Pseudogap phase and duality in a holographic fermionic system with dipole coupling on a Q-lattice (postprint)

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Abstract

We classify the different phases by the "pole-zero mechanism" for a holographic fermionic system which contains a dipole coupling with strength p on a Q-lattice background. A complete phase structure in pspace can be depicted in terms of Fermi liquid, non-Fermi liquid, Mott phase and pseudo-gap phase. In particular, we find that in general the region of the pseudo-gap phase in p space is suppressed when the Q-lattice background is dual to a deep insulating phase, while for an anisotropic background, we have an anisotropic region for the pseudo-gap phase in p space as well. In addition, we find that the duality between zeros and poles always exists regardless of whether or not the model is isotropic.

Full Text

Preamble

The Pseudo-Gap Phase and Duality in Holographic Fermionic Systems with Dipole Coupling on Q-Lattice

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Abstract

We classify different phases using the "pole-zero mechanism" for a holographic fermionic system with dipole coupling of strength p on a Q-lattice background. A complete phase structure in the p-parameter space can be described in terms of Fermi liquid, non-Fermi liquid, Mott phase, and pseudo-gap phase. In particular, we find that the region of the pseudo-gap phase is generally suppressed when the Q-lattice background is dual to a deep insulating phase. For an anisotropic background, the pseudo-gap phase region in p-space becomes anisotropic as well.

In addition, we find that the duality between zeros and poles persists regardless of whether the model is isotropic or not.

Keywords: Holographic Q-lattice, "pole-zero mechanism" , Fermionic system
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Introduction

A general theoretical framework for quantum phases and phase transitions in strongly correlated electron systems, such as cuprates and other oxides, has not yet been established. The AdS/CFT correspondence [1–3] provides a powerful alternative approach to address these strongly correlated problems and gain insight into the fundamental principles underlying these complex electron systems.

Indeed, exotic states of matter including Fermi liquid, non-Fermi liquid, Mott phase, and pseudo-gap phase have been identified using AdS/CFT correspondence [4–11]. By adding a probe fermion to an RN-AdS background, a non-linear dispersion relation emerges [5], indicating a non-Fermi liquid phase. Additionally, the low-energy behavior of fermionic systems on RN-AdS backgrounds is controlled by the AdS near-horizon geometry [6]. Later studies extensively investigated fermionic systems on Gauss-Bonnet, Lifshitz, and hyperscaling violation geometries [12–21]. Furthermore, dipole coupling between the gauge field and Dirac field can model the Mott phase [8, 9], with extended studies exploring dipole coupling effects in more general geometries [22–28].

Recently, the "pole-zero mechanism" has been used to detect a pseudo-gap phase in holographic fermionic systems with dipole coupling in both RN-AdS and Schwarzschild-AdS black holes [10, 11]. Remarkably, a duality between zeros and poles was observed in these systems [10], which should interest experimental condensed matter physicists, although this phenomenon has not yet been experimentally verified. In this paper, we investigate the pseudo-gap phase and duality in a holographic fermionic system with dipole coupling on Q-lattice geometry.

Motivated by Q-balls [29], a Q-lattice model in a holographic framework was first constructed in [30], where translational symmetry was broken in both spatial directions and a metal-insulator transition was observed through optical conductivity studies. Subsequent work explored various aspects of this framework [31–

37]. In [35], we studied a holographic fermionic system with dipole coupling on Q-lattice geometry and found that a Mott gap opens when the dipole coupling parameter p exceeds a critical value p_c. Interestingly, the Mott gap opens more readily when the Q-lattice background is dual to a deep insulating phase rather than a metallic phase. Here, we probe the pseudo-gap phase in this system using the "pole-zero mechanism" and examine how lattice parameters affect pseudo-gap formation.

Our paper is organized as follows. Section II provides a brief review of holographic Q-lattice geometry and the Dirac equation. Section III presents our main results on quantum phase classification for isotropic Q-lattice geometry, focusing on the pseudo-gap phase and lattice parameter effects. Section IV extends this analysis to anisotropic Q-lattice geometry. Finally, Section V concludes with a discussion.

II. Holographic Q-Lattice Geometry and the Dirac Equation

We introduce the holographic Q-lattice model that breaks translational symmetry in both spatial directions and demonstrate how to simplify the Dirac equation over a specific Q-lattice background. For detailed discussions, see [30, 34, 35].

The action with Q-lattice structure in both spatial directions is:

$$S = \int d^4x\sqrt{-g}\left[R + 6 - \frac{1}{4}F^2 - |\partial\phi_1|^2 - m_1^2|\phi_1|^2 - |\partial\phi_2|^2 - m_2^2|\phi_2|^2\right]$$

where $F = dA$, and ϕ_1 and ϕ_2 are complex scalar fields simulating the lattices. The equations of motion are:

$$R_{\mu\nu} = g_{\mu\nu}\left(-3 + \frac{1}{4}(|\phi_1|^2 + |\phi_2|^2)\right) + \frac{1}{2}(F_{\mu\rho}F_\nu{}^\rho - \frac{1}{4}g_{\mu\nu}F^2) + \frac{1}{2}(\partial_\mu\phi_1\partial_\nu\phi_1^* + \partial_\mu\phi_2\partial_\nu\phi_2^*)$$

$$(\nabla^2 - m_1^2)\phi_1 = 0, \quad (\nabla^2 - m_2^2)\phi_2 = 0, \quad \nabla_\mu F^{\mu\nu} = 0$$

To find solutions, we use the ansatz:

$$ds^2 = -g_{tt}(z)dt^2 + g_{zz}(z)dz^2 + g_{xx}(z)dx^2 + g_{yy}(z)dy^2$$

$$\phi_1 = e^{ik_1x}\varphi_1(z), \quad \phi_2 = e^{ik_2y}\varphi_2(z), \quad A = A_t(z)dt$$

with:

$$g_{tt}(z) = \frac{(1-z)P(z)}{z^2 Q(z)}, \quad g_{zz}(z) = \frac{1}{z^2(1-z)P(z)Q(z)}$$

$$g_{xx}(z) = V_1(z), \quad g_{yy}(z) = V_2(z), \quad A_t(z) = \mu(1-z)a(z)$$

$$P(z) = 1 + z + z^2 - \frac{\mu^2 z^3}{12}, \quad Q(z) = \exp\left(\int_0^z \frac{\varphi_1^2(s) + \varphi_2^2(s)}{2s(1-s)P(s)} ds\right)$$

where k_1 and k_2 are wave-numbers along the x and y directions, making $\phi_{1,2}$ periodic with lattice constants $2\pi/k_{1,2}$. We set $m_{1,2}^2 = -5/4$ to avoid violating the AdS BF bound near the horizon.

This ansatz yields five second-order ODEs for $V_1, V_2, a, \varphi_1, \varphi_2$ and one first-order ODE for Q. Numerical solutions impose regular boundary conditions at the horizon $z = 1$ and the following conditions at the conformal boundary:

$$Q(0) = 1, \quad V_1(0) = V_2(0) = 1, \quad a(0) = 1$$

We focus on standard quantization where the scalar fields have asymptotic behavior:

$$\varphi_{1,2} = \lambda_{1,2} z^{\Delta_{1,2}^-} + \cdots$$

with UV behavior corresponding to Q-lattice deformation with amplitude $\lambda_{1,2}$, where $\Delta_{1,2}^{\pm} = 3/2 \pm \sqrt{9/4 + m_{1,2}^2}$ is the scaling dimension of the dual operator. The Hawking temperature is:

$$T = \frac{3P(1)Q(1)}{4\pi}$$

Thus, each Q-lattice solution is specified by five dimensionless quantities: T/μ, $\lambda_1/\mu^{\Delta_1^-}$, $\lambda_2/\mu^{\Delta_2^-}$, k_1/μ, and k_2/μ. For simplicity, we abbreviate these as T, $\lambda_{1,2}$, and $k_{1,2}$.

Now we introduce the Dirac equation with dipole coupling on this Q-lattice geometry. The action for the spinor field interacting with the gauge field is:

$$S_D = \int d^4x \sqrt{-g}\, \bar{\zeta} \left(i\Gamma^a D_a - m_\zeta - ip\Gamma^{\mu\nu} F_{\mu\nu} \right) \zeta$$

where $D_a = \partial_a + \frac{1}{4}(\omega_{\mu\nu})_a \Gamma^{\mu\nu} - iqA_a$ and $\Gamma^{\mu\nu} F_{\mu\nu} = \frac{1}{2}\Gamma^{\mu\nu}(e_\mu)^a (e_\nu)^b F_{ab}$, with $(e_\mu)^a$ forming an orthonormal basis and $(\omega_{\mu\nu})_a$ the spin connection 1-forms.

With the redefinition $\zeta = (g_{tt} g_{xx} g_{yy})^{-1/4} F$ and Fourier transform $F(z,k) \equiv (A_\alpha, B_\alpha)^T$ with $\alpha = 1,2$, and using gamma matrices:

$$\Gamma^z = \sigma_3 \otimes \sigma_3, \quad \Gamma^t = i\sigma_1 \otimes \mathbf{1}, \quad \Gamma^x = \sigma_2 \otimes \sigma_1, \quad \Gamma^y = -\sigma_2 \otimes \sigma_2$$

the Dirac equation simplifies to:

$$(\partial_z \mp m_\zeta \sqrt{g_{zz}})\, A_\alpha \pm \frac{(\omega + qA_t) \pm (-1)^\alpha k_x \sqrt{g_{xx}} \pm (-1)^\alpha k_y \sqrt{g_{yy}}}{\sqrt{g_{tt} g_{zz}}} A_\alpha + \frac{p\, \partial_z A_t}{\sqrt{g_{tt} g_{zz}}} B_\alpha = 0$$

$$(\partial_z \mp m_\zeta \sqrt{g_{zz}})\, B_\alpha \mp \frac{(\omega + qA_t) \pm (-1)^\alpha k_x \sqrt{g_{xx}} \pm (-1)^\alpha k_y \sqrt{g_{yy}}}{\sqrt{g_{tt} g_{zz}}} B_\alpha + \frac{p\, \partial_z A_t}{\sqrt{g_{tt} g_{zz}}} A_\alpha = 0$$

At the horizon $z = 1$, we impose the ingoing boundary condition:

$$\begin{pmatrix} A_\alpha \\ B_\alpha \end{pmatrix} = c_\alpha \begin{pmatrix} 1 \\ i \end{pmatrix} (1-z)^{-i\omega/4\pi T}$$

Near the boundary, the Dirac field behaves as:

$$\begin{pmatrix} A_\alpha \\ B_\alpha \end{pmatrix} \approx a_\alpha z^{m_\zeta} \begin{pmatrix} 0 \\ 1 \end{pmatrix} + b_\alpha z^{-m_\zeta} \begin{pmatrix} 1 \\ 0 \end{pmatrix}$$

The retarded Green' s function is obtained holographically as $a_\alpha = G_{\alpha\alpha'} b_{\alpha'}$. To compute the boundary Green' s function, we construct a basis of finite solutions (A_α^I, B_α^I) and $(A_\alpha^{II}, B_\alpha^{II})$ due to coupling between the four Dirac components.

III. Pseudo-Gap Phases and Duality on an Isotropic Q-Lattice

In condensed matter physics, poles ($k = k_F$) and zeros ($k = k_L$) in the Green' s function of strongly correlated fermionic systems compete with each other. The "pole-zero mechanism" classifies different phases of such systems [38-42]. The phase classification criteria are:

- **Poles** (Non-)Fermi liquid phase
- **Zeros** Mott insulator phase
- **Coexistence of poles and zeros** Pseudo-gap phase

This mechanism was first applied in a holographic framework in [10] to characterize different phases. Here, we use it to probe the pseudo-gap phase in our holographic fermionic system with dipole coupling on Q-lattice geometry. This section explores isotropic Q-lattices ($\lambda_1 = \lambda_2$ and $k_1 = k_2$), where we can set $k_y = 0$ without loss of generality. Anisotropic cases are discussed in the next section.

For definiteness, we fix $m = 0$, $q = 1$, and work at extremely low temperature $T \approx 0.00398$ throughout.

For $p = 0$, neither poles nor zeros appear in the determinant of the Green' s function $\det G_R$ because they cancel out (Fig. 1 [Figure 1: see original paper]). However, once dipole coupling is turned on, poles and zeros emerge in $\det G_R$, enabling phase classification via the pole-zero mechanism. Fig. 2 [Figure 2: see original paper] shows $\det G_R$ versus k_x at $\omega = 0$ for $p = -4.5$ and $p = 4.5$ with $\lambda_1 = \lambda_2 = 0.5$ and $k_1 = k_2 = 0.8$. For $p = -4.5$, a pole appears at $k_x = k_F \approx 1.222$, indicating a (non-)Fermi liquid state, while for $p = 4.5$, a zero appears at the same momentum $k_x = k_L \approx 1.222$, indicating a Mott state. Clearly, a duality exists between zeros and poles under $p \to -p$, first revealed in [10].

When the dipole coupling is decreased to $|p| = 0.1$, both poles and zeros coexist in $\det G_R$ (Fig. 3 [Figure 3: see original paper]), signaling a pseudo-gap phase. This duality persists under $p \to -p$ (Fig. 3). Based on these observations, we conclude that (non-)Fermi liquid, Mott, and pseudo-gap phases emerge in fermionic systems with dipole coupling on Q-lattices.

Using the density of states (DOS) $A(\omega)$, we can determine the critical point p_c for the (non-)Fermi liquid to Mott phase transition and confirm that the Mott gap opens more readily in deep insulating phases than in metallic phases [35]. We now focus on how lattice constants $k_{1,2}$ and amplitudes $\lambda_{1,2}$ affect the pseudo-gap phase.

Through careful numerical calculations, we find that a pseudo-gap emerges when $|p| \lesssim 0.605$ for $\lambda_1 = \lambda_2 = 0.5$ and $k_1 = k_2 = 0.8$. In a deep insulating phase with $\lambda_1 = \lambda_2 = 2$ and $k_1 = k_2 = 1/2^{3/2}$, the pseudo-gap phase appears for $|p| \lesssim 0.335$. Thus, the pseudo-gap region in p-space is suppressed in deep insulating phases.

For comparison, the pseudo-gap phase appears when $|p| \lesssim 0.634$ in the RN-AdS black hole background (obtained by setting $\lambda_1 = \lambda_2 = 0$)[1].

Before concluding this section, we discuss the duality between zeros and poles. With $k_y = 0$, the Dirac equations can be packaged into evolution equations:

$$\partial_z \xi_\alpha + \sqrt{g_{zz}}\, v_- \xi_\alpha + (-1)^\alpha k_x \frac{v_+ - (-1)^\alpha k_x}{\sqrt{g_{zz}}} \xi_\alpha = 0$$

where $\xi_\alpha \equiv A_\alpha / B_\alpha$ and $v_\pm = (\omega + qA_t) \pm p\sqrt{g_{tt}} \partial_z A_t$. For massless fermions, the retarded Green' s function is:

$$G(\omega, k) = \lim_{z \to 0} \xi_\alpha(z, \omega, k)$$

From the evolution equation, we find the symmetry:

$$G_{11}(\omega, k) = G_{22}(\omega, -k)$$

Introducing the reciprocal $\tilde{\xi}_\alpha = 1/\xi_\alpha$, we find it satisfies similar evolution equations with $p \to -p$. Combining these results reveals the duality between zeros and poles under $p \to -p$.

[1]We have set the gauge coupling constant $g_F = 1$ here, which differs from the convention $g_F = 2$ in [10]. Consequently, the charge q and dipole coupling p correspond to products $g_F q$ and $g_F p$ as the relevant quantities.

IV. Pseudo-Gap Phases and Duality on an Anisotropic Q-Lattice

We now investigate pseudo-gap phases and the duality between zeros and poles on anisotropic Q-lattices, with parameters $\lambda_1 = 1$, $\lambda_2 = 0.1$, and $k_1 = k_2 = 0.8$.

First, we explore duality along the k_x direction (setting $k_y = 0$). As shown in Fig. 4 [Figure 4: see original paper] and Fig. 5 [Figure 5: see original paper], (non-)Fermi liquid, Mott insulating, and pseudo-gap phases appear along k_x depending on the dipole coupling p. The duality persists, as understood through analysis similar to the previous section.

Similarly, we locate poles and zeros in $\det G_R$ along the k_y direction (setting $k_x = 0$) for $p = 6$ and $p = -6$. We find $k_y^F \approx 1.983$ for $p = -6$ and $k_y^L \approx 1.983$ for $p = 6$, confirming that duality holds in the y direction. However, $k_x^F \neq k_y^F$ (and $k_x^L \neq k_y^L$), reflecting the system' s anisotropy.

We find that the pseudo-gap phase emerges along k_x for $|p| \lesssim 0.393$, while along k_y it appears for $|p| \lesssim 0.860$. Clearly, the anisotropic geometry produces an anisotropic pseudo-gap region. Along the more insulating direction (k_x), the pseudo-gap region is suppressed, consistent with our isotropic Q-lattice results.

V. Conclusion and Discussion

Using the "pole-zero mechanism," we have classified phases in holographic fermionic systems with dipole coupling on Q-lattice geometry. These phases include Fermi liquid, non-Fermi liquid, Mott phase, and pseudo-gap phase, depending on the dipole coupling strength. Varying the dipole coupling parameter p thus induces quantum phase transitions in our holographic system.

While previous work [35] used spectral functions to determine the critical value p_c for the (non-)Fermi liquid to Mott phase transition and examined how lattice parameters $\lambda_{1,2}$ and $k_{1,2}$ affect Mott phase formation, we have further computed the determinant of the retarded Green' s function to focus on pseudo-gap phase formation. We find that the pseudo-gap region is suppressed in deep insulating phases. For anisotropic Q-lattice geometry, we obtain an anisotropic pseudo-gap region that is also suppressed along the insulating direction. Another interesting result is that the duality between zeros and poles, previously found in [10], persists in both isotropic and anisotropic Q-lattice geometries and is independent of lattice parameters.

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Note: Figure translations are in progress. See original paper for figures.