Entropic force and real-time dynamics of holographic quarkonium in a magnetic field

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Abstract

We continue the study of a recently constructed holographic QCD model supplemented with a magnetic field. We consider the holographic dual of a quark-antiquark pair and investigate its entropy beyond the deconfinement phase transition in terms of interquark distance, temperature and magnetic field. We obtain a clear magnetic field dependence in the strongly decreasing entropy near deconfinement and in the entropy variation for growing interquark separation. We uncover various supporting evidences for inverse magnetic catalysis. The emergent entropic force is found to become stronger with magnetic field, promoting the quarkonium dissociation. We also probe the dynamical dissociation of the quarkonium state, finding a faster dissociation with magnetic field. At least the static predictions should become amenable to a qualitative comparison with future lattice data.

Introduction

Gauge/Gravity Duality, also known as AdS/CFT Correspondence was conjectured by Juan Maldacena in 1997 and claims the following equivalence between two theories:-

Strongly coupled d-dimensional gauge theory = Gravitational theory in (d+1)-dimensional AdS spacetime

This correspondence has provided an elegant technique to probe **QCD**-related physics by doing some modifications to the original conjecture. A very strong magnetic field of order around 0.3 GeV^2 might be produced in the early stages of non-central relativistic heavy-ion collisions and can have important consequences for QCD phases. Here, we concentrate on a particular bottom-up magnetized AdS/QCD model i.e. Einstein-Maxwell-dilaton gravity model to study the effects of background magnetic field on the quark-antiquark free energy, entropy and dissociation time.

Magnetized Einstein-Maxwell-Dilaton Gravity Setup:

The EMD gravity action is given by the expression,

$$S_{EMD} = -\frac{1}{16\pi G_5}\int d^5x\sqrt{-g}\left[R - \frac{f(\phi)}{4}F_{MN}F^{MN} - \frac{1}{2}D_M\phi D^M\phi - V(\phi)\right], \quad (1)$$

We have used the following Ansätze for the metric field g_{MN}, dilaton field ϕ and field tensors F_{MN},

$$ds^2 = \frac{L^2 e^{2A(z)}}{z^2}\left[-g(z)dt^2 + \frac{dz^2}{g(z)} + dx_1^2 + e^{B^2z^2}\left(dx_2^2 + dx_3^2\right)\right],$$
$$\phi = \phi(z), \quad F_{MN} = B dx_2 \wedge dx_3, \quad (2)$$

The EMD equations of motion can be exactly solved in a closed form in terms of a single form factor $A(z)$,

$$g(z) = 1 - \frac{\int_0^z d\xi\, \xi^3 e^{-B^2\xi^2 - 3A(\xi)}}{\int_0^{z_h} d\xi\, \xi^3 e^{-B^2\xi^2 - 3A(\xi)}},$$
$$\phi(z) = \int dz \sqrt{-\frac{2}{z}\left(3zA''(z) - 3zA'(z)^2 + 6A'(z) + 2B^4z^3 + 2B^2z\right)} + K_5,$$
$$f(z) = g(z)e^{2A(z)+2B^2z^2}\left(-\frac{6A'(z)}{z} - 4B^2 + \frac{4}{z^2}\right) - \frac{2e^{2A(z)+2B^2z^2}g'(z)}{z},$$
$$V(z) = g'(z)\left(-3z^2A'(z) - B^2z^3 + 3z\right)e^{-2A(z)} - g(z)\left(12 + 9B^2z^3A'(z)\right)e^{-2A(z)}$$
$$+g(z)\left(-9z^2A'(z)^2 - 3z^2A''(z) + 18zA'(z) - 2B^4z^4 + 8B^2z^2\right)e^{-2A(z)}, \quad (3)$$

Result

Free Energy, Entropy and Entropic Force

The free energy and entropy of the $q\bar{q}$ pair can be computed holographically from the world sheet on-shell action. For the connected case, the free energy expression reduces to

$$\mathcal{F}_{con}^{\|} = \frac{L^2}{\pi l_s^2}\int_0^{z_*^{\|}} dz \frac{z_*^{\|2}}{z^2}\frac{\sqrt{g(z)}e^{2A_s(z)-2A_s(z_*^{\|})}}{\sqrt{g(z)z_*^{\|4}e^{-4A_s(z_*^{\|})} - g(z_*^{\|})z^4e^{-4A_s(z)}}}, \quad (4)$$

The turning point $z = z_*^{\|}$ is related to the separation length $\ell^{\|}$ of the $q\bar{q}$ pair as

$$\ell^{\|} = 2\int_0^{z_*^{\|}} dz \sqrt{\frac{g(z_*^{\|})}{g(z)}}\frac{z^2e^{-2A_s(z)}}{\sqrt{g(z)z_*^{\|4}e^{-4A_s(z_*^{\|})} - g(z_*^{\|})z^4e^{-4A_s(z)}}}. \quad (5)$$

Similarly, the free energy expression of the disconnected string reduces to

$$\mathcal{F}_{discon}^{\|} = \frac{L^2}{\pi l_s^2}\int_0^{z_h} dz \frac{e^{2A_s(z)}}{z^2}. \quad (6)$$

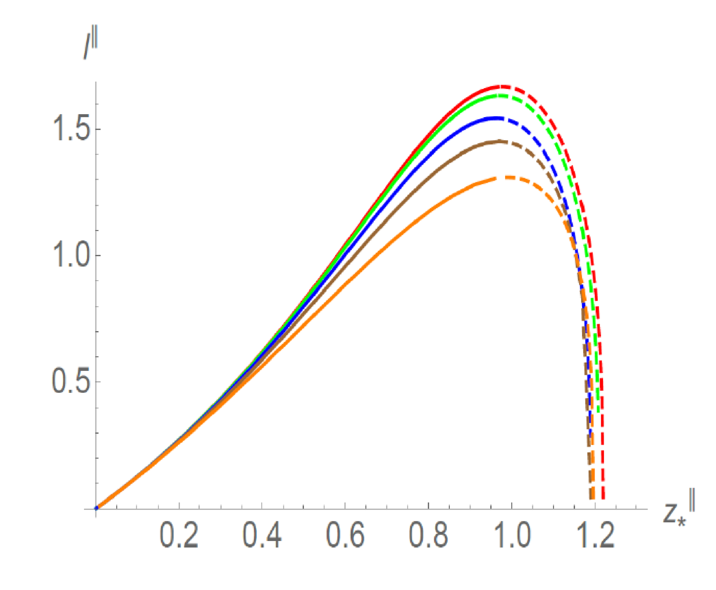

Fig. 1: $\ell^{\|}$ as a function of $z_*^{\|}$ for various values of magnetic field.

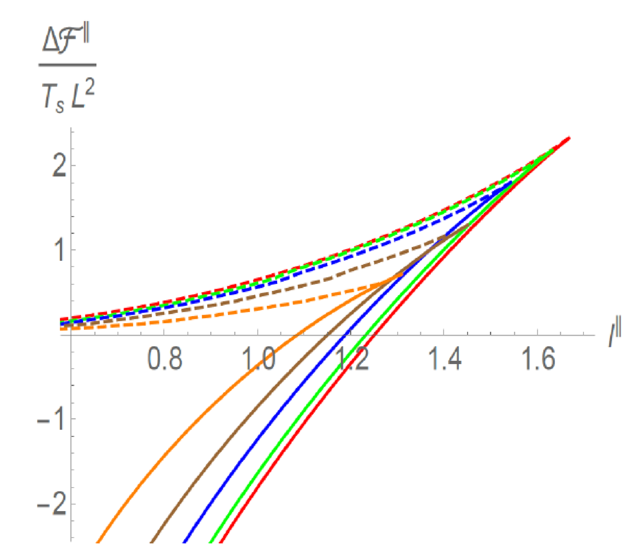

Fig. 2: $\Delta\mathcal{F}^{\|}$ as a function of $\ell^{\|}$ for various values of magnetic field.

The entropy of the quarkonium can be calculated from the free energy by,

$$S^{\|} = -\frac{\partial \mathcal{F}^{\|}}{\partial T}. \quad (7)$$

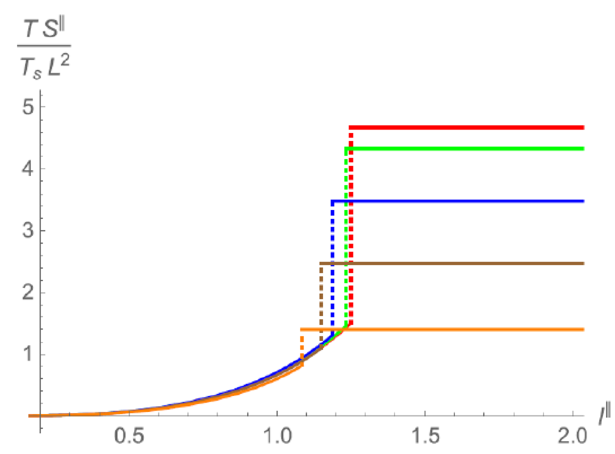

Fig. 3: $S^{\|}$ as a function of $\ell^{\|}$ for various values of magnetic field.

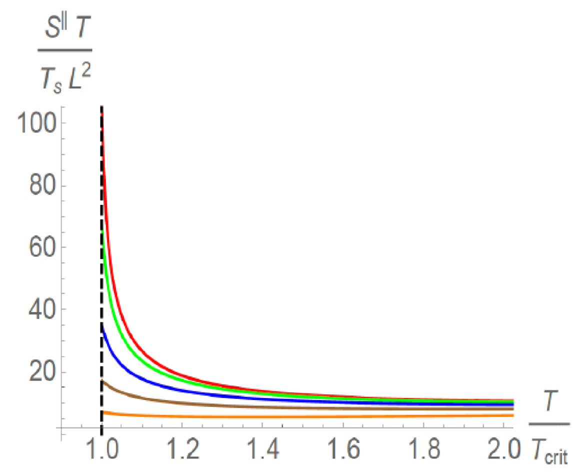

Fig. 4: $S^{\|}$ as a function of temperature for various values of magnetic field.

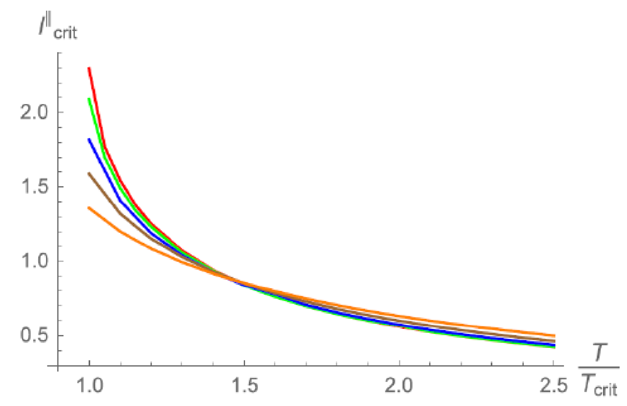

Fig. 5: $\ell_{crit}^{\|}$ as a function of temperature for various values of magnetic field.

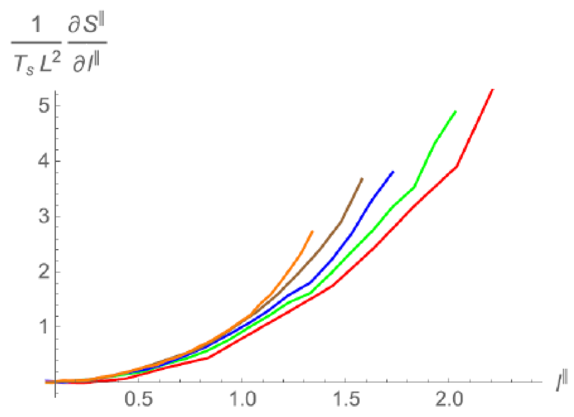

Fig. 6: Entropic force as a function of $\ell^{\|}$ for various values of magnetic field.

Real-Time Dynamics of Quarkonium Dissociation

The holographic prescription of quarkonium dissociation is given by a string with one end fixed at the AdS boundary and the other end at the black hole horizon. When the string reaches the horizon, the system reaches its thermal equilibrium state in which the string is split into two pieces. The time needed for the string to reach the horizon will give us an approximate time scale for the quarkonium dissociation.

We can find the string's motion by integrating its velocity from the boundary to horizon. The velocity of the string is expressed by,

$$\dot{z} = \frac{g(z)}{E}\sqrt{(E^{\|})^2 - \frac{T_s^2 e^{4A_s(z)}g(z)}{z^4}} \quad (8)$$

The dissociation time expression is found to be,

$$t_D^{\|} = \int_{z=\varepsilon_{UV}}^{z_h} dz \frac{1}{g(z)\sqrt{1 - \frac{T_s^2 e^{4A_s(z)}g(z)}{(E^{\|})^2 z^4}}}. \quad (9)$$

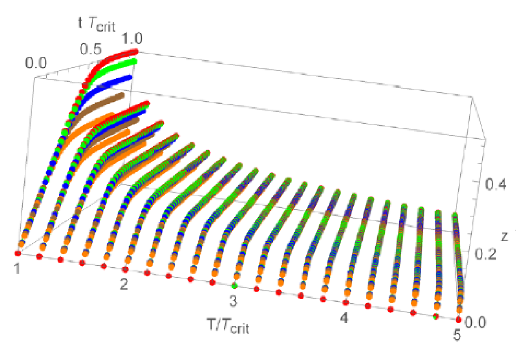

Fig. 7: The string motion from the boundary to the horizon for various values of magnetic field and temperature.

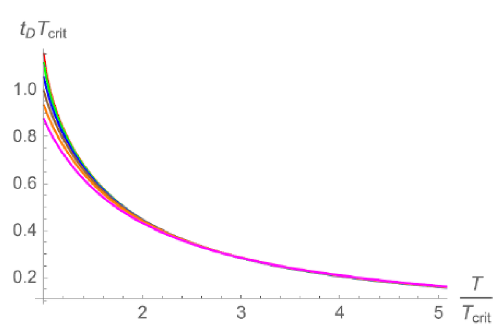

Fig. 8: The quarkonium dissociation time as a function of temperature for various values of magnetic field.

Conclusions

- Our analysis suggests a decrement in the size of the bound state near the deconfinement temperature as the magnetic field increases.
- We found not only a sharp rise and a peak in the entropy of $q\bar{q}$ pair near the deconfinement temperature but also that the entropy saturates to a constant value at large interquark separations for all B.
- The strength of entropic force is found to be increasing with magnetic field near the deconfinement temperature, suggesting a stronger dissociation of heavy quarkonium.
- We finally found that the dissociation time gets smaller for higher temperatures and magnetic fields.

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