Dissociation of quarkonia due to Landau damping in a strong magnetic field

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Motivation and Aim

It is now understood that the strongly interacting matter in the presence of strong magnetic field affects the properties of heavy quarkonia differently than its absence because both magnetic field and heavy quarkonia are simultaneously produced at the very early stages of collisions at RHIC or LHC. Our works are of three folds: first we calculate both the real and imaginary parts of retarded and advanced gluon self energies, using the Keldysh representation in real-time formalism, which, in turn, give the resummed retarded and symmetric gluon propagators. Secondly the resummed propagators in the static limit give complex permittivities, which embody the effect of a strongly magnetized hot QCD medium in terms of real- and imaginary-parts of heavy quark potential, manifested as (Debye) color screening and Landau damping, respectively. Finally we investigate the effect of strong magnetic field on the average sizes, binding energies and thermal widths of different $Q\bar{Q}$ resonance states and then study its dissociation due to the Landau-damping mechanism.

Complex heavy-quark potential

First we calculate the resummed retarded and symmetric gluon propagators from the respective self energies for a hot QCD medium in a strong magnetic field, which, in turn, in the static limit give the real and imaginary part of dielectric permittivities,

$$\Re\epsilon(\mathbf{k})^{-1} = \mathbf{k}^2 \Re D_R^L(\mathbf{k}) = \frac{\mathbf{k}^2}{\mathbf{k}^2+m_D^2}, \quad (1)$$

$$\begin{aligned}\Im\epsilon(\mathbf{k})^{-1} &= \mathbf{k}^2 \frac{\Im D_S^L}{2}(\mathbf{k}),\\ &= -\frac{g^2\sum_f m_f^2 \mid q_f B\mid}{4\pi}\frac{\mathbf{k}^2}{k_z^2(\mathbf{k}^2+m_D^2)^2}\\ &\quad -{g'}^2\pi T^3 \frac{\mathbf{k}^2}{\mathbf{k}(\mathbf{k}^2+m_D^2)^2}, \quad (2)\end{aligned}$$

where the screening masses (m_D) for massless and realistic flavour masses are calculated

$$m_D^2(m_f=0) = {g'}^2T^2 + \frac{g^2}{8\pi^2}\sum_f |q_f B| \quad (3)$$

$$m_D^2(m_f\neq 0) = {g'}^2T^2 + \frac{g^2\sum_f |q_fB|}{4\pi^2 T}\int_0^\infty \frac{dp_z e^{\beta E_z^f}}{(1+e^{\beta E_z^f})^2} \quad (4)$$

respectively.
Since the QCD with realistic flavours at finite temperature is not a sharp phase transition rather a crossover so the string term does not vanish at the deconfined medium so the medium in presence of strong magnetic field affects both the linear and Coulomb terms in a nontrivial manner [1] (with $\hat{r} = rm_D$)

$$\begin{aligned}\Re\mathrm{V}(\mathrm{r};\mathrm{T},\mathrm{B}) &= -\frac{4}{3}\alpha_s m_D \frac{e^{-\hat{r}}}{\hat{r}} + \frac{2\sigma}{m_D}\frac{(e^{-\hat{r}}-1)}{\hat{r}}\\ &\quad - \frac{4}{3}\alpha_s m_D + \frac{2\sigma}{m_D}. \quad (5)\end{aligned}$$

In addition, in the medium the potential develops an imaginary part due to an artifact of Landau damping as

$$\begin{aligned}\Im\mathrm{V}(\mathrm{r};\mathrm{T},\mathrm{B}) &= \frac{\alpha_s g^2\sum_f \mid q_f B\mid m_f^2}{3\pi^2}\Bigg(\frac{\pi}{2m_D^3}\\ &- \left[\frac{\pi e^{-\hat{r}}}{2m_D^3}+\frac{\hat{r}\pi e^{-\hat{r}}}{2m_D^3}\right] - \frac{2\hat{r}}{m_D}\int_0^\infty \frac{dk\ k\ \mathrm{Si}(kr)}{\left(\mathbf{k}^2+m_D^2\right)^2}\Bigg)\\ &+\frac{\sigma g^2\sum_f \mid q_f B\mid m_f^2}{2\pi^2}\Bigg(\frac{\pi}{2m_D^5}\left[\hat{r}e^{-\hat{r}} - 3(1-e^{-\hat{r}}\right)\\ &+ 2\hat{r}] - \frac{2\hat{r}}{m_D}\int_0^\infty \frac{dk\ \mathrm{Si}(kr)}{k\left(\mathbf{k}^2+m_D^2\right)^2}\Bigg)\\ &-\frac{8{\alpha_s}'T}{3}\int_0^\infty \frac{zdz\chi(z\hat{r})}{(z^2+1)^2} - \frac{4\sigma T}{m_D^2}\int_0^\infty \frac{dz\chi(z\hat{r})}{z(z^2+1)^2} \quad (6)\end{aligned}$$

where the functions are $\mathrm{Si}(kr) = \int_0^{kr}\frac{\sin x}{x}dx$ and $\chi(z\hat{r}) = 1 - \frac{\sin z\hat{r}}{z\hat{r}}$.

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Average size, Binding energy and Thermal width

We now solve numerically the Schrödinger equation with the real part of medium-modified potential (5) to obtain the wavefunction (Φ) and binding energy of different $Q\bar{Q}$ states immersed in a hot QCD medium in presence of strong magnetic field. Hence the wavefunctions thus obtained from the in-medium Hamiltonian estimates the size, $\sqrt{r_i{}^2}$ $(=(\int d\tau\ r^2 \mid \Phi_i(r) \mid^2)^{1/2})$ of a particular quarkonia (i) in a magnetized medium, which is found to increase slightly with the magnetic field (Fig.1). On the other hand,

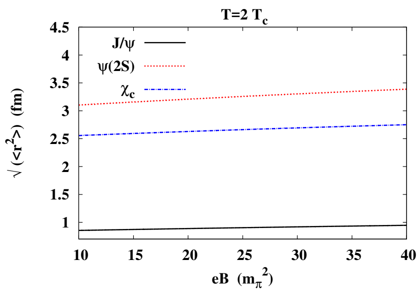

FIG. 1: Variation of average size ($\sqrt{r^2}$) of $Q\bar{Q}$ states in a medium with magnetic field.

the binding energies are found to decrease with the increase of strong magnetic field. However the decrease for J/ψ with magnetic field is faster as compared to the slower decrease of ψ' and χ_c (Fig.2).

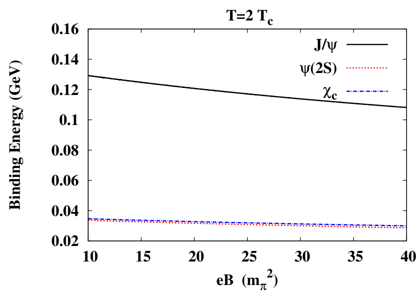

FIG. 2: Variation of binding energies of $Q\bar{Q}$ states in a medium with magnetic field.

Since the imaginary part of the potential (6) is a small perturbation to the real part, thus the first-order perturbation theory evaluates the width, Γ_i $(=-2\int_0^\infty \mathrm{Im}\ \mathrm{V(r;B,T)}|\Phi_\mathrm{i}(\mathrm{r})|^2 \mathrm{d}\tau)$ of a specific quarkonium state by convoluting its eigenstate in the deconfined medium in the presence of magnetic field. We notice that the width is found to increase with the increasing value of magnetic field (Fig.3).

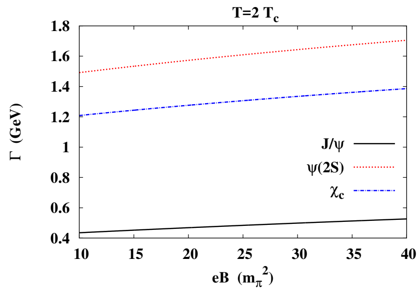

FIG. 3: Variation of thermal width of $Q\bar{Q}$ states in a medium with magnetic field.

Finally we study how the presence of strong magnetic field affects the dissociation of quarkonia, by calculating the dissociation temperature (T_D^i) of a quarkonium state (i) from the criterion: $\Gamma_i \geq 2\mathrm{BE_i}$ in Table I, where the T_D's in presence of magnetic field are found to increase compared to the thermal medium in absence of magnetic field, whereas on increasing the value of magnetic field the T_D starts decreasing. The J/ψ's and χ_c's are dissociated at higher temperatures at 2 T_c and 1.1 T_c at a magnetic field $eB \approx 6\ m_\pi^2$ and 4 m_π^2, respectively, compared to the values 1.60 T_c and 0.8 T_c in the absence of magnetic field [1], respectively.

State	T_D (in T_c)	T_D (in T_c) (eB (m_π^2))
J/ψ	1.60	2.0 (6.50) 1.8 (27.0) 1.5 (68.0)
χ_c	0.80	1.1 (3.7) 1.0 (12)
$\psi(2S)$	0.70	$< 1(< m_\pi^2)$

TABLE I: Dissociation temperatures.

In the present study, the effect of strong magnetic field has been investigated on the various properties of quarkonia and its dissociation due to Landau-damping.

References

[1] M. Hasan, B. K. Patra, B. Chatterjee, and P. Bagchi arxiv:1802.06874[hep-ph].