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Holographic Fermi surface at finite temperature in six-dimensional (2, 0) theory

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We analyzed two-point Green's functions of operators in six-dimensional (2, 0) theory dual to fermions in maximal gauged supergravity in seven dimensions at finite temperature. We have considered backgrounds with both the charge parameters nonzero as well as only one charge parameter nonzero. In the former case we find all the modes admit Fermi surface(s), while in the latter, some of the modes do not have a Fermi surface. We find backgrounds corresponding to nonzero expectation value of the scalar appearing in the dual operator give rise to Fermi surface(s).

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I. INTRODUCTION

AdS/CFT correspondence [1–3] has been proved to be an extremely useful tool for studying strongly interacting fermionic systems using the gravity dual. This has been effectively used to study Fermi surfaces [4–6] showing existence of holographic Fermi liquid as well as non-Fermi liquid, which are characterized by sharp Fermi surfaces but excitations with scaling behavior different from Fermi liquid. Studies of various aspects of these non-Fermi liquid have appeared in literature [7–9], such as effects of variation of mass, charge parameters, Pauli coupling as well as the relation between the scaling exponent of spectral function and dimension of dual operators, to name a few. These analyses are in bottom-up approach where on the gravity side one chooses a Lagrangian, which reflects the effective low energy operators of the system one is interested in, with appropriate symmetries. Though this is a very informative and flexible approach, often the dual theory is not known.

On the other hand, one can begin with a known string or supergravity model, where the dual theory is known. Several studies in this top-down approach [10–14] appeared in the cases of probe branes and $N = 2$ supergravity theories. In particular, no Fermi surface was found in the case of $N = 2$ supergravity [12,14]. Subsequently, systematic studies appeared for maximally gauged supergravity theories in five and four dimensions [15–17], which are dual to $N = 4$ super-Yang-Mills (SYM) in four dimensions and Aharony-Bergman-Jafferis-Maldacena (ABJM) theory in three dimensions. Fermi surfaces were found to be present in both cases, as revealed through analysis at zero temperature for various values of chemical potentials. Later, the zero temperature analyses were extended to the computation of full Green's function at finite temperature for single charge [18], which also studied the role of scalar and spinor operators in the dual field theory. Discussions of Fermi surfaces in a similar context appeared in [19–21]. A model with single charge having vanishing entropy at zero temperature was analyzed in [22] where they found fermionic fluctuations are stable within a gap around the Fermi surface. Studies of Lifshitz geometry at finite temperature in the bottom-up approach have also appeared [23,24], where gapped spectra were found.

Analysis of maximally gauged supergravity in seven dimensions at zero temperature, which is dual to (2, 0) conformal field theory in six dimensions appeared in [25]. The dual theory is one of three maximally superconformal field theories and so it is interesting in its own right. The background considered consists of two nonzero charge parameters and over the range of these parameters, it turned out operators in the dual field theory admit at least one Fermi surface. In particular, operators corresponding to fermionic modes with higher total charge admit two Fermi surfaces, over some region of parameter space.

In the present work we have extended this analysis of zero temperature [25] to finite temperature by computing the full Green's function. We have analyzed behavior of the spectral function for various fermionic modes at nonzero temperature in order to study Fermi surfaces. We find agreement with earlier results for background with two nonzero charge parameters. Furthermore, we set one of the charge parameters to zero that gives rise to different backgrounds, which does not admit extremal limit. Since the dual field theory is known, it enables us to study the role of the operators in the dual field theory in determining the nature of the Fermi surface.

The plan of the article is as follows. In the next section, we briefly describe the black hole solution that we use as the background. In Sec. III we set up the equations to compute Green's function of the dual operators. In Sec. IV we present numerical computation of Green's function for different modes and backgrounds. In Sec. V we conclude with a discussion of the results.

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II. BLACK HOLE SOLUTION

We consider maximal seven-dimensional gauged supergravity [26–28], which is conjectured to be dual to a six-dimensional (2, 0) conformal field theory [1–3]. The seven-dimensional theory has an $SO(5)$ symmetry and it admits an asymptotically AdS black hole solution. In order to obtain the black hole solution one can truncate the theory so as to reduce to gauge group to $U(1)^2$, where two gauge fields in two Cartan of $SO(5)$ are nonzero, while setting other components of the gauge fields and three-form potential to be zero [29,30]. The bosonic Lagrangian with the truncated fields is given by [29]

$$\begin{aligned} 2\kappa^2 e^{-1}\mathcal{L} &= R - \frac{1}{2}m^2\nu(\phi_1,\phi_2) - 6(\partial\phi_1)^2 - 6(\partial\phi_2)^2 \\ &\quad - 8(\partial_\mu\phi_1)(\partial^\mu\phi_2) - e^{-4\phi_1}F^{(1)2}_{\mu\nu} - e^{-4\phi_2}F^{(2)2}_{\mu\nu} \\ &\quad + m^{-1}p_2(A,F), \qquad \text{where} \\ \nu(\phi_1,\phi_2) &= -8e^{2(\phi_1+\phi_2)} - 4e^{-2\phi_1-4\phi_2} \\ &\quad - 4e^{-4\phi_1-2\phi_2} + e^{-8\phi_1-8\phi_2}. \end{aligned} \tag{2.1}$$

The asymptotically AdS black hole solution [29,30] to the equations of motion ensuing from the Lagrangian (2.1) with two charges is as follows [25]. The metric and the gauge fields are given by

$$\begin{aligned} ds^2 &= e^{2A(r)}(h(r)dt^2 - d\vec{x}^2) - \frac{e^{2B(r)}}{h(r)}dr^2, \\ A^{(1)}_\mu dx^\mu &= A^{(1)}_t(r)dt, \qquad A^{(2)}_\mu dx^\mu = A^{(2)}_t(r)dt, \\ \phi_1 &= \phi_1(r), \phi_2 = \phi_2(r). \end{aligned} \tag{2.2}$$

The explicit expressions of the functions appearing on the right-hand side are given by

$$\begin{aligned} e^{2A(r)} &= \frac{m^2}{4}r^2\left(1+\frac{Q_1^2}{r^4}\right)^{\frac{1}{5}}\left(1+\frac{Q_2^2}{r^4}\right)^{\frac{1}{5}}, \\ e^{2B(r)} &= \frac{4}{m^2}\frac{1}{r^2}\left(1+\frac{Q_1^2}{r^4}\right)^{-\frac{4}{5}}\left(1+\frac{Q_2^2}{r^4}\right)^{-\frac{4}{5}}, \\ h(r) &= \left(1 - \frac{r^2}{r_h^2}\frac{(r_h^4+Q_1^2)(r_h^4+Q_2^2)}{(r^4+Q_1^2)(r^4+Q_2^2)}\right), \\ A^{(1)}(r) &= \frac{1}{2}\frac{m}{2}\frac{Q_1}{r_h}\left(\frac{r_h^4+Q_2^2}{r_h^4+Q_1^2}\right)^{\frac{1}{2}}\left(1-\frac{r_h^4+Q_1^2}{r^4+Q_1^2}\right), \\ A^{(2)}(r) &= \frac{1}{2}\frac{m}{2}\frac{Q_2}{r_h}\left(\frac{r_h^4+Q_1^2}{r_h^4+Q_2^2}\right)^{\frac{1}{2}}\left(1-\frac{r_h^4+Q_2^2}{r^4+Q_2^2}\right), \\ e^{2\phi_1(r)} &= r^{\frac{4}{5}}\frac{(r^4+Q_2^2)^{\frac{2}{5}}}{(r^4+Q_1^2)^{\frac{3}{5}}}, \\ e^{2\phi_2(r)} &= r^{\frac{4}{5}}\frac{(r^4+Q_1^2)^{\frac{2}{5}}}{(r^4+Q_2^2)^{\frac{3}{5}}}. \end{aligned} \tag{2.3}$$

$m/2 = 1/L$ where L is the radius of AdS and $g = 2m$. Temperature and entropy density associated with this black hole are given by [17]

$$\begin{aligned} T &= \frac{m^2}{4}\frac{r_h}{2\pi}\frac{3+\frac{Q_1^2}{r_h^4}+\frac{Q_2^2}{r_h^4}-\frac{Q_1^2Q_2^2}{r_h^8}}{\sqrt{1+\frac{Q_1^2}{r_h^4}}\sqrt{1+\frac{Q_2^2}{r_h^4}}}, \\ s &= (m/2)^5\frac{r_h}{4G}\sqrt{(r_h^4+Q_1^2)(r_h^4+Q_2^2)}. \end{aligned} \tag{2.4}$$

The chemical potentials and charge densities are given by

$$\begin{aligned} \mu_1 &= \frac{1}{2}\frac{m^2}{4}\frac{Q_1}{r_h}\left(\frac{r_h^4+Q_2^2}{r_h^4+Q_1^2}\right)^{\frac{1}{2}}, \qquad \mu_2 = \frac{1}{2}\frac{m^2}{4}\frac{Q_2}{r_h}\left(\frac{r_h^4+Q_1^2}{r_h^4+Q_2^2}\right)^{\frac{1}{2}}, \\ \rho_i &= \frac{Q_i s}{2\pi r_h^2}. \end{aligned} \tag{2.5}$$

Fermionic field content consists of gravitini and spin-$1/2$ fermions, transforming in 4 and 16 of $SO(5)$ respectively. We are denoting the spin-$1/2$ fermions by $\lambda^{1\pm}(s_{12}, s_{34})$, $\lambda^{2\pm}(s_{12}, s_{34})$, where s_{12}, $s_{34} = \pm\frac{1}{2}$ are charges of spinor representation of two generators in Cartan of $SO(5)$, as explained in [25]. Our objective is to study Fermi surfaces associated with the operators dual to these Fermionic modes. Out of these 16 fermions we will consider eight fermions that do not couple to the gravitini. The charges, masses and other parameters of these fermions are summarized in Table I.

The dual field theory contains [31] self-dual two-form potential transforming as **1**, five scalars Σ^i transforming as **5** and four symplectic Majorana-Weyl spinors ψ^A transforming as **4** under the R-symmetry group. We denote scalars by $\Sigma^{1\pm}$, $\Sigma^{2\pm}$ and Σ^0 having $U(1)\times U(1)$ charges $(\mp 1, 0)$, $(0, \mp 1)$ and (0, 0) respectively and spinors by $\psi(s_{12}, s_{34})$ with s_{12}, $s_{34} = \pm 1/2$. Operators dual to the fermions λ^i in the supergravity, transforming as **16**, are of the form $\mathrm{tr}(\Sigma\psi)$ [31,32]. These operators may be organized as $\mathrm{tr}(\Sigma^{1\pm}\psi(s_{12}, s_{34}))$ and $\mathrm{tr}(\Sigma^{2\pm}\psi(s_{12}, s_{34}))$ with $s_{12}, s_{34} = \pm 1/2$ on the basis of the $U(1)\times U(1)$ charges. Operators dual to each fermion in supergravity are given in Table I.

III. GREEN'S FUNCTION

In order to study Fermi surfaces in boundary theory we consider solutions of Dirac equations for spin-$1/2$ fermions λ^i in the supergravity theory. The Dirac equations for the eight spinors in the supergravity theory, in which we are interested, are given by [25]

$$\begin{aligned} &[i\Gamma^\mu\nabla_\mu - m(m_1e^{2\phi_1} + m_2e^{2\phi_2} + m_3e^{-4(\phi_1+\phi_2)}) \\ &\quad + 2m(q_1A^{(1)}_\mu + q_2A^{(2)}_\mu) \\ &\quad + i(p_1e^{-2\phi_1}F^{(1)}_{\mu\nu} + p_2e^{-2\phi_2}F^{(2)}_{\mu\nu})\Gamma^{\mu\nu}]\lambda^i(s_{12}, s_{34}) = 0, \end{aligned} \tag{3.1}$$

TABLE I. Charges, masses, Pauli terms coupling and dual operators corresponding to the fermionic modes.

No.	$\lambda^I(s_{12},s_{34})$	m_1	m_2	m_3	q_1	q_2	p_1	p_2	dual operator
1	$\lambda^{1-}(\frac{1}{2},\frac{1}{2})$	$\frac{3}{2}$	$-\frac{1}{2}$	$-\frac{1}{4}$	$\frac{3}{2}$	$\frac{1}{2}$	$-\frac{1}{4}$	$-\frac{1}{4}$	$\mathrm{tr}(\Sigma^{1-}\psi(\frac{1}{2},\frac{1}{2}))$
2	$\lambda^{1-}(\frac{1}{2},-\frac{1}{2})$	$\frac{3}{2}$	$-\frac{1}{2}$	$-\frac{1}{4}$	$\frac{3}{2}$	$-\frac{1}{2}$	$-\frac{1}{4}$	$\frac{1}{4}$	$\mathrm{tr}(\Sigma^{1-}\psi(\frac{1}{2},-\frac{1}{2}))$
3	$\lambda^{1+}(-\frac{1}{2},\frac{1}{2})$	$\frac{3}{2}$	$-\frac{1}{2}$	$-\frac{1}{4}$	$-\frac{3}{2}$	$\frac{1}{2}$	$\frac{1}{4}$	$-\frac{1}{4}$	$\mathrm{tr}(\Sigma^{1+}\psi(-\frac{1}{2},\frac{1}{2}))$
4	$\lambda^{1+}(-\frac{1}{2},-\frac{1}{2})$	$\frac{3}{2}$	$-\frac{1}{2}$	$-\frac{1}{4}$	$-\frac{3}{2}$	$-\frac{1}{2}$	$\frac{1}{4}$	$\frac{1}{4}$	$\mathrm{tr}(\Sigma^{1+}\psi(-\frac{1}{2},-\frac{1}{2}))$
5	$\lambda^{2-}(\frac{1}{2},\frac{1}{2})$	$-\frac{1}{2}$	$\frac{3}{2}$	$-\frac{1}{4}$	$\frac{1}{2}$	$\frac{3}{2}$	$-\frac{1}{4}$	$-\frac{1}{4}$	$\mathrm{tr}(\Sigma^{2-}\psi(\frac{1}{2},\frac{1}{2}))$
6	$\lambda^{2-}(-\frac{1}{2},\frac{1}{2})$	$-\frac{1}{2}$	$\frac{3}{2}$	$-\frac{1}{4}$	$-\frac{1}{2}$	$\frac{3}{2}$	$\frac{1}{4}$	$-\frac{1}{4}$	$\mathrm{tr}(\Sigma^{2-}\psi(-\frac{1}{2},\frac{1}{2}))$
7	$\lambda^{2+}(\frac{1}{2},-\frac{1}{2})$	$-\frac{1}{2}$	$\frac{3}{2}$	$-\frac{1}{4}$	$\frac{1}{2}$	$-\frac{3}{2}$	$-\frac{1}{4}$	$\frac{1}{4}$	$\mathrm{tr}(\Sigma^{2+}\psi(\frac{1}{2},-\frac{1}{2}))$
8	$\lambda^{2+}(-\frac{1}{2},-\frac{1}{2})$	$-\frac{1}{2}$	$\frac{3}{2}$	$-\frac{1}{4}$	$-\frac{1}{2}$	$-\frac{3}{2}$	$\frac{1}{4}$	$\frac{1}{4}$	$\mathrm{tr}(\Sigma^{2+}\psi(-\frac{1}{2},-\frac{1}{2}))$

where we introduce parameters m_1, m_2, m_3, q_1, q_2, p_1 and p_2. The values of the parameters for different fermions in supergravity theory are summarized in Table I. We will use the following simplification as explained in detail in [25]. By introducing suitable Γ matrices and t and x dependences, as $\lambda^i = e^{-A(r)}h(r)^{-1/4}e^{-i\omega t+ikx}\binom{\psi^i}{\eta^i}$ one can see both four-component spinors, ψ^i and η^i satisfy the same equation and so it is sufficient to study the equations satisfied by ψ^i. Choosing

$$\psi^i = \begin{pmatrix}\psi^i_1\\ \psi^i_2\end{pmatrix}, \qquad \psi^i_\alpha = \begin{pmatrix}\psi^i_{\alpha-}\\ \psi^i_{\alpha+}\end{pmatrix}, \qquad \alpha = 1,2, \tag{3.2}$$

where ψ^i_α are two-component spinors the equations reduce to the following form (suppressing i index):

$$\begin{aligned}
&(\partial_r + X\sigma_3 + Yi\sigma_2 + Z\sigma_1)\psi_\alpha = 0,\\
&\text{where } X = m\frac{e^B}{\sqrt{h}}M(\phi_1,\phi_2), \qquad Y = -\frac{e^{B-A}}{\sqrt{h}}u(r),\\
&Z = -\frac{e^{B-A}}{\sqrt{h}}[(-1)^\alpha k - v(r)],\\
&\text{and} \quad M(\phi_1,\phi_2) = (m_1e^{2\phi_1} + m_2e^{2\phi_2} + m_3e^{-4(\phi_1+\phi_2)})\\
&u(r) = \frac{1}{\sqrt{h}}[\omega + 2m(q_1A_t^{(1)} + q_2A_t^{(2)})]\\
&v(r) = 2e^{-B}[p_1e^{-2\phi_1}F_{rt}^{(1)} + p_2e^{-2\phi_2}F_{rt}^{(2)}].
\end{aligned} \tag{3.3}$$

One can observe, changing the value of α is associated with flipping of the sign of k. Therefore, if for one value of α it admits a Fermi surface at $k = k_F$, for the other value of α, the Fermi surface will appear at $k = -k_F$, provided other parameters remain the same. So one can choose a specific value of α without loss of generality.

Since the fermions have oscillatory behavior at the near horizon limit, following [18], we introduce the following quantities, termed as generalized fluxes. Unlike the fermions, these generalized fluxes have nonoscillatory behavior near the horizon:

$$\begin{aligned}
&U_\pm = \psi_- \pm i\psi_+, \qquad \mathcal{F} = |U_+|^2 - |U_-|^2\\
&\mathcal{I} = U_+U_-^* + U_+^*U_-, \qquad \mathcal{J} = i(U_+U_-^* - U_+^*U_-),\\
&\mathcal{K} = |U_+|^2 + |U_-|^2.
\end{aligned} \tag{3.4}$$

The equations satisfied by the generalized fluxes, as follows from (3.3) are

$$\begin{aligned}
&\partial_r\mathcal{F} = 0, \qquad \partial_r\mathcal{I} = 2Y\mathcal{J} - 2X\mathcal{K},\\
&\partial_r\mathcal{J} = -2Y\mathcal{I} + 2Z\mathcal{K}, \qquad \partial_r\mathcal{K} = -2X\mathcal{I} + 2Z\mathcal{J}.
\end{aligned} \tag{3.5}$$

At the near horizon limit, behaviors of fermion fields [33] for any specific α are given by

$$\psi_- = i\psi_+ = \frac{i}{2}(r-r_h)^{-\frac{i\omega}{4\pi T}}, \tag{3.6}$$

along with corrections of order $\sqrt{r-r_h}$. Leading order behavior of the generalized fluxes at the near horizon limit follows from (3.5) and near horizon expansion of X, Y and Z [25], as given by

$$\mathcal{F} = 1, \quad \mathcal{I} = i_1\sqrt{r-r_h}, \quad \mathcal{J} = j_1\sqrt{r-r_h}, \quad \mathcal{K} = 1, \tag{3.7}$$

where i_1 and j_1 depend on ω, k, r_h and parameters associated with fermions.

At the asymptotic limit $r\to\infty$, behavior of the fermions is given by [25]

$$\psi_+ = Ar^{\frac{3}{2}} + Br^{-\frac{5}{2}}, \qquad \psi_- = Cr^{\frac{1}{2}} + Dr^{-\frac{3}{2}}. \tag{3.8}$$

Using (3.4), one can relate the asymptotic behaviors of generalized fluxes with the coefficients, A, B, C and D, given in (3.8). In particular, we obtain the following expressions:

$$\mathcal{F}_0 = 2i(AD^* - A^*D) = 1, \qquad \mathcal{J}_0 = -2(A^*D + AD^*),$$
$$\mathcal{K}_3 = 2|A|^2 = -\mathcal{I}_3, \tag{3.9}$$

where the subscript in the coefficient refers to the power of r in the asymptotic expansion.

The expression of Green's function depends on the coefficients in the asymptotic expansion in (3.8). It is given by

$$G_R = \frac{D}{A}, \tag{3.10}$$

and it is retarded because of in-falling boundary condition. The imaginary and real parts of Green's function are given by

$$\mathcal{I}m(G_R) = \frac{1}{2i}\frac{A^*D - AD^*}{|A|^2} = \frac{1}{2\mathcal{K}_3},$$
$$\mathcal{R}e(G_R) = \frac{1}{2}\frac{A^*D + AD^*}{|A|^2} = -\frac{\mathcal{J}_0}{2\mathcal{K}_3}. \tag{3.11}$$

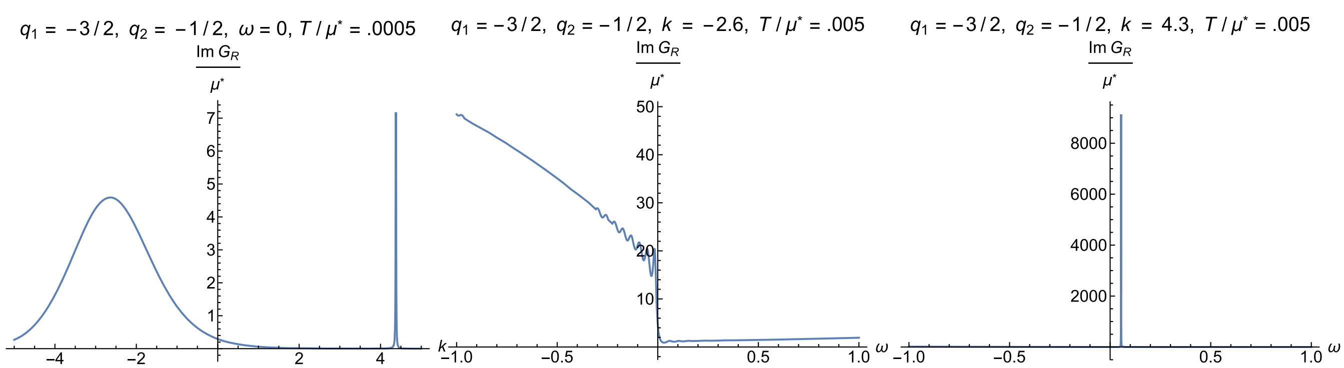
In general, the Green's function according to our notation is a 2×2 matrix $G_{\alpha\beta}$. However, in the present case it turns out to be diagonal. We will be considering G_{11}, corresponding to $\alpha = 1$. Changing the value of α would correspond to flipping of the sign of Fermi momentum as mentioned earlier.

IV. RESULTS

In the present section we have studied spectral function associated with the operators dual to the fermions in the supergravity theory, given in the Table I. All eight fermions are charged with respect to both the $U(1)$ gauge fields. As explained in [25], the different fermionic modes are related to each other through interchanging of charge parameters Q_1 and Q_2 and flipping of the sign of q_i and p_i associated with alteration of signs of k and ω. For the general background, where both charge parameters Q_1 and Q_2 are nonzero, we have discussed the result only for two different modes, namely, $q_1 = -3/2$, $q_2 = -1/2$ and $q_1 = -3/2$, $q_2 = 1/2$. For the other modes in this background, behaviors are similar. We have termed these as two-charge cases. For each of the two modes, setting $m = 2$ we numerically solve (3.3) subject to the boundary condition (3.7) and obtain ImG_R using (3.11). In addition, we have studied the spectral function for fermions in the background with one charge, as well. This background is obtained by setting one of the charge parameters, $Q_2 = 0$, and then using a similar procedure we examined the modes with $q_1 = 3/2$, $q_2 = 1/2$ and $q_1 = 1/2$, $q_2 = 1/2$. Once again, due to symmetry, other modes in Table I have similar behaviors. We have termed these as one-charge cases. It may be mentioned that, since $Q_2 = 0$ does not admit an extremal limit, Fermi surfaces of one-charge cases can only be studied at finite temperature.

In order to see the existence of Fermi surface at finite temperature we have used the following criteria [18]. If there is a Fermi surface at a certain value of $k = k_F$, it shows up as a peak in the spectral function for $\omega = 0$ around k_F, which has a width small enough compared to the temperature. Furthermore, if we plot the spectral function vs ω at $k = k_F$ that should show a peak near $\omega = 0$, which is consistent with quasiparticle. Furthermore, the maximum value of the spectral function at $\omega = 0$ should be large enough. Since the underlying theory is conformal, we considered ratio of spectral function and $\mu^* = \sqrt{T^2 + \mu_1^2 + \mu_2^2}$ in the plots.

We have studied Fermi surfaces for the two-charge cases at zero temperature in [25]. We found the operator dual to the fermionic mode with $q_1 = -3/2$, $q_2 = -1/2$ admits two Fermi surfaces; one of the Fermi surfaces is in the Fermi liquid regime while the other one is in the non-Fermi liquid regime, both approaching marginal Fermi liquid as Q_1 approaches infinity. The operator dual to the mode with charges $q_1 = -3/2$, $q_2 = 1/2$ admits one Fermi surface, which is partly in the Fermi liquid regime and partly in the non-Fermi liquid regime.



(a) ImG_R vs. k (b) ImG_R vs. ω (c) ImG_R vs. ω

FIG. 1. Spectral function for fermionic mode with $q_1 = -3/2, q_2 = -1/2$, $Q_1^2/r_h^4 = 10$.

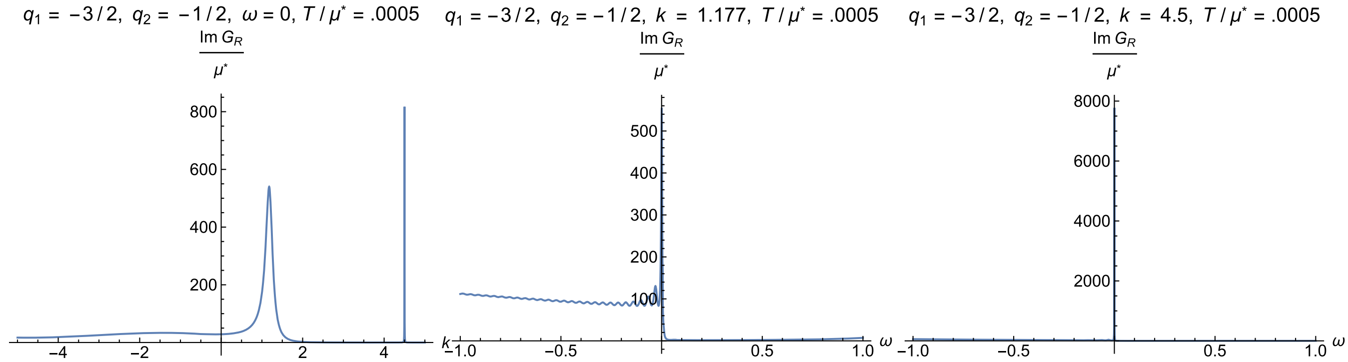


FIG. 2. Spectral function for fermionic mode with $q_1 = -3/2, q_2 = -1/2$ for $Q_1^2/r_h^4 = 2$.

At finite temperature, we begin with $q_1 = -3/2$, $q_2 = -1/2$ at $T = 0.0005$. In order to demonstrate the dependence on the charge parameters we have considered two different values, $Q_1^2/r_h^4 = 10$ and $Q_1^2/r_h^4 = 2$. For $Q_1^2/r_h^4 = 10$, spectral function at $\omega = 0$, as shown in Fig. 1, shows two peaks at around two different k values, $k_1 = -2.6$ and $k_2 = 4.3$. Clearly, the former peak is quite broad while the latter is sharp indicating that the former does not correspond to a Fermi surface while the latter does. Looking into the zero temperature behavior [25] one can observe at that value of charge parameter, there is only one branch that admits the Fermi surface, while the other branch has entered the oscillatory region. Plots of spectral function vs ω for $k_1 = -2.6$ and $k_2 = 4.3$ as given in Fig. 1 confirm this, as the former does not have a sharp peak around $\omega = 0$. For $Q_1^2/r_h^4 = 2$, the plot of spectral function vs k is given in Fig. 2, where it shows two sharp peaks at $k_1 = 1.177$ and $k_2 = 4.5$, indicating existence of two Fermi surfaces. Plots of spectral function vs ω at those values of k are given in Fig. 2, showing peaks at around $\omega = 0$, establishing the fact that both correspond to Fermi surfaces. This also confirms the result obtained at $T = 0$ [25], that at this value of charge parameter, there are two Fermi surfaces.

We have plotted the spectral function for the operator dual to the fermionic mode with charges $q_1 = -3/2, q_2 = 1/2$ at the same temperature at $T = 0.0005$. For $Q_1^2/r_h^4 = 10$ and $Q_1^2/r_h^4 = 2$ plots are given in Figs. 3 and 4, respectively. As one can observe, it has a single peak in both cases, at $k = -0.1572$ and at $k = 3.054$ for $Q_1^2/r_h^4 = 10$ and $Q_1^2/r_h^4 = 2$, respectively. This implies that the mode admits a single Fermi surface for both values, which is consistent with the result obtained in the $T = 0$ analysis. For both values of charge parameter, it shows the peak of spectral function around $\omega = 0$ at respective k values.

We have extended this analysis to one-charge cases, by setting $Q_2 = 0$. We first consider the operator dual to the mode with $q_1 = 3/2$, $q_2 = 1/2$ and plotted the spectral function vs k at $\omega = 0$. As is apparent from Fig. 5, it is showing a peak at around $k = -0.899$. Plotting the spectral function vs ω at $k = -0.899$, we find a peak around $\omega = 0$ and so we conclude this mode admits a Fermi surface. Similar plots for the operators, dual to the fermionic mode with $q_1 = 1/2$, $q_2 = 3/2$ are given in Fig. 6. While considering the plot vs k, it does show a peak at $k = 0.451$. However, the ω plot at that k value does not show any peak at all around $\omega = 0$. Therefore we can conclude, for operator dual to the mode with charges $q_1 = 1/2$, $q_2 = 3/2$ there exists no Fermi surface.

From the results of the two-charge cases, it appears fermions with higher charge tend to have Fermi surfaces.

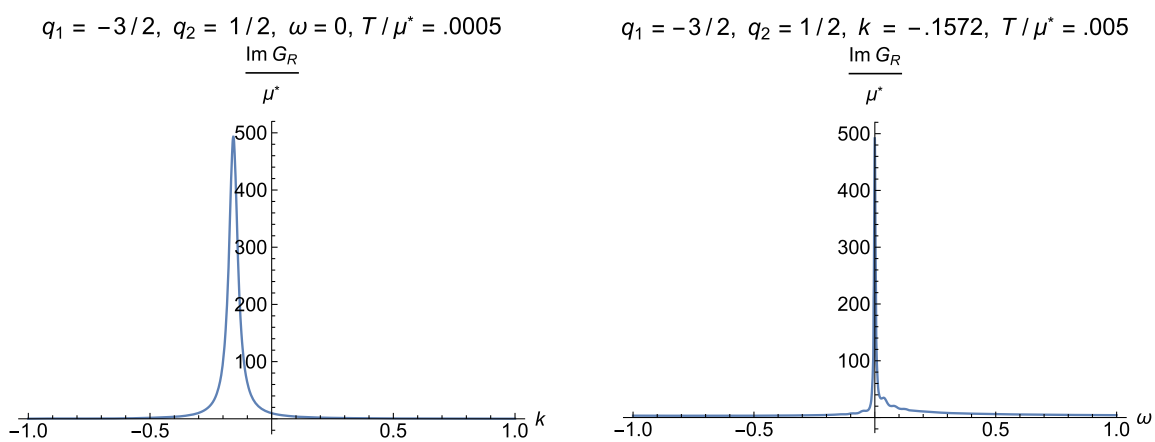


FIG. 3. Spectral function for fermionic mode with $q_1 = -3/2, q_2 = 1/2$ for $Q_1^2/r_h^4 = 10$.

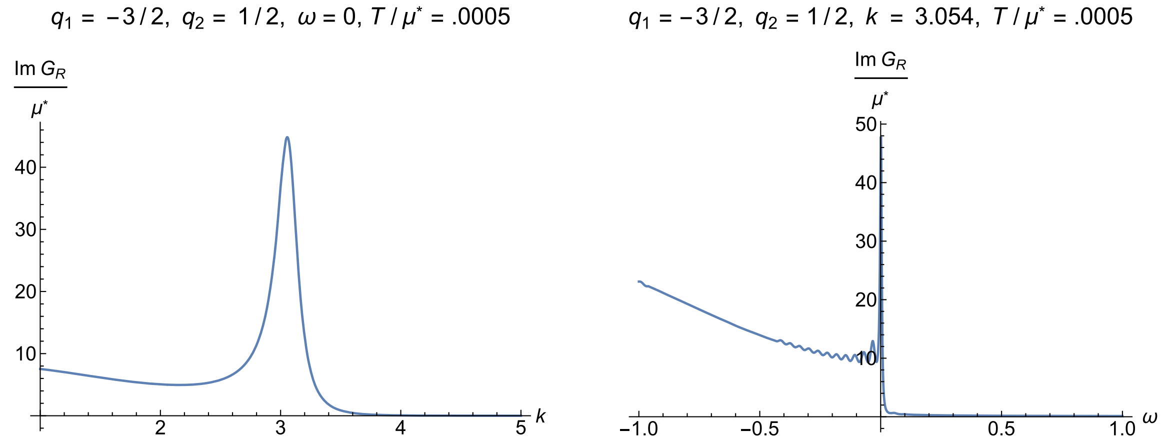


FIG. 4. Spectral function for fermionic mode with $q_1 = -3/2, q_2 = 1/2$ for $Q_1^2/r_h^4 = 2$.

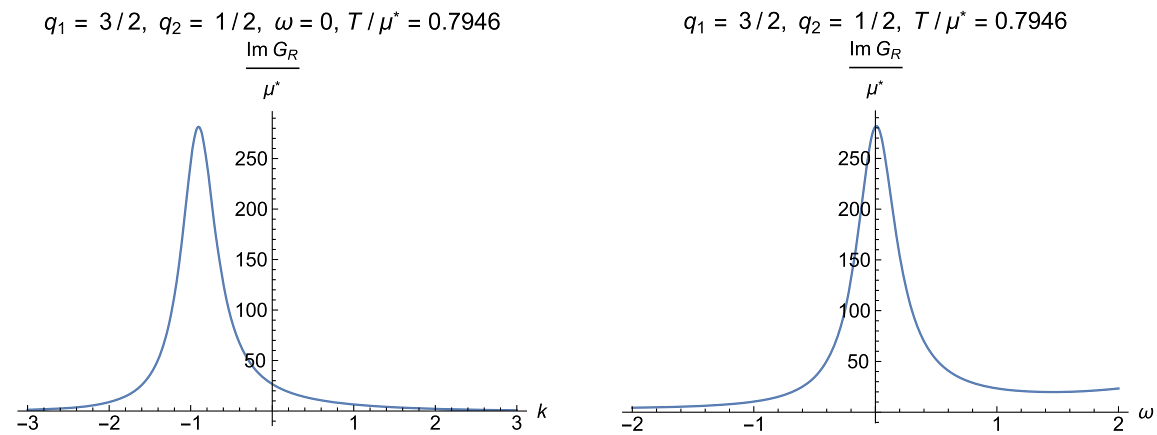


FIG. 5. Spectral function $q_1 = 3/2$, $q_2 = 1/2$. The left figure is at $\omega = 0$ and the right figure is the plot vs ω.

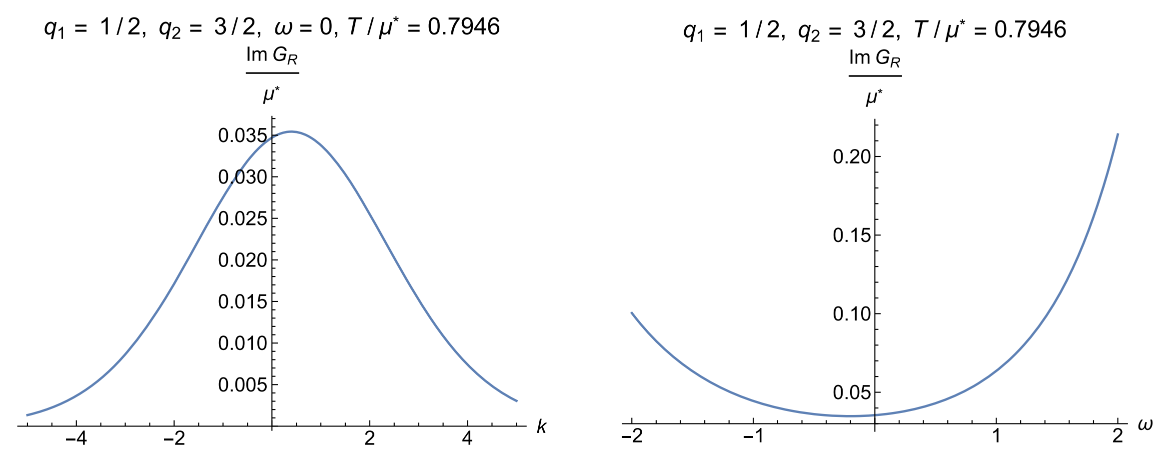


FIG. 6. Spectral function $q_1 = 1/2$, $q_2 = 3/2$. The left figure is at $\omega = 0$ and the right figure is the plot vs ω.

In particular, operators involving gauginos $\psi(\pm 1/2, \pm 1/2)$ have two Fermi surfaces, while operators involving gauginos $\psi(\pm 1/2, \mp 1/2)$ have one Fermi surface. So it seems that it is the gauginos that determine the nature of the Fermi surface admitted by the operator. In order to understand the role played by the scalars in the dual field theory we consider the relation between ϕ_1 and ϕ_2 in the supergravity and the scalar operator in the dual field theory. Our solution has a $U(1) \times U(1)$ symmetry that rotates phases of $\Sigma^{1\pm}$ and $\Sigma^{2\pm}$ respectively. This implies distribution of the $M5$-branes should be symmetric in the large N limit. In terms of Σ^i, $i = 1, 2, \ldots 5$ (they are related to $\Sigma^{1\pm}$ and $\Sigma^{2\pm}$

through $\Sigma^{1\pm} = \Sigma^1 \pm i\Sigma^2, \Sigma^{2\pm} = \Sigma^3 \pm i\Sigma^4$ [25]) this implies the scalar operators in the dual field theory satisfy $\mathrm{tr}((\Sigma^1)^2) = \mathrm{tr}((\Sigma^2)^2)$ and $\mathrm{tr}((\Sigma^3)^2) = \mathrm{tr}((\Sigma^4)^2)$, which we call $\mathrm{tr}(\Sigma_A^2)$ and $\mathrm{tr}(\Sigma_B^2)$ respectively, while we write $(\Sigma^5)^2 = \Sigma_C^2$. In presence of this symmetry, the operators dual to the supergravity field ϕ_1 and ϕ_2 are given by [34]

$$\mathcal{O}_{\phi_1} \sim \frac{1}{5}\mathrm{tr}(-3\Sigma_A^2 + 2\Sigma_B^2 + \Sigma_C^2) \quad \text{and}$$
$$\mathcal{O}_{\phi_2} \sim \frac{1}{5}\mathrm{tr}(2\Sigma_A^2 - 3\Sigma_B^2 + \Sigma_C^2). \tag{4.1}$$

From the asymptotic expansion of ϕ_1 and ϕ_2, as given in supergravity solution (2.3), one can see for the one-charge case, where we set $Q_2 = 0$, $\langle\mathcal{O}_{\phi_1}\rangle$ is negative and $\langle\mathcal{O}_{\phi_2}\rangle$ is positive. This implies Σ_A, or in other words $\Sigma^{1\pm}$ has a nonzero expectation value. From our analysis given above we find that the operators involving $\Sigma^{1\pm}$ give rise to the Fermi surface, while operators involving $\Sigma^{2\pm}$ do not admit one. It suggests that expectation values of the scalars appearing in the dual operator play a role in determining the Fermi surface. A similar result has been found in $N = 4$ SYM and the ABJM model [18]. It may be mentioned that in the present case the near horizon geometry is AdS_2 with a nonzero entropy at $T = 0$, while the models discussed in [18] have vanishing zero entropy, and so this feature seems to be quite general. In the cases where both charge parameters are nonzero, it is plausible to assume that both $\Sigma^{1\pm}$ and $\Sigma^{2\pm}$ have nonzero expectation value in general, giving rise to Fermi surface(s) for all the operators.

V. DISCUSSION

To summarize, we have studied the Fermi surface in the six-dimensional (2, 0) theory at finite temperature, both for two charge parameters and one charge parameter. In the case of two charge parameters we find operators dual to the fermionic modes with higher charge are more likely to admit the Fermi surface, confirming the result we obtained in the zero temperature analysis. We find the one with higher charge admits two Fermi surfaces, while the one with less charge admits one. It appears the Fermi surface associated with dual operator of the form $\mathrm{tr}(\Sigma\psi)$ depends on the charge of the gaugino ψ. At finite temperature, we have extended the analysis to the cases of one-charge, obtained by setting one of the charge parameters equal to zero. We considered all the fermionic modes and found that only operators dual to some of the modes are admitting the Fermi surface while others do not. By analyzing the dual field theory, we find if the background corresponds to a nonzero expectation value of the scalar, the corresponding operator admits the Fermi surface. On the other hand when both the charge parameters are nonzero, probably all the scalars have expectation values and dual operators associated with all the fermionic modes, as we have seen in the present model, admit one or more Fermi surface. If that is the case as explained elsewhere [18], it is the colored gaugino that gives rise to the singularity associated with Fermi surface. However, there are counter examples [18] found in the analysis of $N = 4$ SYM [16] and so understanding the roles of scalar operators requires more study.

As explained above, obtaining a clear picture regarding roles played by various operators in the dual field theory in the context of Fermi surfaces requires models amenable to more precise and detailed analysis. The Luttinger count of charge density may also shed light on it [15]. In the present work, we have considered only those fermionic modes, which do not couple to gravitini in supergravity theory. An analysis of other modes, as well as that of the gravitini itself, may lead to further insight into the dual field theory. In the earlier work [25] we have observed that in the two-charge cases, for limiting values of the charge parameters, the dual field theory is in the regime of marginal Fermi liquid. Optimally doped cuprates [35] are thought to be examples of marginal Fermi liquid and so it will be interesting to extend the study for such limiting values of charge parameters. A study of transport phenomena at finite temperature for the present model may also lead to better understanding. Finally, a thermodynamic analysis may illuminate stability issues of the present model. In five dimensions similar black hole solutions show instability through development of charge density leading to spontaneous breaking of $SU(2) \subset SO(6)$ and translational invariance [36]. In the present case, the theory has an $SO(5)$ symmetry and it may be interesting to see whether similar symmetry breaking may render it unstable.

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