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Research Article

Entropic Destruction of Heavy Quarkonium from a Deformed AdS_5 Model

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We study the destruction of heavy quarkonium due to the entropic force in a deformed AdS_5 model. The effects of the deformation parameter on the interdistance and the entropic force are investigated. The influence of the deformation parameter on the quarkonium dissociation is analyzed. It is shown that the interdistance increases in the presence of the deformation parameter. In addition, the deformation parameter has the effect of decreasing the entropic force. These results imply that the quarkonium dissociates harder in a deformed AdS background than in a usual AdS background, in agreement with earlier findings.

1. Introduction

It is well-known that the dissociation of heavy quarkonium can be regarded as an important experimental signal of the formation of strongly coupled quark-gluon plasma (QGP) [1]. It was argued earlier that the quarkonium suppression is due to the Debye screening effects induced by the high density of color charges in QGP. But the recent experimental research showed a puzzle: the charmonium suppression at RHIC (lower energy density) is stronger than that at LHC (larger energy density) [2, 3]. Obviously, this is in contradiction to the Debye screening scenario [1] as well as the thermal activation through the impact of gluons [4, 5]. To explain this puzzle, some authors suggested that the recombination of the produced charm quarks into charmonia may be a solution. This argument was based on the results [6, 7] that if a region of deconfined quarks and gluons is formed, the quarkonia (or bound states) can be formed from a quark and an antiquark which were originally produced in separate incoherent interactions. Recently, Kharzeev [8] argued that this puzzle may be related to the nature of deconfinement and the entropic force would be responsible for melting the quarkonium. This argument originated from the Lattice results that a large amount of entropy associated with the heavy quarkonium placed in QGP [9–11].

AdS/CFT, which maps a d-dimensional quantum field theory to its dual gravitational theory, living in $d+1$-dimensional, has yielded many important insights into the dynamics of strongly coupled gauge theories [12–14]. In this approach, Hashimoto and Kharzeev have studied the entropic destruction of static heavy quarkonium in $\mathcal{N}=4$ SYM theory and a confining YM theory firstly. They found that in both cases the entropy grows as a function of the interquark distance giving rise to the entropic force [15]. Recently, these studies have been extended to the case of moving quarkonium [16]. It was shown that the velocity has the effect of increasing the entropic force, thus making the quarkonium melt easier. In a more recent work, we have analyzed the effect of chemical potential on the entropic force and observed that the moving quarkonium dissociates easier at finite density [17].

Now, we would like to give such analyses from AdS/QCD. The motivation is that AdS/QCD models can provide a nice phenomenological description of hadronic properties as well as quark-antiquark interaction; see [18–26] and references therein. In this paper, we will study the entropic force in the Andreev-Zakharov model [21], one of "soft wall" models. The Andreev-Zakharov model has some properties: (1) the positive quadratic term modification in the deformed warp factor $h(z)=e^{(1/2)cz^2}$ produces linear behavior of heavy flavor potential; namely, it can provide confinement at low temperature. (2) The value of c can be fixed from the ρ meson trajectory, so that the metric contains no free parameter. Actually, this model has been used to investigate some quantities, such as thermal phase transition [27], thermal width [28, 29], and heavy quark potential [30]. Likewise, it is of interest to study the entropic force in this model. Besides that, we have several other reasons: first, we want to know what will happen if we have meson in a deformed AdS background or how the deformation parameter affects the quarkonium dissociation? Moreover, evaluation of the entropic force helps us to understand the "usual" or "unusual" behavior of meson, because one can compare the results of $c \neq 0$ with $c = 0$, while the "usual" behavior of meson can be recovered in the limit $c \to 0$. On the other hand, such an investigation can be regarded as a good test of AdS/QCD.

The paper is organized as follows. In the next section, we briefly review the action of holographic models and then introduce the Andreev-Zakharov model. In Section 3, we study the effects of the deformation parameter on the interdistance as well as the entropic force and then analyze how the deformation parameter affects the quarkonium dissociation. The last part is devoted to discussion and conclusion.

2. The Andreev-Zakharov Model

Before reviewing the Andreev-Zakharov model, let us briefly introduce the holographic models in terms of the action [26]:

$$S = \frac{1}{16\pi G_5}\int d^5x\sqrt{g}\left(\mathcal{R} - \frac{1}{2}\left(\partial\phi\right)^2 - V\left(\phi\right) - \frac{f\left(\phi\right)}{4}F_{MN}F^{MN}\right), \tag{1}$$

where G_5 is the five-dimensional Newton constant. g denotes the determinant of the metric g_{MN}. $\mathcal{R}$ refers to the Ricci scalar. ϕ is called the scalar and induces the deformation away from conformality. $f(\phi)$ represents the gauge kinetic function. F_{MN} stands for the field strength associated with an Abelian gauge connection A_M. $V(\phi)$ is the potential which contains the cosmological constant term 2Λ and some other terms.

To obtain an AdS-black hole space-time, one considers a constant scalar field ϕ (or called dilaton) and assumes that $V(\phi) = 2\Lambda$ as well as $f(\phi) = 1$. Then the action of (1) can be simplified as

$$S = \frac{1}{16\pi G_5} \cdot \int d^5x\sqrt{g}\left(\mathcal{R} - 2\Lambda - \frac{1}{4}F_{MN}F^{MN}\right), \tag{2}$$

with the equations of motion

$$\mathcal{R}_{MN} - \frac{1}{2}\mathcal{R}g_{MN} + \Lambda g_{MN} = \frac{1}{2}\left(F_{MA}F_N^A - \frac{1}{4}g_{MN}F_{AB}F^{AB}\right), \tag{3}$$

$$\nabla_M F^{MN} = 0, \tag{4}$$

where ∇_M is the Levi-Civita covariant derivative with respect to the metric g_{MN}.

Supposing that the horizon function $f(z)$ vanishes at the point $z = z_h$, then the solution of (3) (with vanishing right-hand side) becomes the AdS$_5$-Schwarzschild metric:

$$ds^2 = \frac{R^2}{z^2}\left(-f\left(z\right)dt^2 + d\vec{x}^2 + \frac{1}{f\left(z\right)}dz^2\right), \tag{5}$$

with

$$f\left(z\right) = 1 - \frac{z^4}{z_h^4}, \tag{6}$$

where z_h can be related to the temperature as $T = 1/(\pi z_h)$. Notice that, in the limit $z_h \to \infty$ (correspond to zero temperature), the metric of (5) reduces to the AdS$_5$ metric, as expected.

To emulate confinement in the boundary theory, one can introduce a quadratic dilaton, $\phi \propto z^2$, similar to the manipulation mentioned in [20]. To this end, the Andreev-Zakharov model can be defined by the metric of (5) multiplied by a warp factor, $h(z) = e^{\phi} = e^{(1/2)cz^2}$, where c is the deformation parameter whose value can be fixed from the ρ meson trajectory as $c \sim 0.9\,\mathrm{GeV}^2$ [27]. Then the metric of the Andreev-Zakharov model is given by [21]

$$ds^2 = \frac{R^2 h\left(z\right)}{z^2}\left(-f\left(z\right)dt^2 + d\vec{x}^2 + \frac{1}{f\left(z\right)}dz^2\right). \tag{7}$$

If one works with $r = R^2/z$ as the radial coordinate, the metric of (7) turns into

$$ds^2 = \frac{r^2 h\left(r\right)}{R^2}\left(-f\left(r\right)dt^2 + d\vec{x}^2\right) + \frac{R^2 h\left(r\right)}{r^2 f\left(r\right)}dr^2, \tag{8}$$

with

$$f\left(r\right) = 1 - \frac{r_h^4}{r^4}. \tag{9}$$

Now, the wrap factor becomes $h(r) = e^{cR^4/2r^2}$ and the temperature is $T = r_h/(\pi R^2)$ with $r = r_h$ as the horizon. Note that the two metrics (7) and (8) are equal but only with different coordinate systems.

3. The Entropic Force

The entropic force is an emergent force. According to the second law of thermodynamics, it stems from multiple interactions which drive the system toward the state with a larger entropy. This force was originally introduced in [31] many years ago and proposed to responsible for the gravity [32] recently. In a more recent work, Kharzeev [8] argued that it would be responsible for dissociating the quarkonium.

In [8], the entropic force is expressed as

$$\mathscr{F} = T\frac{\partial S}{\partial L}, \tag{10}$$

where T is the temperature of the plasma, L represents the interdistance of $Q\overline{Q}$, and S stands for the entropy.

On the other hand, the entropy is given by

$$S = -\frac{\partial F}{\partial T}, \tag{11}$$

where F is the free energy of $Q\overline{Q}$, which is equal to the on-shell action of the fundamental string in the dual geometry from the holographic point of view. In fact, the free energy has been studied, for example, in [33–35].

We now follow the calculations of [15] to analyze the entropic force with the metric (8). The Nambu-Goto action is

$$S = T_F \int d\tau\, d\sigma \mathscr{L} = T_F \int d\tau\, d\sigma \sqrt{g}, \tag{12}$$

where $T_F = 1/2\pi\alpha'$ is the fundamental string tension and α' can be related to the 't Hooft coupling constant by $\alpha' = R^2/\sqrt{\lambda}$. g denotes the determinant of the induced metric with

$$g_{\alpha\beta} = g_{\mu\nu}\frac{\partial X^\mu}{\partial\sigma^\alpha}\frac{\partial X^\nu}{\partial\sigma^\beta}, \tag{13}$$

where X^μ is the target space coordinates and $g_{\mu\nu}$ is the metric.

Parameterizing the static string coordinates by

$$X^\mu = \left(\tau, \sigma, 0, 0, r(\sigma)\right), \tag{14}$$

one finds the induced metric as

$$\begin{aligned} g_{00} &= \frac{r^2}{R^2}h(r) f(r), \\ g_{01} &= g_{10} = 0, \\ g_{11} &= \frac{r^2}{R^2}h(r) + \frac{R^2}{r^2}h(r) f(r)^{-1}\dot{r}^2, \end{aligned} \tag{15}$$

with $\dot{r} = \partial r/\partial\sigma$.

Then the Lagrangian density is found to be

$$\mathscr{L} = \sqrt{a(r) + b(r)\dot{r}^2}, \tag{16}$$

with

$$\begin{aligned} a(r) &= \frac{h^2(r) f(r) r^4}{R^4}, \\ b(r) &= h^2(r). \end{aligned} \tag{17}$$

Note that $\mathscr{L}$ does not depend on σ explicitly, so the Hamiltonian density is a constant:

$$\mathscr{H} = \mathscr{L} - \frac{\partial\mathscr{L}}{\partial\dot{r}}\dot{r} = \text{constant}. \tag{18}$$

Applying the boundary condition at $\sigma = 0$,

$$\begin{aligned} \dot{r} &= 0, \\ r &= r_c, \end{aligned} \tag{19}$$

one finds

$$\mathscr{H} = \sqrt{\frac{h^2(r_c) f(r_c) r_c^4}{R^4}}, \tag{20}$$

with

$$\begin{aligned} f(r_c) &= 1 - \frac{r_h^4}{r_c^4}, \\ h(r_c) &= e^{cR^4/2r_c^2}, \end{aligned} \tag{21}$$

where r_c is the lowest position of the string in the bulk.

From (16), (18), and (20), one gets

$$\dot{r} = \frac{dr}{d\sigma} = \sqrt{\frac{a^2(r) - a(r)a(r_c)}{a(r_c)b(r)}}. \tag{22}$$

By integrating (22), the interquark distance is obtained:

$$L = 2\int_{r_c}^{\infty} dr \sqrt{\frac{a(r_c)b(r)}{a^2(r) - a(r)a(r_c)}}, \tag{23}$$

with

$$a(r_c) = \frac{h^2(r_c) f(r_c) r_c^4}{R^4}. \tag{24}$$

To analyze the effect of the deformation parameter on the interdistance, we plot LT as a function of ε with $\varepsilon \equiv r_h/r_c$ for $c = 0$ and $c = 0.9\,\text{GeV}^2$ in Figure 1. From the figures, one can see that LT increases in the presence of c. Namely, the deformation parameter has the effect of increasing the interdistance.

Moreover, one finds that for each plot LT is an increasing function for $\varepsilon < \varepsilon_{\max}$ but a decreasing one for $\varepsilon > \varepsilon_{\max}$. In fact, in the latter case, some new configurations [36] should be taken into account. However, these configurations are not solutions of the Nambu-Goto action so that the range of $LT > LT_{\max}$ is not trusted. In other words, we have more interest in the range of $LT < LT_{\max}$. For convenience, we write $b = LT_{\max}$. With numerical methods, we find $b \simeq 0.31$ for $c = 0.9\,\text{GeV}^2$ and $b \simeq 0.27$ for $c = 0$.

Next, we discuss the free energy. There are two cases.

(1) If $L > b/T$, the fundamental string will break in two pieces implying that the quarks are completely screened. For this case, the choice of the free energy $F^{(2)}$ is not unique [37],

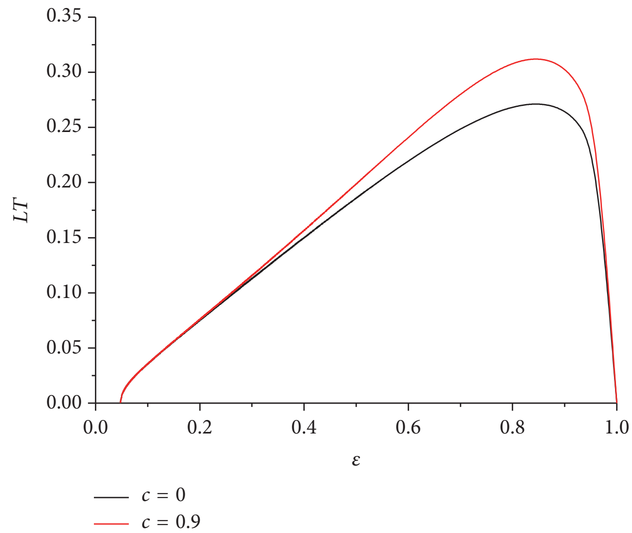

FIGURE 1: LT versus ε with $\varepsilon \equiv r_h/r_c$. From top to bottom, $c = 0.9\,\text{GeV}^2$ and $c = 0$, respectively. Here, we take $R = 1$.

and we here choose a configuration of two disconnected trailing drag strings [38]; that is,

$$F^{(2)} = 2T_F \int_{r_h}^{\infty} h(r)\, dr. \tag{25}$$

In terms of (11), one finds

$$S^{(2)} \simeq e^{c/2r_h^2}\left(1 - \frac{c}{r_h^2}\right)\sqrt{\lambda}\theta\left(L - \frac{b}{T}\right). \tag{26}$$

Notice that the results of [15] can be reproduced if one neglects the effect of the reformation parameter by plugging $c = 0$ in (26).

(2) If $L < b/T$, the fundamental string is connected. The free energy of the quark-antiquark pair can be obtained by substituting (22) into (12); that is,

$$F^{(1)} = \frac{1}{\pi\alpha'}\int_{r_c}^{\infty} dr \sqrt{\frac{a(r)\, b(r)}{a(r) - a(r_c)}}. \tag{27}$$

Likewise, using (11), one finds

$$S^{(1)} = -\frac{\sqrt{\lambda}}{2\pi}\int_{r_c}^{\infty} dr \frac{\left[a'(r)\, b(r) + a(r)\, b'(r)\right]\left[a(r) - a(r_c)\right] - a(r)\, b(r)\left[a'(r) - a'(r_c)\right]}{\sqrt{a(r)\, b(r)\left[a(r) - a(r_c)\right]^3}}, \tag{28}$$

where the derivatives are with respect to r_h and we have used the relation $\alpha' = R^2/\sqrt{\lambda}$.

To analyze the effect of the deformation parameter on the entropic force, we plot $S^{(1)}/\sqrt{\lambda}$ as a function of LT for $c = 0$ and $c = 0.9\,\text{GeV}^2$ in Figure 2, respectively. One can see that increasing c leads to smaller entropy at small distances. In addition, from (10), one knows that the entropic force is related to the growth of the entropy with the distance, so one finds that increasing c leads to decreasing the entropic force. On the other hand, the entropic force is responsible for melting the quarkonium. Thus, one concludes that the presence of the deformation parameter tends to decrease the entropic force, thus making the heavy quarkonium dissociates harder. These results can be understood as follows. Increase of the interdistance can be regarded as decrease of r_h or decrease of the system temperature. Since the deformation parameter has the effect of increasing the interdistance, it will cool the system temperature, thus making the quarkonium dissociates harder. Interestingly, it was argued [29] that the deformation parameter has the effect of increasing the thermal width, thus increasing the dissociation length, in agreement with our findings.

4. Summary and Discussions

In heavy ion collisions, the dissociation of heavy quarkonium is an important experimental signal for QGP formation. Recently, the destruction of heavy quarkonium due to the entropic force has been discussed in the context of AdS/CFT [15]. It was shown that a sharp peak of the entropy exists near the deconfinement transition and the growth of the entropy with the distance is responsible for the entropic force.

In this paper, we have investigated the destruction of heavy quarkonium in a deformed AdS_5 model. The effect of the deformation parameter on the interdistance was analyzed. The influence of the deformation parameter on

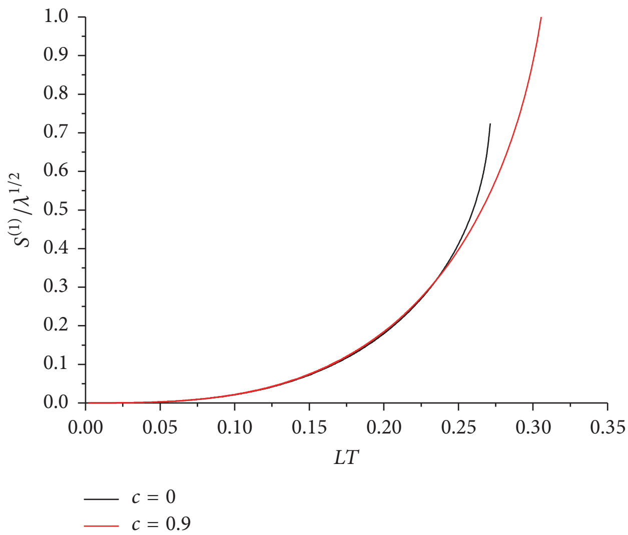

FIGURE 2: $S^{(1)}/\sqrt{\lambda}$ against LT. Here, we take $R = 1$.

the entropic force was also studied. It is shown that the interquark distance increases in the presence of the deformation parameter. Moreover, the deformation parameter has the effect of decreasing the entropic force. Since the entropic force is responsible for destroying the bound quarkonium states, we conclude that the presence of the deformation parameter tends to decrease the entropic force, thus making the quarkonium melt harder, consistent with the findings of [29]. Also, we have presented a possible understanding to this result: increase of the interdistance is equivalent to decrease of r_h or decrease of the system temperature. As the deformation parameter can increase the interdistance, it will cool the system temperature, thus making the quarkonium dissociate harder.

In addition, to understand the "usual" or "unusual" behavior of meson, we have compared the results between $c \neq 0$ and $c = 0$. It is found that the quarkonium dissociates harder in a deformed AdS background than in a usual AdS background.

Finally, it would be interesting to study the entropic force in some other holographic QCD models, such as the Sakai-Sugimoto model [18] and the Pirner-Galow model [24]. This will be left as a further investigation.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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