oblate form) or stretching ($-1 < \zeta < 0$, prolate form) along the $\hat{\mathbf{n}}$ direction.

Using T_{eff} and ζ in the complex potential, we have obtained particle velocity-dependent net decay width (Γ_D) and regeneration reactivity (Γ_F). The Γ_D accounts for the effects of gluonic dissociation and collision damping while Γ_F is obtained by taking the thermal average of the recombination cross-section for correlated $q-\bar{q}$ pair [2].

Results and Discussions

We show the relativistic Doppler effect and anisotropic properties of the medium through our prediction for T_{eff}, Γ_D and Γ_F as the function of velocity (v_Q) for J/ψ and Υ(1S) with masses 3.1 GeV and 9.46 GeV, respectively. In the first row of Fig. 1, variation in the T_{eff} for J/ψ and Υ(1S) versus v_Q comes out precisely same at three different temperature sets T = 200, 300, and 400 MeV. It is same because mass dependence is omitted in the first plot.

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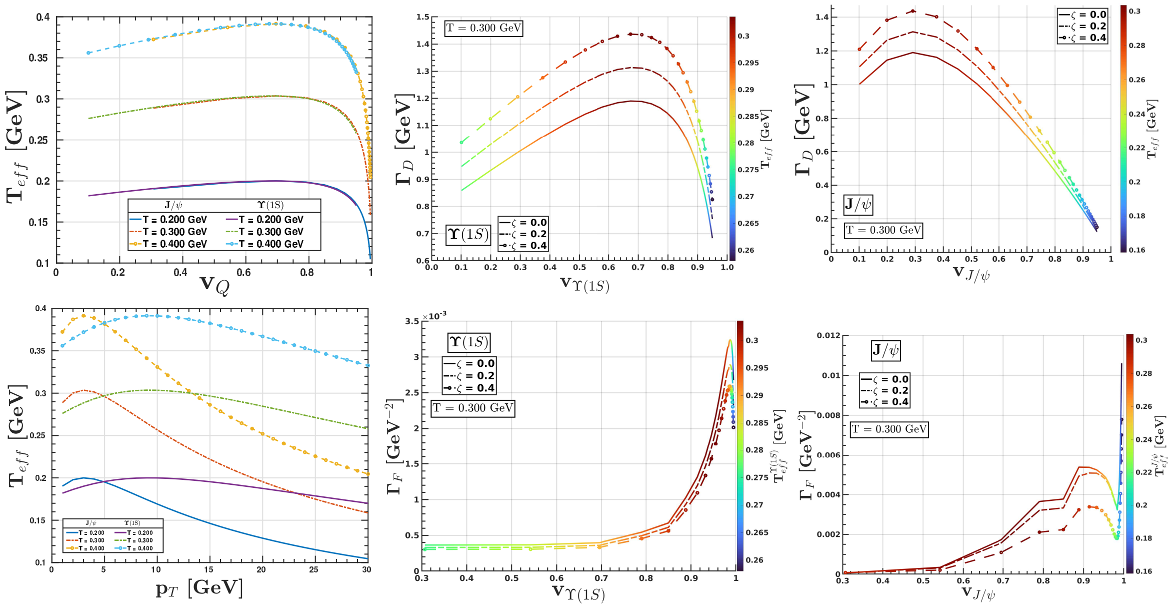

FIG. 1: (Color Online) In the first row **Left to Right:** Change in T_{eff} and Γ_D verus v_Q are shown for Υ(1S) and J/ψ, respectively. In second row, first plot shows the variation in T_{eff} with p_T corresponding to Υ(1S) and J/ψ and variation in Γ_F with v_Q is shown in the last two plots.

However, the effect of particle masses appears in the first plot of the second row of Fig. 1, as in this one change in T_{eff} is shown with transverse momentum p_T. It shows that J/ψ being lighter than Υ(1S) feels very less temperature at high p_T while the change in the T_{eff} corresponding to Υ(1S) is slower over all the chosen p_T-range.

Subsequently, we investigate the effect of anisotropy on quarkonia via considering the following values of $\zeta = 0.2$, 0.4 at T = 300 MeV. The Γ_D for Υ(1S) and J/ψ against their velocities is shown in the middle and right, respectively, in the first row of the Fig. 1. It shows that particle decay width, Γ_D, increases with increasing medium anisotropy for both mesons. The difference in the pattern of the Γ_D's respective to Υ(1S) and J/ψ is the consequence of the relativistic Doppler shift encoded with the mass of the particles, which is shown through the color map attached with each plot. These results imply that dissociation of the Υ(1S) is higher due to gluonic-excitation and collisional damping in comparison with J/ψ, which is contrary to color screening suppression mechanisms. The color screening suppression mechanism predicts negligible dissociation for Υ(1S) while J/ψ dissociation probability is relatively large [1, 3]. Next, in the middle and last plots of the second row of Fig. 1, the regeneration probability in terms of the Γ_F is depicted with respect to v_Q, it shows rapid increase in the Γ_F at $v_{\Upsilon(1S)} > 0.8$, however, the overall regeneration for Υ(1S) in the anisotropic medium is marginal. While the regeneration of J/ψ is relatively higher and dominates at $v_{J/\psi} > 0.6$ in comparison with Υ(1S). Obtained results suggest that the correlated regeneration of quarkonia in an anisotropic medium decreases for quarkonia. The findings revealed distinct effects of relativistic Doppler shift in an anisotropic medium on the dissociation and regeneration of Υ(1S) and J/ψ mesons.

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