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Holographic responses of fermion matter

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Abstract

We consider the D4–D8–$\overline{\text{D8}}$ brane system which serves as ultraviolet completion of the Nambu–Jona-Lasinio model, where the only degrees of freedom carrying baryon charge are fermions. By turning on chemical potential for this charge one may expect the formation of the Fermi liquid ground state. At strong coupling we use the dual holographic description to investigate the responses of the system to small perturbations. In the chirally symmetric phase we find that the density-dependent part of the heat capacity vanishes linearly with temperature. We also observe a zero sound excitation in the collisionless regime, whose speed is equal to that of normal sound in the hydrodynamic regime. Both the linear dependence of the heat capacity and the existence of zero sound are properties of the Fermi liquid ground state. We also compute the two-point function of the currents at vanishing frequency but do not find any singularities at finite values of the momentum.

1. Introduction

Understanding QCD at finite baryon density or finite chemical potential is an important and difficult problem. Lattice computations are complicated by the sign problem, and one largely has to rely on phenomenological models. At large values of the chemical potential asymptotic freedom ensures that the physics is determined by the dynamics of the quarks near the Fermi surface. The physics simplifies in the planar limit, since some of the perturbative instabilities are suppressed (see [1] and references therein for the recent work in this direction).

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It is interesting to compare the predictions of perturbative QCD with those coming from string theoretic models. Consider the holographic model of QCD [2,3] at finite temperature T and baryon chemical potential μ. An incomplete list of references where this setup was analyzed includes [4–15]. The holographic model is by no means equivalent to QCD, and in fact lacks asymptotic freedom. In the holographic model it is possible to adjust the glueball mass scale to be lower than the meson mass scale. This leads to the existence of the deconfined but chirally broken phase. The phase diagram then contains a line of first order phase transitions between a chirally symmetric phase at larger values of μ and T and a broken phase at smaller values of these parameters [5,6]. In addition, at large values of μ there is a phase with condensed baryons [10,12], which is not what we naively expect from perturbative QCD. One may ask whether the physics of the system resembles that of perturbative QCD, and, in particular whether one can see signatures of Fermi liquid formation.

The question is actually more general that this.[1] Generic attractive interactions are believed to destabilize the Fermi surface, leading to the formation of a gap and a superconducting ground state. (For a holographic description of superconductivity see [22–31] and references therein.) In the 't Hooft limit the perturbative quark–quark interactions are suppressed, and there is an opportunity for the Fermi liquid ground state to survive, even though the coupling is strong. In this paper we attempt to analyze the fate of the fermion matter from the D4–D8 strings by studying its responses to small external perturbations. Since our main interest is not QCD dynamics and the Yang–Mills degrees of freedom simply provide the strong interaction between quarks, we consider the (decompactification) limit which corresponds, in the field theoretic regime, to a certain UV completion of the Nambu–Jona-Lasinio model [32]. (See [33] for more details.) We turn on chemical potential which is expected to lead to the formation of charged matter, whose ingredients, at least in the field theoretic regime are fundamental fermions. We consider the phase where chiral symmetry is restored, which corresponds to the D8–$\overline{\text{D8}}$ branes falling into the horizon of the black hole. Such a phase is perturbatively stable for a wide range of μ and T.

We show that the density-dependent part of the heat capacity at low temperature is linear in T. This is the behavior expected for systems with a Fermi surface, where only a fraction of quasiparticles is excited at small temperatures. We also observe that at arbitrarily low temperatures there exists a massless excitation (zero sound) whose speed is equal to the speed of normal sound in the hydrodynamic regime. The existence of zero sound is also a feature of the Fermi liquid and corresponds to the deformation of the Fermi surface away from the spherical shape. We then compute the current–current two-point function at vanishing frequency $\omega = 0$ and finite spacial momentum q using the holographic techniques. Such a two-point function should be sensitive to the finite gap in the distribution function at the Fermi momentum $q = q_F$. We do not find any singular features however. As we discuss below, this might be related to a non-generic dispersion relation of the quasiparticles near the Fermi surface.

The rest of the paper is organized as follows. In the next section we review the D4–D8–$\overline{\text{D8}}$ system at finite chemical potential, including phase structure and thermodynamics. We compute the speed of normal sound in the hydrodynamic regime and show that the density dependent part of the heat capacity vanishes linearly with T at small temperatures. We then study small fluctuations at small temperature (collisionless regime) and find the massless excitation (zero sound) in Section 3. The speed of zero sound is equal to the speed of normal sound in the hydrodynamic regime. In Section 4 we compute the current–current two-point function and show that no visible

[1] Recent work on holographic Fermi systems includes [16–20], see also [21].