Holographic melting of heavy baryons in plasma with gluon condensation

JHEP05(2009)044

(http://iopscience.iop.org/1126-6708/2009/05/044)

Published by IOP Publishing for SISSA

Received: *March 12, 2009*
Accepted: *May 7, 2009*
Published: *May 12, 2009*

Holographic melting of heavy baryons in plasma with gluon condensation

Sang-Jin Sin[a] **and Yang Zhou**[b]

[a] *Department of Physics, Hanyang University,*
Seoul 133-791, Korea
[b] *Institute of Theoretical Physics, Chinese Academic of Science,*
Beijing 100190, P.R. China

E-mail: `sangjin.sin@gmail.com`, `yzhou@itp.ac.cn`

Abstract: We propose a Dirac-Born-Infeld (DBI) D5 vertex brane plus N_c fundamental strings configuration to describe a baryon probe in strongly coupled gauge theory with gluon condensation at finite temperature via AdS/CFT correspondence. We investigate properties of this configuration in a dilaton deformed $\mathrm{AdS}_5{\times}\mathrm{S}^5$ background, in which IIB string theory is dual to super Yang-Mills theory in a state with a constant self-dual gauge field ($F_{mn} = F^*_{mn}$) background. We find that for most values of temperature T and gluon condensation parameter q ($q = \pi^2 < F_{mn}F_{mn} >$), there always exists a screening length L_s. The relation $L_s \sim \frac{1}{T}$ has been checked. We give the q dependence of L_s. We calculate the boost velocity $v(v = -\tanh\eta)$ and angular velocity ω dependence of L_s for a baryon probe, and obtain $L_s = L_0 * (1 - v^2)^{1/4}$ for large v and $L_s \sim \omega^{-1}$, which are consistent with those dependence relations in the point brane plus strings case, and find that the usual relations have been modified by q. We also calculate the mass of baryon and find T dependence of baryon mass.

Keywords: AdS-CFT Correspondence, Thermal Field Theory

ArXiv ePrint: 0904.4249

doi:10.1088/1126-6708/2009/05/044

Contents

1 Introduction and Summary

There has been much interest in studying hadrons in strongly coupled QCD in terms of AdS/CFT correspondence. One interesting topic is the investigation of holographic baryons [2–5]. A holographic baryon model in gauge/gravity duality was first introduced by Witten, where a baryon is identified with a compact D brane wrapped on a transverse sphere with N_c fundamental strings attached to it. Investigations of baryons in AdS/CFT has been started ten years ago, in order to find a solution with a compact vertex brane and Dirac-Born-Infeld strings, but there are many challenges [9, 10, 13, 17, 18]. One big problem is how to get a closed brane solution for a baryon vertex from the DBI + CS(Chern-Simons) action in a certain gravity background. We construct a new configuration with a wrapped D5 vertex brane and N_c strings under the background with gluon condensation, to solve these problems. We investigate properties of this configuration in a dilaton deformed AdS$_5 \times$S^5 background, in which IIB string theory is dual to super Yang-Mills theory in a state with a constant self-dual gauge field ($F_{mn} = F^*_{mn}$) background. The gluon condensation parameter q appears in our dilaton and can be related to the self-dual gauge field by $q = \pi^2 < F_{mn}F_{mn} >$ [12]. In the string side, this dilaton comes from D-instantons homogeneously distributed over D3-brane world-volume. More descriptions of this solution can be found in [12]. In particular, we investigate properties of this configuration in a probe limit and argue that this configuration may describe a heavy baryon well in a certain plasma background.

Recently, authors of the work [29] proposed a simple configuration of baryon in a hot strongly coupled super Yang-Mills plasma, analyzed the velocity dependence of baryon screening length L_s and found that there was a relation $L_s \sim L_0{*}(1-v^2)^{1/4}$ for baryon when v went to one, which has been found in quark and anti-quark screening [27]. Furthermore, screening length and $J - E^2$ behavior (J is angular momentum and E is baryon mass) of high spin baryons were analyzed [30]. All these investigations are in the framework of thermal super Yang-Mills gauge theory/AdS balck hole duality and component quarks are considered as probes. Many results of these investigations are similar to those of meson case [27], because there the vertex brane is treated as a massive point in AdS$_5$, with an action depending only on the gravity potential.

In general, the vertex brane is not a point in AdS space, but an extended object. It is difficult to find a closed vertex brane in many gravity backgrounds, especially for D5 vertex brane. Baryon configurations with D4 vertex brane and N_c fundamental strings were investigated very recently in work [6] and there were many interesting properties. Recently a closed baryon vertex was found in the D3 branes background with gluon condensation [4]. We propose a full baryon probe configuration in this background in the present paper and find many interesting properties of this configuration.

The present paper is organized as follows. In section 2, we construct the general baryon configurations. We analyze the different baryon vertex solutions from the DBI + CS action of D5 compact brane and give the force balance condition between the D5 vertex and N_c fundamental strings. In section 3, we give a general analysis of screening length in a standard way. We find that for most values of temperature T and gluon condensation parameter q, there always exists a screening length L_s. The relation $L_s \sim \frac{1}{T}$ has been checked. We also give the q dependence of L_s. We also calculate the boost velocity $v = -\tanh\eta$ and angular velocity ω dependence of L_s for a baryon probe, which are consistent to those dependence relations in the point brane plus strings case, and find that the usual relations have been modified by q. We also calculate the mass of baryon and find T dependence of baryon mass. We give our conclusion and discussion in section 4.

2 General baryon configurations

The baryon construction in gravity involves N_c fundamental strings with the same orientation, beginning at the heavy quarks on the flavor brane and ending on the baryon vertex in the interior of bulk geometry, which is a D5 brane wrapped on the S^5 (AdS$_5\times$S^5 background). Generally, N_c quarks are allowed to be placed at arbitrary positions in $\vec{x}$ space on the boundary. Note that these quarks are heavier than component quarks of mesons, and the N_c quarks bound states can not easily be considered as an effective field on the boundary (fluctuations of flavor brane in picture with flavor).

The gravity theory dual to the thermal four-dimensional gauge theory is a solution of 10D Type-IIB supergravity under the Freund-Rubin ansatz for self-dual five form field strength [1, 11, 12]. In string frame, the solution can be written as follows

$$e^{-\frac{1}{2}\phi}\mathrm{d}s_{10}^2 = -\frac{r^2}{r_+^2}\left(1-\frac{r_0^4}{r^4}\right)\mathrm{d}t^2 + \frac{r^2}{r_+^2}\mathrm{d}x_i\mathrm{d}x^i + \frac{1}{1-\frac{r_0^4}{r^4}}\frac{r_+^2}{r^2}\mathrm{d}r^2 + r_+^2\mathrm{d}\Omega_5^2, \tag{2.1}$$

with a dilaton and an axion

$$e^{\phi} = 1 + \frac{q}{r_0^4} \log \frac{1}{1 - \frac{r_0^4}{r^4}}, \quad \chi = -e^{-\phi} + \chi_0, \tag{2.2}$$

where $i = 1, 2, 3$ and q is gauge fields condensate parameter [1, 12]. ϕ and χ denote the dilaton and the axion respectively, and no other field configurations are considered here. This metric includes an AdS black hole times a five-dimensional sphere, and the dilaton and axion depending on r. r_+ is the curvature radius of the AdS metric, r is the coordinate of the fifth dimension of AdS$_5$ and r_0 is the position of black hole horizon. The temperature of the gauge theory is given by Hawking temperature of the black hole, $T = \frac{r_0}{\pi R^2}$. By duality, the gauge theory parameters N_c (color number) and λ (t'Hooft coupling constant) are given by

$$\sqrt{\lambda} = \frac{r_+^2}{\alpha'}, \qquad \frac{\lambda}{N_c} = g_{\mathrm{YM}}^2 = 4\pi g_s, \tag{2.3}$$

where $\frac{1}{2\pi\alpha'}$ is string tension and g_s is the string coupling constant. The self-dual Ramond-Ramond field strength is

$$F_{(5)} = \mathrm{d}C_{(4)} = 4r_+^4 \Omega_5 \mathrm{d}\theta_1 \wedge \ldots \wedge \mathrm{d}\theta_5 - 4\frac{r^3}{r_+^4} \mathrm{d}t \wedge \mathrm{d}x_1 \wedge \mathrm{d}x_2 \wedge \mathrm{d}x_3 \wedge dr, \tag{2.4}$$

where $\Omega_5 = \sin^4\theta_1 \sin^3\theta_2 \sin^2\theta_3 \sin\theta_4$. The D5 brane carries a radial U(1) flux and wraps the S^5 with radial extension. The action of D5 brane includes DBI action plus Chern-Simons action, given by

$$S_{D5} = -T_5 \int \mathrm{d}^6\sigma e^{-\phi} \sqrt{-\det(g_{ab} + 2\pi\alpha' F_{ab})} + T_5 2\pi\alpha' \int A_{(1)} \wedge \mathcal{P}(F_{(5)}), \tag{2.5}$$

where the 6D world volume induced metric $g_{ab} = \partial_a X^\mu \partial_b X^\nu G_{\mu\nu}$, and the pull back of five form $\mathcal{P}(F_{(5)}) = \partial_{a_1} X^{\mu_1} \ldots \partial_{a_4} X^{\mu_5} F_{\mu_1 \ldots \mu_5}$. The D5 brane tension $T_5 = \frac{1}{g_s (2\pi)^5 l_s^6}$, and the world volume field strength of U(1) flux $F_{(2)} = \mathrm{d}A_{(1)}$. The Chern-Simons term endows D5 brane with U(1) charge. By the following consistent ansatz that describes the embedding D5 brane

$$\tau = t, \quad \sigma_1 = \theta, \quad \sigma_2 = \theta_2, \ldots \sigma_5 = \theta_5, \quad r = r(\theta), \quad x = x(\theta), \tag{2.6}$$

we see only SO(5) symmetric configurations of D5 brane which stand for baryons in 4D real spacetime $(t, \vec{x})$ are considered, and the embedding function can be determined by $r(\theta)$ and $x(\theta)$. The gauge field on D5 can also be written as $A_t(\theta)$ for symmetry. The action of D5 brane is given by

$$\begin{aligned} S = T_5 \Omega_4 r_+^4 \int \mathrm{d}t \mathrm{d}\theta \sin^4\theta \\ \left\{ -e^{\frac{\phi}{2}} \sqrt{\left[\left(1 - \frac{r_0^4}{r^4}\right) r^2 + r'^2 + \left(1 - \frac{r_0^4}{r^4}\right) \frac{r^4}{r_+^4} x'^2 \right]} - F_{\theta t}^2 + 4A_t \right\}, \end{aligned} \tag{2.7}$$

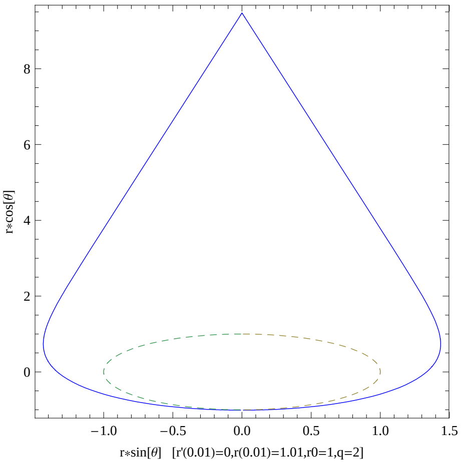

Figure 1. Baryon vertex configuration.

where $\Omega_4 = 8\pi^2/3$ is the volume of unit four sphere. To obtain the configuration of D5 brane, we should solve the gauge field at first. The equation of motion turns to be

$$\partial_\theta D = -4\sin^4\theta. \tag{2.8}$$

The solution to the above equation is

$$\begin{gathered} D(\nu,\theta) = \frac{3}{2}(\sin\theta\cos\theta - \theta + \nu\pi) + \sin^3\theta\cos\theta, \\ 0 \le \nu = \frac{k}{N_c} \le 1, \end{gathered} \tag{2.9}$$

where k denotes the number of Born-Infeld strings emerging from south pole of S^5. More details about this solution can be found in [4]. To eliminate the gauge field in favor of D, we shall transform the original Lagrangian to obtain an energy functional of the embedding function as follows

$$\mathcal{H} = T_5\Omega_4 r_+^4 \int \mathrm{d}\theta e^{\frac{\phi}{2}} \sqrt{\left[\left(1-\frac{r_0^4}{r^4}\right)r^2 + r'^2 + \left(1-\frac{r_0^4}{r^4}\right)\frac{r^4}{r_+^4}x'^2\right]} \times \sqrt{D^2+\sin^8\theta}\,. \tag{2.10}$$

In order to find the configuration of D5 brane, one must extremize $\mathcal{H}$, with respect to $r(\theta)$ and $x(\theta)$ respectively. A closed solution of D5 is argued as a physical baryon vertex. More discussion about these solutions can be found in [2]. By solving equation of motion for $r(\theta)$ and $x(\theta)$ in (2.10), we can find different kinds of solutions for baryon vertex.

2.1 Baryon vertex solutions

Note that point vertices in real spacetime correspond to $x'(\theta) = 0$. Thus the new action in (2.10) turns to be

$$\mathcal{H} = T_5\Omega_4 r_+^4 \int \mathrm{d}\theta e^{\frac{\phi}{2}} \sqrt{\left[\left(1-\frac{r_0^4}{r^4}\right)r^2 + r'^2\right]} \times \sqrt{D^2+\sin^8\theta}\,. \tag{2.11}$$

If $q = 0$, the gravity theory is the usual AdS black hole. In that case, vertex D5 brane with a DBI+CS action can not have a closed solution. Here, we choose $q > 0$(or some critical value) to keep closed D5 solutions, generally as in figure 1. The solutions are independent on r_+, if $x'(\theta) = 0$. Only two parameters q and r_0 determine behaviors of solutions. When we choose suitable parameters $q = 2, r_0 \in (0.1, 0.689)$, the vertex brane solutions can have four kinds of typical behaviors if we choose different initial $r(0)$. Four kinds of typical behaviors correspond to four different kinds of configurations of baryon. From these solutions, we see that there is always a singularity in $r_e = r(\pi)$, if we give initial conditions

$$r'(0) = 0, \quad r(0) = C, \tag{2.12}$$

where C is a constant.

2.2 Force balance condition

Adding fundamental strings can help to eliminate this singularity and keep charge conserved. For simplicity, consider that N_c fundamental strings all attach the north pole of S^5, which means $\nu = 0$. N_c static quarks are arranged on a circle in (x_1, x_2) space, whose coordinates can also be written as (ρ, α). By the following consistent ansatz that describes the embedding fundamental strings

$$\tau = t, \quad \sigma = r, \quad \rho = \rho(r), \tag{2.13}$$

we write the string action

$$S_F = \frac{1}{2\pi\alpha'} \int \mathrm{d}t\mathrm{d}r e^{\frac{\phi}{2}} \sqrt{\left(1 + \frac{r^4 - r_0^4}{r_+^4} \rho'^2\right)} = \frac{1}{2\pi\alpha'} \int \mathrm{d}t\mathrm{d}r \mathcal{L}_F \, . \tag{2.14}$$

To eliminate the singularity of cusp of D5 brane at r_e, one needs force balance conditions. One force balance condition in ρ direction is satisfied for central symmetry. Another force balance condition in r direction is given by

$$N_c \left\{ \mathcal{L}_F - \rho' \frac{\partial \mathcal{L}_F}{\partial \rho'} \right\} \Bigg|_{r_e} = 2\pi\alpha' \frac{\partial \mathcal{H}}{\partial r_e} \, . \tag{2.15}$$

The left hand of equation (2.15) is the upward force of string and the right hand is the downward force of brane. The balance point is the singularity of vertex solution.

3 Holographic melting

3.1 General analysis of screening length

In the simplest example of the AdS/CFT correspondence provided by the duality between $\mathcal{N} = 4$ supersymmetric Yang-Mills theory and classical gravity in $\mathrm{AdS}_5 \times \mathrm{S}^5$, external quarks can be introduced by fundamental strings hanging from the boundary. At nonzero temperature, the potential between an external quark and an antiquark has discontinuous behavior when their separation $L = L_s$. It's argued that the lower energy branch corresponding to larger r_e stands for real baryons, and L_s is defined as "screening length". If quark separation $L > L_s$, the quark-antiquark bound state will dissociate or melt in the medium. A similar screening length for baryons with multi quarks waits to be analyzed. We shall calculate the screening effect for our baryon configuration. For the given initial condition (2.12), one can obtain the cusp position r_e (the end of string in the bulk) by solving the equation of motion for $r(\theta)$. For different values of $r(0)$, the cusp attached by fundamental strings can have different r positions in the bulk geometry. In a recent work [6], we analyzed the screening length for D4 vertex brane plus N_c fundamental strings, and found that the lower energy branch corresponded to smaller r_e but not larger one. This is a very interesting finding. To see what screening effect will happen, let us turn to our analysis for the present baryon configurations.

We shall consider quarks moving in medium and rotating in a plane, corresponding to boosted and high spin hadron state respectively.[1] A static and spin zero state can be obtained by simplification from complex states (with more finite quantum numbers) directly. The medium wind will effect the vertex brane and fundamental strings at the same time, and the vertex brane can not feel the rotating effect, because it is a central point in the rotation plane for symmetry. In the present case, we consider quarks moving in x_3 direction and rotating in (ρ, α) plane. For simplicity, we shall stand in the rest frame of the baryon configuration. The metric (2.1) can be boosted such that it describes a gauge plasma moving with a wind velocity v in the negative x_3-direction. The boosted metric is given by [29]

$$e^{-\frac{1}{2}\phi} ds_{10}^2 = -A\mathrm{d}t^2 + 2B\mathrm{d}t\mathrm{d}x_3 + C\mathrm{d}x_3^2 + \frac{r^2}{r_+^2}(\mathrm{d}\rho^2 + \rho^2\mathrm{d}\alpha^2) + \frac{r_+^2}{r^2}\frac{1}{f(r)}\mathrm{d}r^2 + r_+^2\mathrm{d}\Omega_5^2 \tag{3.1}$$

where

$$A = \frac{r^2}{r_+^2}\left(1 - \frac{r_1^4}{r^4}\right), \quad B = \frac{r_1^2 r_2^2}{r^2 r_+^2}, \quad C = \frac{r^2}{r_+^2}\left(1 + \frac{r_2^4}{r^4}\right), \tag{3.2}$$

with

$$r_1^4 = r_0^4 \cosh^2\eta, \quad r_2^4 = r_0^4 \sinh^2\eta, \quad v = -\tanh\eta, \quad f = 1 - \frac{r_0^4}{r^4}. \tag{3.3}$$

In the boosted metric, baryon configuration will depend on η. Both vertex brane and fundamental string solutions will be different from the original ones with $\eta = 0$. First, we pay attention to vertex brane solutions. For point brane vertex, one notes that x^i is independent on θ. The D5 brane action in boosted metric is given by

$$\mathcal{H}_\eta = T_5\Omega_4 r_+^4 \int \mathrm{d}\theta e^{\frac{\phi}{2}} \sqrt{\left(r^2 + f^{-1}r'^2\right)\left(1 - \frac{r_0^4\cosh^2\eta}{r^4}\right)} \times \sqrt{D^2 + \sin^8\theta}\,. \tag{3.4}$$

---

[1] Actually, the general shape of multi quarks is a sphere in 3D space for largest symmetry, we argue that results of a circle analyse is typical.

To obtain rotating fundamental string configuration, we give the following consistent ansatz of embedding function

$$\tau = t, \quad \sigma = r, \quad \alpha = \omega t, \quad \rho = \rho(r). \tag{3.5}$$

Facing the wind in x_3 direction, quarks arranged on the circle in $x_1 - x_2$ plane will keep staying in $x_1 - x_2$ plane and stand on a circle, because they all have the same force. Then the rotating string action in the boosted metric can be written as

$$\tilde{S}_F = \frac{\mathcal{T}}{2\pi\alpha'} \int_{r_e}^{r_\Lambda} \mathrm{d}r \tilde{\mathcal{L}}_F \ , \tag{3.6}$$

where the Lagrangian

$$\tilde{\mathcal{L}}_F = e^{\frac{\phi}{2}} \sqrt{\frac{r^2}{r_+^2}\left(1 - \frac{r_0^4 \cosh^2\eta}{r^4} - \rho^2\omega^2\right)\left(\frac{r_+^2}{r^2 f} + \frac{r^2}{r_+^2}\rho'^2\right)} \ . \tag{3.7}$$

The force balance condition between D5 brane and N_c fundamental strings turns to be

$$N_c \left\{ \tilde{\mathcal{L}}_F - \rho' \frac{\partial \tilde{\mathcal{L}}_F}{\partial \rho'} \right\}\Bigg|_{r_e} = 2\pi\alpha' \Sigma(r_e, \eta) \ . \tag{3.8}$$

To calculate $\frac{\partial \mathcal{H}'}{\partial r_e}$, we rewrite $\tilde{\mathcal{H}} = \mathcal{H}_\eta$ as[2]

$$\tilde{\mathcal{H}} = T_5 \Omega_4 r_+^4 \int_{r_i = r(0)}^{r_e} \mathrm{d}r e^{\frac{\phi}{2}} \sqrt{\left(f^{-1} + r^2\theta'(r)^2\right)\left(1 - \frac{r_0^4\cosh^2\eta}{r^4}\right)} \times \sqrt{D^2 + \sin^8\theta(r)} \ . \tag{3.9}$$

Considering r as "time", the "hamiltonian" shows the force of vertex brane

$$\Sigma(r_e, \eta) = \frac{3\pi}{2} T_5 \Omega_4 \frac{r_+^4}{r^2} e^{\frac{\phi(r_e)}{2}} \frac{\sqrt{r_e^4 - r_0^4\cosh^2\eta}}{\sqrt{r^2\theta'^2 + f^{-1}}} * \frac{1}{f}. \tag{3.10}$$

The left hand in equation(3.8) shows the force of strings

$$\tilde{\mathcal{L}}_F - \rho' \partial_{\rho'} \tilde{\mathcal{L}}_F = \frac{1}{\tilde{\mathcal{L}}_F(r_e)} \frac{e^\phi}{f} \left(1 - \frac{r_0^4 \cosh^2\eta}{r_e^4}\right). \tag{3.11}$$

To solve the equation of motion of strings, we need two initial conditions. One is known by $\rho(r_e) = 0$ for symmetry, and the other must be calculated by the force balance condition (3.8). To get the baryon radius in the boundary, we define

$$L_q = \int_{r_e}^{r_\Lambda} \rho'(r) \mathrm{d}r. \tag{3.12}$$

For $\eta > 0, \omega = 0$, the string Lagrangian (3.6) contains no ρ and one can solve for ρ' from the equation of motion of ρ and express the baryon radius L_q in terms of r_e and η as follows

$$L_q(r_e, \eta) = \int_{r_e}^{r_\Lambda} \mathrm{d}r \frac{K(r_e,\eta) r_+^4}{\sqrt{r^4 - r_0^4}\sqrt{e^\phi(r^4 - r_0^4\cosh^2\eta) - K^2(r_e,\eta) r_+^4}} \tag{3.13}$$

---

[2] We assume that the vertex brane can not feel the rotation.

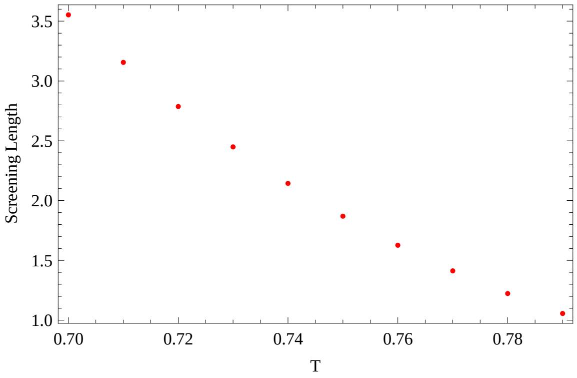

Figure 2. T dependence of screening length. Usually, in plasma, L_s is proportional to inverse Temperature. This figure shows that our result is consistent with this point.

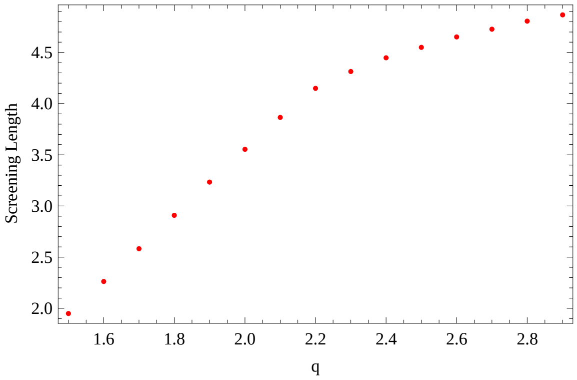

Figure 3. q dependence of screening length.

where $K(r_e, \eta)$ is constant by the equation of motion of $\rho(r)$, $\partial_{\rho'}\tilde{\mathcal{L}_F} = K$, determined by the force balance condition

$$K(r_e, \eta) = \frac{1}{r_+^2}\sqrt{(r_e^4 - r_0^4 \cos^2\eta)e^{\phi(r_e)}} \Big/ \sqrt{1 + \theta'^{-2} r_e^{-2} f^{-1}}\,. \tag{3.14}$$

For $\eta > 0, \omega > 0$, the equation of motion of ρ is difficult to solve analytically. One must search for the numerical result. In both cases, screening length is always defined as the maximum value of $L(r_e, \eta, \omega)$ (as function of r_e)

$$L_s(\eta, \omega) = \mathbf{Max}\Big\{L(r_e, \eta, \omega), r_e\Big\}. \tag{3.15}$$

3.2 q dependence of L_s

In this gluon condensation background, we mainly modified the background with a dilaton factor $e^\phi = 1 + \frac{q}{r_0^4}\log\frac{1}{1-\frac{r_0^4}{r^4}}$, and q is the condensation parameter. If $q = 0$, this background is same as the AdS-black hole background. In that case, it is found that many properties of baryon screening are similar to those of meson screening. The results are novel but the construction of baryon holographic model is not completed. Using the DBI plus CS action of D5 vertex brane, one can not obtain a closed solution for baryon vertex in AdS-black

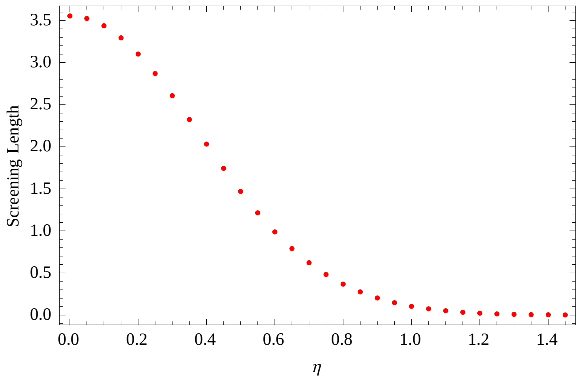

Figure 4. η dependence of screening length. Here, we plot $L_s * \sqrt{\cosh\eta}$ vs η.

hole background. The usual physical explanation is that we can not get a closed baryon vertex in a deconfined gauge field background which is dual to an AdS-black hole. In order to uncover the properties of thermal plasma by analyzing the heavy probe behavior, we consider the gluon condensation modification in the present work. In this case, a closed vertex brane can show us some interesting physical information. The solution of baryon vertex was firstly investigated in [2], and here we use the traditional method to add N_c fundamental string by force balance condition. We go through the traditional screening length calculation and find the screening length is modified by q as shown in figure 3. As q increases, L_s increases, which means that if we enhance the gluon condensation in the plasma, the largest size of existing baryon increases. In another word, gluon condensate makes the plasma favor more baryons.

3.3 η dependence of L_s

Considering a probe of multi quark bound state with relative velocity v in a plasma, the interaction between quarks will be modified by v. The earliest work about this effect is [29]. It's found that when v goes to one, L_s is asymptotic to $L_0*(1-v^2)^{1/4}$. Here we use the same method to analyze the baryon probe in gluon condensation background and find the result which is consistent to the result in [29]. Note that the boost parameter also effects the D5 vertex brane solution. In this work, when $\eta \geq 1.6(q = 2, r_0 = 0.7)$, since the solution of η dependent vertex brane action does not have a finite value at $\theta = \pi$ (it diverges), one can not find a closed solution. The physical explanation is that the brane+strings configuration disappears above a critical boost velocity, which implies that a heavy baryon with a very large velocity can not exist in the plasma or it dissociates very quickly. This critical value of velocity depends on q and T. This point is different from [29], where the ideal model of baryon still holds at a infinite η though the screening length is almost zero. We can find the behavior when $0 \leq \eta < 1.6$. In this area, we observe that $L_s * \sqrt{\cosh\eta}$ ~constant at a large η in figure 4. Our results are consistent with the [29], and we observe that our screening length is larger than that in [29], caused by the gluon condensation q.

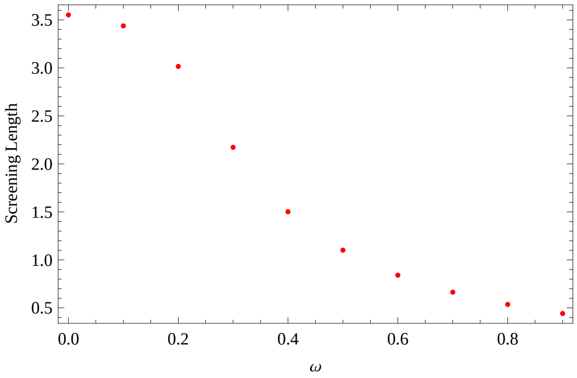

Figure 5. ω dependence of screening length.

3.4 ω dependence of L_s

High spin meson can be presented with spinning string configuration [28]. The same kind of spinning string configurations have been investigated in [30] and the ω dependence behavior of screening length has been found numerically. Here we do the same thing and find the result $L_s \sim \omega^{-1}$ in figure 5 which is similar to the result in [30].

4 Baryon mass and melting analysis

After calculating the screening length of holographic baryon probe, one wants to see how baryons dissociate in the medium. As is well known, screening length is a property of the hot quark gluon plasma. If we want to judge whether a baryon can survive in the plasma, we should compare the baryon radius with screening length of the plasma. Actually, the life of real quark gluon plasma is very short, and the temperature of quark gluon plasma decreases very quickly. Screening length L_s always depends on temperature by $L_s \propto \frac{\beta}{T}$, where β is determined by the properties of the real plasma. For a baryon with radius held fixed, as T rises, it is going to melt. To make this process clear, we should compute the interaction potential of baryon. The definition of baryon mass and interaction potential are shown as follows. In a very general way, baryon mass is given by summation of the energy of N_c strings and the vertex brane as follows

$$E_{\text{total}} = N_c E_{\text{string}} + E_{D5}, \tag{4.1}$$

where the masses of string and vertex brane are given by

$$E_{\text{string}} = \omega \frac{\partial \tilde{L}}{\partial \omega} - \tilde{L}\,, \quad E_{D5} = \tilde{\mathcal{H}}\,, \tag{4.2}$$

Where $\tilde{L} = \frac{1}{2\pi\alpha'}\int_{r_e}^{r_\Lambda} \mathrm{d}r \tilde{\mathcal{L}}_F$ is the string Lagrangian. In order to obtain the interaction potential, one should analyze the free quarks case, in which N_c strings hang from the boundary to r_0 and compact D5 brane almost wrapped on the $r = r_0$ contributes zero energy. Interaction potential is given by subtracting the energy of the free strings . The radial distance of r_0 and boundary is $r_\Lambda - r_0$, the mass of free quark is given respectively

$$E_q = \frac{1}{2\pi\alpha'}\int_{r_0}^{r_\Lambda} e^{\phi/2} \mathrm{d}r \tag{4.3}$$

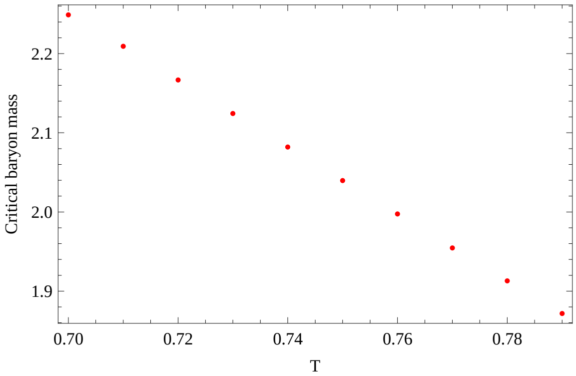

Figure 6. T dependence of critical baryon mass. Since we have no bound state among the baryon configurations. We can just pick some special baryon mass and find how it depends on Temperature. Here we choose the critical mass corresponding to the screening point. The mean of this mass is the highest energy of physical baryons surviving in the plasma. From this figure, we can see that mass is also proportional to inverse Temperature.

Then the interaction potential of baryon is obtained by

$$E_I = E_{\text{total}} - N_c E_q \,. \tag{4.4}$$

Concretely, interaction potential can be written by

$$E_I = \frac{N_c}{2\pi\alpha'}\int_{r_e}^{r_\Lambda} \mathrm{d}r \frac{e^{\phi}}{\tilde{\mathcal{L}}_F}\left(\frac{1}{f}+\frac{r^4\rho'^2}{r_+^4}\right)\left(1-\frac{r_0^4\cosh^2\eta}{r^4}\right)+\tilde{\mathcal{H}}-\frac{N_c}{2\pi\alpha'}\int_{r_0}^{r_\Lambda} e^{\phi/2}\mathrm{d}r \tag{4.5}$$

Plotting the $E_I - L_q$ relation, as shown in figure 7, we see that there exists two branches for each curve, which shows that there are two energy states for fixed quark separation. We choose the low energy branch and argue that it corresponds to the real physical baryon states. Similar curves were obtained for mesons and baryons in the usual $\mathrm{AdS}_5\times\mathrm{S}^5$ background and other different backgrounds [6, 30]. One indeed can calculate screening length and their dependence on speed and spin, but we can not give the exact prediction of the size and energy of any heavy bound states. In our present gluon condensate case, we will find that the mass of baryons has interesting behaviors and we hope it can give useful predictions for experiments [42]. We can also compare baryons with mesons in gluon condensation background.

5 Conclusion and discussion

How to understand confinement and calculate hadron spectrum are considered as two biggest problems in QCD(or non-perturbative QCD exactly). So far we know little about the non-perturbative world and have almost no general powerful tool to study the strongly coupling problem. AdS/CFT correspondence, which is usually called gauge/gravity duality in general, is believed as a useful framework to study these problems. In the experiment side, it is found that there exists a QGP(quark gluon plasma) state in RHIC, which is a strongly coupled quark and gluon thermal state like a fluid, investigated in many works [34–36, 38–41]. How to describe this QGP and understand the strongly coupled behavior is still

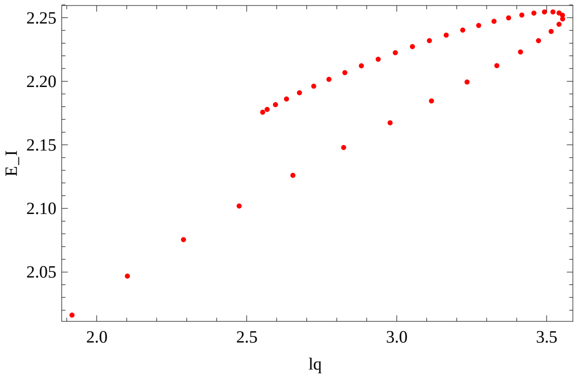

Figure 7. l_q dependence of interaction potential.

a problem, though it is very useful for solving confinement and hadron spectrum problem. It is believed that heavy quark bound state can be alive in QGP, including J/ψ meson and some multi-quark bound states [26]. We call these multi-quark bound states baryons, though they may be different from baryons we see when they survive within QGP. Using meson or baryon as a probe is the simplest method to study the properties of the strongly coupled quark gluon state.

In the gauge/gravity duality framework, we calculate properties of the probe in the classical gravity background. From the strong/weak duality, we know these results are always suitable for the probe in the strongly coupled background in the field side. A lot of works have been done on the meson spectrum and meson melting process in different gauge/gravity systems [22, 23, 28].

In the present paper, we study holographic baryon probe with DBI + CS D5 vertex brane plus N_c fundamental strings in N_c D3 branes background with gluon condensation at finite temperature. We investigate properties of this configuration in a dilaton deformed $\mathrm{AdS}_5 \times \mathrm{S}^5$ background [3]. We find that for most values of temperature T and gluon condensation parameter q, there always exists a screening length L_s. The relation $L_s \sim \frac{1}{T}$ has been checked. We give the q dependence of L_s. We also calculate the boost velocity $v = -\tanh\eta$ and angular velocity ω dependence of L_s for a baryon probe, which are consistent to those dependence relations in the point brane plus strings case, and find that the usual relations have been modified by q. We also calculate the mass of baryon and find T dependence of baryon mass.

Another interesting way to investigate the baryon configuration in gauge/gravity duality is through the finite quark density. The chemical potential of a finite quark density was introduced as a time component of the U(1) gauge filed on flavor brane [22]. Finite quark density affect embedding of the flavor brane, as well as the phase transition corresponding

---

[3] Besides the configuration considered in the present work, where the D5 brane is pointlike along the gauge theory directions, one might envision the D5 growing Nc (or fewer) spikes (i.e., Born-Infeld strings) which extend some distance along ρ and then end at cusps, where they are then continued by strings. Or perhaps the spikes could even extend all the way to the boundary, with the fundamental strings shrinking down to zero length. Needless to say, it would be very difficult to find such solutions explicitly. We ignore them purely in the construction of heavy baryon model in plasma for simplicity.

to meson dissociation. Following the present paper we can study the chemical potential dependence of the baryon mass.

Acknowledgments

Y.Zhou would like to acknowledge helpful discussions with Shi Pu and thank Pu for numerical help.

References

[1] K. Ghoroku, T. Sakaguchi, N. Uekusa and M. Yahiro, *Flavor quark at high temperature from a holographic model*, *Phys. Rev.* **D 71** (2005) 106002 [`hep-th/0502088`] [SPIRES].

[2] K. Ghoroku and M. Ishihara, *Baryons with D_5 brane vertex and k-quarks*, *Phys. Rev.* **D 77** (2008) 086003 [`arXiv:0801.4216`] [SPIRES].

[3] Y. Seo and S.-J. Sin, *Baryon Mass in medium with Holographic QCD*, *JHEP* **04** (2008) 010 [`arXiv:0802.0568`] [SPIRES].

[4] K. Ghoroku, M. Ishihara, A. Nakamura and F. Toyoda, *Multi-quark baryons and color screening at finite temperature*, *Phys. Rev.* **D 79** (2009) 066009 [`arXiv:0806.0195`] [SPIRES].

[5] K. Sfetsos and K. Siampos, *Stability issues with baryons in AdS/CFT*, *JHEP* **08** (2008) 071 [`arXiv:0807.0236`] [SPIRES].

[6] Y. Zhou, *D_4 brane probes in gauge/gravity duality*, *Phys. Rev.* **D 79** (2009) 066005 [`arXiv:0809.1360`] [SPIRES].

[7] E. Witten, *Baryons and branes in Anti de Sitter space*, *JHEP* **07** (1998) 006 [`hep-th/9805112`] [SPIRES].

[8] M. Chernicoff and A. Guijosa, *Energy loss of gluons, baryons and k-quarks in an $N = 4$ SYM plasma*, *JHEP* **02** (2007) 084 [`hep-th/0611155`] [SPIRES].

[9] B. Janssen, Y. Lozano and D. Rodriguez-Gomez, *The baryon vertex with magnetic flux*, *JHEP* **11** (2006) 082 [`hep-th/0606264`] [SPIRES].

[10] S.A. Hartnoll and R. Portugues, *Deforming baryons into confining strings*, *Phys. Rev.* **D 70** (2004) 066007 [`hep-th/0405214`] [SPIRES].

[11] A. Kehagias and K. Sfetsos, *On asymptotic freedom and confinement from type- IIB supergravity*, *Phys. Lett.* **B 456** (1999) 22 [`hep-th/9903109`] [SPIRES].

[12] H. Liu and A.A. Tseytlin, *D3-brane D-instanton configuration and $N = 4$ super YM theory in constant self-dual background*, *Nucl. Phys.* **B 553** (1999) 231 [`hep-th/9903091`] [SPIRES].

[13] Y. Imamura, *On string junctions in supersymmetric gauge theories*, *Prog. Theor. Phys.* **112** (2004) 1061 [`hep-th/0410138`] [SPIRES].

[14] H. Hata, T. Sakai, S. Sugimoto and S. Yamato, *Baryons from instantons in holographic QCD*, `hep-th/0701280` [SPIRES].

[15] N. Kim, *Intersecting noncommutative D-branes and baryons in magnetic fields*, *Phys. Rev.* **D 62** (2000) 066002 [`hep-th/0002086`] [SPIRES].

[16] J. Gomis, A.V. Ramallo, J. Simon and P.K. Townsend, *Supersymmetric baryonic branes*, *JHEP* **11** (1999) 019 [`hep-th/9907022`] [SPIRES].

[17] C.G. Callan Jr., A. Guijosa, K.G. Savvidy and O. Tafjord, *Baryons and flux tubes in confining gauge theories from brane actions*, *Nucl. Phys.* **B 555** (1999) 183 [`hep-th/9902197`] [SPIRES].

[18] C.G. Callan Jr., A. Guijosa and K.G. Savvidy, *Baryons and string creation from the fivebrane worldvolume action*, *Nucl. Phys.* **B 547** (1999) 127 [`hep-th/9810092`] [SPIRES].

[19] T. Sakai and S. Sugimoto, *Low energy hadron physics in holographic QCD*, *Prog. Theor. Phys.* **113** (2005) 843 [`hep-th/0412141`] [SPIRES]; *More on a holographic dual of QCD*, *Prog. Theor. Phys.* **114** (2005) 1083 [`hep-th/0507073`] [SPIRES].

[20] D.K. Hong, M. Rho, H.-U. Yee and P. Yi, *Chiral dynamics of baryons from string theory*, *Phys. Rev.* **D 76** (2007) 061901 [`hep-th/0701276`] [SPIRES].

[21] D.K. Hong, M. Rho, H.-U. Yee and P. Yi, *Dynamics of baryons from string theory and vector dominance*, *JHEP* **09** (2007) 063 [`arXiv:0705.2632`] [SPIRES].

[22] S. Kobayashi, D. Mateos, S. Matsuura, R.C. Myers and R.M. Thomson, *Holographic phase transitions at finite baryon density*, *JHEP* **02** (2007) 016 [`hep-th/0611099`] [SPIRES].

[23] J. Erdmenger, M. Kaminski and F. Rust, *Holographic vector mesons from spectral functions at finite baryon or isospin density*, *Phys. Rev.* **D 77** (2008) 046005 [`arXiv:0710.0334`] [SPIRES].

[24] J. Erdmenger, M. Kaminski, P. Kerner and F. Rust, *Finite baryon and isospin chemical potential in AdS/CFT with flavor*, *JHEP* **11** (2008) 031 [`arXiv:0807.2663`] [SPIRES].

[25] J. Mas, J.P. Shock, J. Tarrio and D. Zoakos, *Holographic spectral functions at finite baryon density*, *JHEP* **09** (2008) 009 [`arXiv:0805.2601`] [SPIRES].

[26] QCD-TARO collaboration, P. de Forcrand et al., *Meson correlators in finite temperature lattice QCD*, *Phys. Rev.* **D 63** (2001) 054501 [`hep-lat/0008005`] [SPIRES].

[27] H. Liu, K. Rajagopal and U.A. Wiedemann, *An AdS/CFT calculation of screening in a hot wind*, *Phys. Rev. Lett.* **98** (2007) 182301 [`hep-ph/0607062`] [SPIRES].

[28] K. Peeters, J. Sonnenschein and M. Zamaklar, *Holographic melting and related properties of mesons in a quark gluon plasma*, *Phys. Rev.* **D 74** (2006) 106008 [`hep-th/0606195`] [SPIRES].

[29] C. Athanasiou, H. Liu and K. Rajagopal, *Velocity dependence of baryon screening in a hot strongly coupled plasma*, *JHEP* **05** (2008) 083 [`arXiv:0801.1117`] [SPIRES].

[30] M. Li, Y. Zhou and P. Pu, *High spin baryon in hot strongly coupled plasma*, *JHEP* **10** (2008) 010 [`arXiv:0805.1611`] [SPIRES].

[31] O. Aharony, J. Sonnenschein and S. Yankielowicz, *A holographic model of deconfinement and chiral symmetry restoration*, *Annals Phys.* **322** (2007) 1420 [`hep-th/0604161`] [SPIRES].

[32] A. Brandhuber, N. Itzhaki, J. Sonnenschein and S. Yankielowicz, *Baryons from supergravity*, *JHEP* **07** (1998) 020 [`hep-th/9806158`] [SPIRES].

[33] H. Liu, K. Rajagopal and Y. Shi, *Robustness and infrared sensitivity of various observables in the application of AdS/CFT to heavy ion collisions*, *JHEP* **08** (2008) 048 [`arXiv:0803.3214`] [SPIRES].

[34] J. Erdmenger, M. Haack, M. Kaminski and A. Yarom, *Fluid dynamics of R-charged black holes*, *JHEP* **01** (2009) 055 [`arXiv:0809.2488`] [SPIRES].

[35] K. Dusling et al., *Quarkonium transport in thermal AdS/CFT*, *JHEP* **10** (2008) 098 [`arXiv:0808.0957`] [SPIRES].

[36] R.-G. Cai and Y.-W. Sun, *Shear viscosity from AdS Born-Infeld black holes*, *JHEP* **09** (2008) 115 [`arXiv:0807.2377`] [SPIRES].

[37] S. Pu and Q. Wang, *Shear viscosity in late time of hydrodynamic evolution in AdS/CFT duality*, `arXiv:0810.5271` [SPIRES].

[38] R.-G. Cai, Z.-Y. Nie and Y.-W. Sun, *Shear viscosity from effective couplings of gravitons*, *Phys. Rev.* **D 78** (2008) 126007 [`arXiv:0811.1665`] [SPIRES].

[39] S. Bhattacharyya, V.E. Hubeny, S. Minwalla and M. Rangamani, *Nonlinear fluid dynamics from gravity*, *JHEP* **02** (2008) 045 [`arXiv:0712.2456`] [SPIRES].

[40] P. Figueras, V.E. Hubeny, M. Rangamani and S.F. Ross, *Dynamical black holes and expanding plasmas*, `arXiv:0902.4696` [SPIRES].

[41] M. Rangamani, S.F. Ross, D.T. Son and E.G. Thompson, *Conformal non-relativistic hydrodynamics from gravity*, *JHEP* **01** (2009) 075 [`arXiv:0811.2049`] [SPIRES].

[42] S.-J. Sin, Y. Shuo and Y. Zhou, the work to appear.

[43] C. Hoyos-Badajoz, K. Landsteiner and S. Montero, *Holographic meson melting*, *JHEP* **04** (2007) 031 [`hep-th/0612169`] [SPIRES].

[44] C. Krishnan, *Baryon dissociation in a strongly coupled plasma*, *JHEP* **12** (2008) 019 [`arXiv:0809.5143`] [SPIRES].