Holographic paramagnetic-ferromagnetic phase transition with Power-Maxwell electrodynamics

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We explore the effects of Power-Maxwell nonlinear electrodynamics on the properties of holographic s-wave paramagnetic-ferromagnetic phase transition in the background of Schwarzschild Anti-de Sitter (AdS) black hole. For this purpose, we introduce a massive 2-form coupled to the Power-Maxwell field. We perform the numerical shooting method in the probe limit by assuming the Power-Maxwell and the 2-form fields do not back react on the background geometry. We observe that increasing the strength of the power parameter causes the formation of magnetic moment in the black hole background harder and critical temperature lower. In the absence of external magnetic field and at the low temperatures, the spontaneous magnetization and the ferromagnetic phase transition happen. In this case, the critical exponent for magnetic moment is always 1/2 which is in agreement with the result from the mean field theory. In the presence of external magnetic field, the magnetic susceptibility satisfies the Cure-Weiss law.

I. INTRODUCTION

The AdS/CFT duality provides a correspondence between a strongly coupled conformal field theory (CFT) in \(d\)-dimensions and a weakly coupled gravity theory in \((d+1)\)-dimensional anti-de Sitter (AdS) spacetime \([1-3]\). Since it is a duality between two theories with different dimensions, it is commonly called holography. The idea of holography has been employed in the condensed matter physics to study the various phenomena such as superconductivity \([4-8]\). For describing the properties of low temperature superconductors, the BCS theory can work very well \([9, 10]\). The electronic properties of materials have been studied using the duality in strongly correlated systems. Recently, the magnetism also have been attracted the attentions about the duality application to the condensed matter physics. There are a few works in investigating the magnetism from the holographic superconductors point of view \([11-15]\). An example is the holographic paramagnetic-ferromagnetic phase transition in a dyonic Reissner-Nordstrom-AdS black brane which was introduced in Ref. \([16]\). This model gives a starting point for exploration of more complicated magnetic phenomena and quantum phase transition. It was considered that the magnetic moment could be realized by a real antisymmetric tensor field which is coupled to the background gauge field strength in the bulk. It was found that the spontaneous magnetization happens in the absence of external magnetic field, and it can be realized as the paramagnetic-ferromagnetic phase transition. This model was extended by introducing two antisymmetric tensor fields which correspond with two magnetic sublattices in the materials \([17]\). In the framework of usual Maxwell electrodynamics, holographic paramagnetism-ferromagnetism phase transition have been investigated \([17, 24]\). However, it is interesting to investigate the effects of nonlinear electrodynamics on the properties of the holographic paramagnetic-ferromagnetic phase transition. Considering three types of nonlinear electrodynamics, namely, Born-Infeld, logarithmic and exponential nonlinear electrodynamics, and using the numerical methods, it has been observed that in the Schwarzschild AdS black hole background, the higher nonlinear electrodynamics corrections make the magnetic moment harder to form in the absence of external magnetic field \([25, 26]\). Although, the properties of holographic superconductor with conformally invariant Power-Maxwell electrodynamics have been studied in \([27-31]\), the properties of holographic paramagnetic-ferromagnetic phase transition coupled to the Power-Maxwell field have not been explored yet. In this paper, we are going to extend the study on the holographic paramagnetic-ferromagnetic phase transition by taking into account the nonlinear Power-Maxwell electrodynamics. In particular, we shall investigate how the Power-Maxwell electrodynamics influence the critical temperature and magnetic moment. Interestingly, we find that the effect of sublinear Power-Maxwell field can lead to the easier formation of the magnetic moment at higher critical temperature. We shall focus on 4D and 5D holographic paramagnetic-ferromagnetic phase transition in probe limit by neglecting the back reaction of both gauge and the 2-form fields on the background geometry. We employ the numerical shooting method to investigate the features of our holographic model.

This paper is organized as follows. In section \([11]\) we introduce the action and basic field equations in the presence of Power-Maxwell electrodynamics. In section \([11]\) we employ the shooting method for our numerical calculation and

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obtain the critical temperature and magnetic moment. In that section, we also study the magnetic susceptibility density. In the last section, we summarize our results.

II. HOLOGRAPHIC SET-UP

We consider a holographic ferromagnetism model in Einstein gravity in a $d$-dimensional AdS spacetime which is given by the action,

$$ S = \frac{1}{2\kappa^2} \int d^dx \sqrt{-g} \left( R - 2\Lambda + L_1 (F) + \lambda^2 L_2 \right), $$

where $\kappa^2 = 8\pi G$ with $G$ is Newtonian gravitational constant, $g$ is the determinant of metric, $R$ is Ricci scalar and $\Lambda = -(d-1)(d-2)/2l^2$ is the cosmological constant of $d$–dimensional AdS spacetime with radius $l$. $L_1 (F) = -(F)^{a}/4$, where $F = F_{\mu\nu}F^{\mu\nu}$ in which $F_{\mu\nu} = \nabla_{[\mu}A_{\nu]}$ and $A_{\mu}$ is the gauge potential of U(1) gauge field and $\alpha$ is the power parameter of the Power-Maxwell field. In the case where $\alpha$ tend to zero the Power-Maxwell Lagrangian will reduce to the Maxwell case ($L_1 \rightarrow -F_{\mu\nu}F^{\mu\nu}/4$) and the Einstein-Maxwell theory is recovered. Besides, for $\alpha = d/4$, the energy-momentum tensor of the Power-Maxwell Lagrangian is traceless in all dimension and the theory is conformally invariant [32]. $L_2$ is defined as [20].

$$ L_2 = -\frac{1}{12}(dM)^2 - \frac{m^2}{4}M_{\mu\nu}M^{\mu\nu} - \frac{1}{2}M^{\mu\nu}F_{\mu\nu} - \frac{J}{8}V(M), $$

where $\lambda$ and $J$ are two constants with $J < 0$ for producing the spontaneous magnetization and $\lambda^2$ characterizes the back reaction of the two polarization field $M_{\mu\nu}$ and the Maxwell field strength on the background geometry. In addition, $m$ is the mass of 2-form field $M_{\mu\nu}$ being greater than zero [20] and $dM$ is the exterior differential 2-form field $M_{\mu\nu}$. The nonlinear potential of 2-form field $M_{\mu\nu}$, $V(M_{\mu\nu})$, describes the self interaction of polarization tensor which should be expanded as the even power of $M_{\mu\nu}$. In this model, we take the following form for the potential

$$ V(M) = (M_{\mu\nu}M^{\mu\nu})^2 = (\ast (M \wedge M))^2, $$

where $\ast$ is the Hodge star operator. We choose this form just for simplicity. This potential shows a global minimum at some nonzero value of $\rho$ [20].

Varying the action (1) with respect to $M_{\mu\nu}$ and $A_\nu$, the field equation read, respectively,

$$ 0 = \nabla_{\tau}(dM)_{\tau\mu\nu} - m^2 M_{\mu\nu} - J(\ast M_{\tau\sigma}M^{\tau\sigma})(\ast M_{\mu\nu}) - F_{\mu\nu} $$

$$ 0 = \nabla_{\mu} \left( \alpha F_{\mu\nu}(F)^{\alpha-1} + \frac{\lambda^2}{4}M_{\mu\nu} \right). $$

In the probe limit, we can neglect the back reaction of the 2-form field. As the background geometry, we consider the $d$–dimensional Schwarzschild AdS black hole which its metric reads

$$ ds^2 = L^2 \left( -r^2 f(r)dt^2 + \frac{dr^2}{r^2 f(r)} + r^2 \sum_{i=1}^{d} dx_i^2 \right), $$

with

$$ f(r) = 1 - \left( \frac{r_+}{r} \right)^{d-1}, $$

where $r_+$ is the event horizon radius of the black hole. The Hawking temperature of black hole on the horizon which will be interpreted as the temperature of CFT, is given by [33]

$$ T = \frac{f'(r_+)}{4\pi} = \frac{(d-1)r_+}{4\pi}, $$

In order to explore the effects of the power parameter $\alpha$ on the holographic ferromagnetic phase transition, we take the self-consistent ansatz with matter fields as follows,

$$ M_{\mu\nu} = -p(r)dt \wedge dr + \rho(r)dx \wedge dy, $$
where $B$ is a constant magnetic field which is considered as an external magnetic field of dual boundary field theory. Inserting this ansatz into Eqs. (4) and (9), we arrive at

\begin{align*}
0 &= \rho'' + \rho' \left[ f' + \frac{d-2}{r} \right] - \frac{\rho}{r^2 f} \left[ m^2 + 4Jp^2 \right] + \frac{B}{r^2 f}, \\
0 &= \left( m^2 - \frac{4Jp^2}{r^4} \right) p - \rho', \\
0 &= \phi'' + \frac{2\phi'}{r^3} \left[ \frac{d-2}{2} \phi'^2 - \frac{(2\alpha - d + 2)B^2}{2r^2} \right] + \\
&\quad + \frac{\lambda^2}{2\alpha+1} \alpha \left( p' + \frac{2\phi'}{r^2} \right) \left[ \frac{(\phi'^2 - B^2)^{2-\alpha}}{(2\alpha - 1)\phi'^2 - B^2} \right],
\end{align*}

where the prime denotes the derivative with respect to $r$. Obviously, the above equations reduce to the corresponding equations in Ref. [20] when $\alpha \to 1$ and $d = 4$. We should specify boundary conditions for the fields to solve Eq. (10) numerically. At the horizon, we need to impose a regular boundary condition. Therefore, in addition to $f(r_+) = 0$, because the norm of the gauge field, namely $g_{\mu\nu}A^\mu A^\nu$, should be finite at the horizon, we require $\phi(r_+) = 0$ and $\rho(r_+) = \frac{(d-1)r_+}{m^2} \rho' + \frac{B}{m^2}$. The behaviors of model functions governed by the field equations (10) near the boundary ($r \to \infty$) are given by

\begin{align*}
\phi(r) &\sim \mu - \frac{\sigma}{r^{\frac{d-1}{2\alpha-1}}}, & p(r) &\sim \frac{\sigma}{m^2 r^{(d-2)/2}}, \\
\psi(r) &\sim \frac{\psi_+}{r^{\Delta_+}} + \frac{\psi_-}{r^{\Delta_-}} + \frac{B}{m^2},
\end{align*}

where $\mu$ and $\sigma$ are respectively interpreted as the chemical potential and charge density of dual field theory, and

\begin{equation}
\Delta_\pm = \frac{1}{2} \left[ (5 - d) \pm \sqrt{4m^2 + 16 + (d - 1)(d - 9)} \right].
\end{equation}

According to AdS/CFT correspondence, $\rho_+$ and $\rho_-$ are two constants correspond to the source and vacuum expectation value of dual operator when $B = 0$. Therefore, condensation happens spontaneously below a critical temperature when we set $\rho_+ = 0$. By considering $B \neq 0$, the asymptotic behavior is governed by external magnetic field $B$. It is important to note that the boundary condition for the gauge field $\phi$ depends on the power parameter $\alpha$ of the Power-Maxwell field unlike other nonlinear electrodynamics such as Born-Infeld-like electrodynamics [34, 35]. Using boundary condition Eq. (11) and the fact that $\phi$ should be finite as $r \to \infty$, we require that $\frac{d-2}{2\alpha-1} > 1$, which restricts the values of $\alpha$ to be $\alpha < \frac{d-1}{2}$. On the other hand since $\frac{d-2}{2\alpha-1} > 1$, it must be a positive real number, it leads to the range of the parameter $\alpha$ to be $1/2 < \alpha < \frac{d-1}{2}$.

In the following sections, we will study the holographic ferromagnetic-paramagnetic phase transition numerically.

\begin{table}[h]
\centering
\begin{tabular}{cc}
\hline
$\alpha$ & \multicolumn{2}{c}{3/4} & 1 & 5/4 \tabularnewline
\hline
4D & 3.6023 & 1.7840 & \tabularnewline
5D & 3.9388 & 2.4367 & 2.0103 \tabularnewline
\hline
\end{tabular}
\caption{Numerical results of $T_c/\mu$ for different values of $\alpha$ in two dimensions.}
\end{table}

\begin{table}[h]
\centering
\begin{tabular}{cc}
\hline
$\alpha$ & \multicolumn{2}{c}{3/4} & 1 & 5/4 \tabularnewline
\hline
4D & 6.0253(1 - T/T_c)^{1/2} & 2.9409(1 - T/T_c)^{1/2} & \tabularnewline
5D & 6.5128(1 - T/T_c)^{1/2} & 4.7654(1 - T/T_c)^{1/2} & 4.2327(1 - T/T_c)^{1/2} \tabularnewline
\hline
\end{tabular}
\caption{The magnetic moment $N$ with different values of $\alpha$ for two dimensions.}
\end{table}
III. NUMERICAL CALCULATION FOR SPONTANEOUS MAGNETIZATION AND SUSCEPTIBILITY

In this paper, we work in the grand canonical ensemble where the chemical potential $\mu$ is a fixed quantity. We have to solve Eq. (10) to get the solution of the order parameter $\rho$, and then compute the value of magnetic moment $N$, which is defined by

$$N = -\lambda^2 \int \frac{\rho}{2r^2} dr.$$  

(13)

Since different parameters will give similar results, here we choose $m^2 = -J = 1/8$ and $\lambda = 1/2$ as a typical example in the numerical computation. In this section, we employ the shooting method [4] to numerically investigate the holographic phase transition. Hereafter, we define the dimensionless coordinate $z = r_+/r$ instead of $r$, since it is easier to work with it. In terms of this new coordinate, $z = 0$ and $z = 1$ correspond to the boundary and horizon respectively. Besides setting $l$ to unity, we also set $r_+ = 1$ in the numerical calculation, for simplicity, which may be justified by virtue of the field equation symmetry

$$r \to ar, \quad f \to a^2 f, \quad \phi \to a\phi.$$  

First, we expand Eqs. (11) near black hole horizon ($z = 1$)

$$\rho \approx \rho(1) + \rho'(1)(1-z) + \frac{\rho''(1)}{2}(1-z)^2 + \cdots,$$  

(14)

$$\phi \approx \phi'(1)(1-z) + \frac{\phi''(1)}{2}(1-z)^2 + \cdots.$$  

(15)

In above equations, we have imposed $\phi(1) = 0$. In our numerical process, we will find $\rho(1)$, $\phi'(1)$ such that the desired values for boundary parameters in Eq. (11) are attained. At boundary, one can set either $\rho_-$ or $\rho_+$ to zero as source and find the value of the other one as the expectation value of order parameter $\langle O \rangle$. We consider the cases of different power parameter $\alpha$ in $4D$ spacetime as examples, and then extend to the case of $5D$ spacetime. We present our results in Fig. 1. From the left panel of this figure we observe the magnetic moment with two different values of power parameters in $d = 4$ dimension. Our numerical calculation is presented for $d = 5$ dimension in the right panel of Fig. 1. When the temperature is lower than $T_C$, the spontaneous magnetization appears in the absence of external magnetic field. In the vicinity of critical temperature, the numerical results show that the second order
phase transition happen which its behavior obtain by fitting this curve \( N \propto \sqrt{1 - T/T_C} \). The results have been shown in Table I. We find that there is a square root behavior for the magnetic moment versus temperature, and it can be found that the critical exponent \( (1/2) \) is the same as the one from the mean field theory. In other words, the holographic paramagnetic-ferromagnetic phase transition exists by considering the Power-Maxwell electrodynamics similar to the cases of Born-Infeld-like nonlinear electrodynamic discussed in Ref. [25]. As it can be found from this Figure, the magnetic moment decreases with increasing the power parameter \( \alpha \). It means that the magnetic moment is harder to be formed which is in a good agreement with similar works [25, 26]. This behavior has been seen for the holographic superconductor in the Schwarzschild-AdS black hole, where the three types of nonlinear electrodynamics make scalar condensation harder to be formed [34]. In Table I, our numerical results for critical temperature with different values of power parameter \( \alpha \) and for two cases of dimensions \( (d = 4, 5) \) are presented. In the Maxwell limit \( (\alpha \to 1) \), our numerical results reproduce the ones of [25] for \( d = 4 \). We see from Table I that the critical temperature \( T_c \) increases by decreasing the power parameter for fixed dimension. As the power parameter \( \alpha \) becomes larger, the critical temperature decreases. It means that the magnetic moment is harder to be formed. This behavior have been reported previously in [25] too. Fig. I confirms above results. The behavior of susceptibility density of the material in the external magnetic field is a remarkable characteristic properties of ferromagnetic material. The static susceptibility density is defined by

\[
\chi = \lim_{B \to 0} \frac{\partial N}{\partial B}.
\]

In the presence of magnetic field, the function \( \rho \) is nonzero at any temperature. The magnetic susceptibility obtained by solving the Eq. (3) based on the previous analysis which one has been discussed in Ref. [20]. We need to shoot for boundary conditions with one parameter \( \rho(r_+) \) for computing the susceptibility density. Fig. I shows the behavior of susceptibility density near the critical temperature for \( 4D \) and \( 5D \). One can see that when the temperature decreases,
\( \chi \) increases. In the region of \( T \to T^+_c \), the susceptibility density satisfies the cure-Weiss law of ferromagnetism

\[
\chi = \frac{C}{T + \theta}, \quad T > T_C, \theta < 0,
\]

where \( C \) and \( \theta \) are two constants. The results have been presented in Table III. Obviously we can see that the coefficient in front of \( T/T_c \) for \( 1/\chi \) increases, when the power parameter (\( \alpha \)) decreases.

\[
\begin{array}{cccc}
\alpha & 3/4 & 1 & 5/4 \\
4D \ 
\chi^2/\chi_H & 3.7667(T/Tc + 0.0034) & 3.9906(T/Tc - 1) & - \\
\theta/\mu & 0.0124039 & -1.7871 & - \\
5D \ 
\chi^2/\chi_H & 4.1219(T/Tc + 0.0018) & 2.5349(T/Tc + 0.014) & 2.0606(T/Tc + 0.048) \\
\theta/\mu & 0.00697 & 0.0343 & 0.0968 \\
\end{array}
\]

**TABLE III:** The magnetic susceptibility \( \chi \) with different values of \( \alpha \).

**IV. CONCLUSION**

In this work, we have studied the properties of one-dimensional holographic paramagnetic-ferromagnetic phase transition in the presence of Power-Maxwell electrodynamics. We have also investigated the effects of different dimensions on the system. We have performed numerical shooting methods for studying our holographic model. It was shown that the enhancement in power parameter of electrodynamic model causes the paramagnetic phase more difficult to be appeared. This result is reflected from our data. We observed that the increase of the effects of power parameter makes the lower values for the critical temperature in our model. Besides, for smaller values of the power parameter, the gap in the magnetic moment in the absence of magnetic field, is larger which in turn exhibits that the condensation is formed harder. We have also observed that the behavior of the magnetic moment is always as \((1 - T/T_c)^{1/2}\). This is in agreement with the result from mean field theory. In the presence of external magnetic field, the inverse magnetic susceptibility near the critical point behaves as \((C/T)^{1/2}\) for different values of power parameters in two dimensions, and therefore it satisfies the Cure-Weiss law. The absolute value of \( \theta \) increases by increasing the power parameter \( \alpha \).

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