Physics Letters B 723 (2013) 207–212

Contents lists available at SciVerse ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

Self-energy of strongly interacting fermions in medium: A holographic approach

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ARTICLE INFO

Article history:
Received 1 March 2013
Received in revised form 20 April 2013
Accepted 29 April 2013
Available online 3 May 2013
Editor: L. Alvarez-Gaumé

ABSTRACT

We consider the self-energy of strongly interacting fermions in the medium using gauge/gravity duality of $D4/D8$ system. We study the mass generation of the thermal and/or dense medium and the collective excitation called plasmino, by considering the spectral function of fermion and its dispersion relation. Our results are very different from those of the hard thermal loop method: for zero density, there is no thermal mass or plasmino in any phase. Plasmino in the deconfined phase is not allowed in $D4/D8$ setup. In the confined phase, there is a plasmino mode only for a window of density.

1. Introduction

The study of fermion self-energy in medium has a long history due to its fundamental importance in studying electronic as well as nuclear matter system. When the excitations are strongly interacting, perturbative field theory method cannot give a reliable result since the diagrams should be truncated to the ladder or rainbow types, which cannot be justified in strong coupling. Furthermore in the presence of chemical potential, the lattice technique is not much useful due to the sign problem. Therefore it is worthwhile to utilize the gauge/gravity duality for this tantalizing problem. The gauge/gravity duality was used to study the fuzzy Fermi surface [1] and the non-Fermi liquid nature [2–4] of the strongly interacting system, for recent developments, we refer to [5–8].

The weakly interacting field theory (QED or QCD) results for the fermion self-energy in medium can be summarized by the existence of the plasmino mode [9] and thermal mass generation of order gT. Plasmino is a collective mode whose dispersion curve has a minimum at finite momentum. However, the recent study of the thermal field theory [10,11], by solving Schwinger–Dyson equation numerically, showed that the thermal mass is reduced as the coupling grows. It raises an interesting questions what happens to the thermal mass and more generally to the hard and soft momentum scales and magnetic mass scale, T, gT, g^2T respectively, in the strong coupling limit.

In this Letter we study the dispersion relation and thermal mass generation using gauge/gravity duality and report a feature of plasmino in strongly coupled system. We consider $D4/D8$ model [12] and turn on a fermion field on the flavor brane world volume with finite quark/baryon number density [13–15]. In the deconfined phase, the fermions represent the fundamental strings, connecting the horizon of black branes and the probe $D8$. In the zero 't Hooft coupling limit, it is a bi-fundamental representation. In the large 't Hooft coupling limit, $D4$ branes disappear and the color index of the fermions should disappear also. In the confined phase, to describe a baryon we need to introduce Witten's baryon vertex [16]. N_c strings are connecting it to the probe $D8/\overline{D8}$. The dynamics of connecting open strings defines that of the baryon vertex as well as the $D8$. Since each string gives fermionic mode, total vibrational dynamics should be described by the composite operator coming from the product of all N_c fermions. This is the baryon in confined phase which is fermion if N_c is odd. We replace this composite operator by a massive fermion field. So our construction for baryon is rather phenomenological. We consider just one flavor brane case mostly. Previously fermions on a probe brane in adjoint representation, called mesino, were studied in [17,18], which are different from ours.

By solving the Dirac equations in each phase, we obtain dispersion relations for the fermionic excitations in medium. Our results show that for zero density, there is no thermal mass generation and no plasmino in any phase, which is sharply different from weakly coupled field theory result. To get plasmino in the deconfined phase we need to add quark mass as well as quark density. In $D4/D8$ setup, the quark mass is not allowed so plasmino is forbidden in the deconfined phase. In the confined phase, there is a plasmino mode only for a certain window of density.

2. Plasmino in field theory

We begin our discussion by giving a brief discussion of fermionic collective excitations in a plasma. The fermion propagator is written as

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0370-2693/$ – see front matter
http://dx.doi.org/10.1016/j.physletb.2013.04.059

$$G(p) = \frac{1}{\gamma \cdot p - m - \Sigma(p)}, \tag{1}$$

where $\Sigma = \gamma_\mu \Sigma^\mu$ is a self-energy. The gauge invariant result is available in the hard (high temperature) thermal loop approximation (HTL) where fermion mass m can be ignored since it is small compared with T or μ. The most noticeable effect of the medium is the effective mass generation. The HTL result of effective mass is given by [19] $m_f^2 = \frac{1}{8} g^2 C_F (T^2 + \frac{\mu^2}{\pi^2})$, where $C_F = 1$ for electron and $C_F = 4/3$ for quark. There are two branches of dispersion curves $\omega = \omega_\pm(p)$ whose asymptotic forms are given by

$$p \ll m_f: \quad \omega_\pm(p) \simeq m_f \pm \frac{1}{3} p, \tag{2}$$

$$p \gg m_f: \quad \omega_\pm(p) \simeq p. \tag{3}$$

ω_+ is the normal branch and ω_- is the one describing plasmino that has been extensively investigated [9,19–31]. For a review we refer to [32,33]. The presence of plasmino is important since it may enhance the production rate of the light di-lepton [30].

In HTL approximation, fermions can be regarded as massless therefore two branches $\omega_\pm$ can be characterized by chirality and helicity. The ratios of chirality and helicity for $\omega_\pm$ are ± 1 respectively. In our work, we do not neglect the fermion mass so we consider the presence of plasmino as the presence of the minimum of dispersion curve at finite momentum. We will conclude that the plasmino exists if the dispersion relation has a minimum at finite momentum.

Notice that plasmino in HTL approximation exists in high temperature whatever the density is. However, in the strongly coupled limit, we will show that plasmino disappears at zero density in the deconfined phase. And it can survive only for a certain window of chemical potential in confined medium. Especially, at zero chemical potential, there is no plasmino. We find that the constant value 1/3 in Eq. (2) will be replaced by a function of density. See Fig. 5.

3. Holographic setup

Let us now set up a holographic model to calculate the fermion self-energy, first in the confined phase. We use the Sakai–Sugimoto (SS) model [12] where probe $D8/\overline{D}8$ is embedded in black $D4$ branes background. To introduce finite density, we turn on $U(1)$ gauge field on the probe brane. The sources of the $U(1)$ gauge field are end points of strings which are emanating from horizon in the deconfined phase and from baryon vertex in the confined phase.

3.1. Confined phase

The geometry of confined phase with Euclidean signature is given by

$$ds^2 = \left(\frac{U}{R}\right)^{3/2} \left(\delta_{\mu\nu}\, dx^\mu\, dx^\nu + f(U)\, dx_4^2\right) + \left(\frac{R}{U}\right)^{3/2} \left(\frac{dU^2}{f(U)} + U^2\, d\Omega_4^2\right), \tag{4}$$

where both the time and the Kaluza–Klein direction are periodic: $x^0 \sim x^0 + \delta x^0$, $x_4 \sim x_4 + \delta x_4$ and $f(U) = 1 - \frac{U_{KK}^3}{U^3}$, $U_{KK} = (\frac{4\pi}{3})^2 \frac{R^3}{\delta x_4^2}$. Here following the original Sakai–Sugimoto model, we consider only trivial embedding of the flavor eight brane where $D8$ and $\overline{D8}$ brane are located at the antipodal position in x_4 direction. The dynamics of probe branes with $U(1)$ gauge field on it can be governed by the DBI action as follows

$$S_{D8} = -T_8 \int d^9x\, e^{-\phi} \sqrt{\det\left(g_{MN} + 2\pi\alpha' F_{MN}\right)} = \mathcal{N} \int dr\, r^4 \left[r^{-3}\left(1/f(r) - a_0'(r)^2\right)\right]^{1/2}, \tag{5}$$

where $\mathcal{N} = T_8 \Omega_4 v_3 \delta x^0 R^5 / g_s$, and Ω_4 is the unit four sphere volume and v_3 is the three Euclidean space volume. Notice that in the case of antipodal configuration of $D8/\overline{D8}$, the embedding becomes trivial, i.e. $x_4'(r) = 0$. For later convenience, we use dimensionless quantities

$$r = U/R, \qquad r_0 = U_{KK}/R, \qquad a_0 = 2\pi\alpha' A_0/R. \tag{6}$$

From the equation of motion for $U(1)$ gauge field, we get conserved dimensionless quantity $\frac{r a_0'(r)}{\sqrt{r^{-3}(1/f(r) - a_0'(r)^2)}} = D$, where D is an integral constant representing the baryon density.

Chemical potential can be defined as the value of $a_0(r)$ at the infinity, once proper IR boundary condition is imposed at $r = r_0$. In the confined case, the baryon vertex which is $D4$ brane wrapping on S^4 with N_C fundamental strings plays the role of source of the $U(1)$ gauge field. The energy of the source should be included in the total free energy of the system and it contributes to the chemical potential also.

Accordingly we set $a_0(r_0) = m/q$ to include the baryon mass m in the chemical potential μ:

$$\mu = m/q + \mu_0 = m/q + \int_{r_0}^{\infty} a_0'\, dr. \tag{7}$$

In the confined phase, μ_0 is the contribution only from the gauge potential and m is identified as baryon mass, which can be calculated from the DBI action of the baryon vertex. It is related to the 5 dimensional Lagrangian mass m_5 as we will see later. Notice that such identification is not true in bottom up AdS model, where bulk fermion mass should be related to the conformal dimension of an operator.

3.2. Deconfined phase

The deconfined geometry is given by double Wick rotating x_4 and time from the confined one. The DBI action for probe brane can be written as

$$S_{D8} = \mathcal{N}' \int dr\, r^4 \sqrt{r^{-3}\left(1 - a_0'(r)^2\right)}. \tag{8}$$

The gauge field profile on eight brane is solved as before, $\frac{r a_0'(r)}{\sqrt{r^{-3}(1 - a_0'(r)^2)}} = D'$, where D' is a constant. In the deconfined phase the end points of fundamental strings play the role of sources of the $U(1)$ gauge field. Since the probe branes always fall into the black hole horizon, the fermion representing quark is massless in this phase.

The IR boundary condition of a_0 field determined by the regularity condition at the horizon is given by $a_0(r_H) = 0$, where $r_H = U_H/R$. This condition is also consistent with the argument in the previous section. In the deconfined case, mass of source is zero hence it does not contribute to the IR boundary condition for chemical potential.