Holographic paramagnetic-ferromagnetic phase transition of Power-Maxwell-Gauss-Bonnet black holes

B. Binaei Ghotbabadi,1,2 A. Sheykhi,1,2, * G. H. Bordbar,1,† and A. Montakhab1

1Physics Department, College of Sciences, Shiraz University, Shiraz 71454, Iran
2Biruni Observatory, College of Sciences, Shiraz University, Shiraz 71454, Iran

Based on the shooting method, we numerically investigate the properties of holographic paramagnetism-ferromagnetism phase transition in the presence of higher order Gauss-Bonnet (GB) correction terms on the gravity side. On the matter field side, however, we consider the effects of the Power-Maxwell (PM) nonlinear electrodynamics on the phase transition of this system. For this purpose, we introduce a massive 2-form coupled to PM field, and neglect the effects of 2-form fields and gauge field on the background geometry. We observe that increasing the strength of both the power parameter $q$ and GB coupling constant $\alpha$ decrease the critical temperature of the holographic model, and lead to the harder formation of magnetic moment in the black hole background. Interestingly, we find out that at low temperatures, the spontaneous magnetization and ferromagnetic phase transition happen in the absence of external magnetic field. In this case, the critical exponent for magnetic moment has the mean field value, $1/2$, regardless of the values of $q$ and $\alpha$. In the presence of external magnetic field, however, the magnetic susceptibility satisfies the Curie-Weiss law.

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I. INTRODUCTION

The duality between gravity in an anti-de Sitter (AdS) spacetime and a conformal field theory (CFT), known as AdS/CFT correspondence, provides a powerful tool to investigate strongly coupled systems [1–5]. A significant applications of this conjecture is investigation of the electronic properties of materials and magnetism [6–15]. The gauge/gravity duality, which is a new approach for calculating the properties of superconductors using a dual classical gravity, also provides a fascinating tool to shed light on high temperature superconductors. Based on this theory, one can describe a superconductor using a dual classical gravity description. It has been shown that some properties of strongly coupled superconductors can be potentially described by classical general relativity living in one higher dimension, which is known as holographic superconductors [16]. The idea of holographic superconductor was initiated by Hartnol, et. al. [16, 17]. They considered a four-dimensional Schwarzschild-AdS black hole coupled to a Maxwell and a scalar fields to construct a holographic $s$-wave superconductor. Based on their model, in order to describe a holographic superconductor on the boundary, a transition from hairy black hole to a no hair black hole in the bulk for temperatures below and upper the critical value is required [16]. The appearance of hair corresponds to the spontaneous $U(1)$ symmetry breaking [16]. This theory opened up a new perspective in condensed matter physics to study the high temperature superconductors. During the past decade, the explorations on the holographic dual models have attracted considerable attention (see e.g. [18–33] and reference therein). The studies were also generalized to investigate paramagnetic-ferromagnetic phase transition using the holographic description [34–44]. The first holographic paramagnetic-ferromagnetic phase transition model was a dyonic Reissner-Nordstrom-AdS black brane [34]. This model provides a starting point for exploration of more complicated magnetic phenomena and quantum phase transition, by considering a real antisymmetric tensor field which is coupled to the background gauge field strength in the bulk. It was argued that the spontaneous magnetization which happens in the absence of an external magnetic field, can be realized as the paramagnetic-ferromagnetic phase transition. Most investigations on holographic paramagnetism-ferromagnetism phase transition have been carried out by considering the gauge field as a linear Maxwell field in Einstein gravity [35–42]. It is also of great interest to explore the effects of nonlinear electrodynamics on the properties of the holographic ferromagnetic-paramagnetic phase transition. These holographic setups have been widely studied in the presence of nonlinear electrodynamics, those involve more information than the usual Maxwell state [43, 44]. It has been observed that in the Schwarzschild AdS black hole background and in the absence of external magnetic field, the higher nonlinear electrodynamics corrections make the magnetization harder to be

*Electronic address: asheykhi@shirazu.ac.ir
†Electronic address: ghbordbar@shirazu.ac.ir
formed. Among various nonlinear extension of Maxwell electrodynamics, the PM nonlinear electrodynamics which preserves the conformally invariant feature in higher dimensions has received more attraction [45]. The conformally invariant PM action in \((n + 1)\)-dimensional may be written, 

\[ I_{PM} = \int d^{n+1}x \sqrt{-g} (-\mathcal{F})^q, \]  

where \(\mathcal{F} = F_{\mu\nu} F^{\mu\nu}\) is the Maxwell invariant and \(q\) is the power parameter. Under conformal transformation \(g_{\mu\nu} \rightarrow \Omega^2 g_{\mu\nu}\) and \(A_\mu \rightarrow A_\mu\), the above action remains invariant. The corresponding energy-momentum tensor given by 

\[ T_{\mu\nu} = 2 \left( q F_{\mu\rho} F^\rho_{\nu} \mathcal{F}^{n-1} - \frac{1}{4} g_{\mu\nu} \mathcal{F}^q \right), \]  

is traceless for \(4q = n + 1\). Black hole solutions in the presence of PM electrodynamics have been constructed by many authors (see e.g. [46-52] and references therein). The properties of holographic superconductor with conformally invariant PM electrodynamics have been studied in Refs.[53-59]. Recently, we explored the effects of PM nonlinear electrodynamics on the properties of holographic paramagnetic-ferromagnetic phase transition in the background of Schwarzschild-AdS black hole [60]. We investigated how the PM electrodynamics influences the critical temperature and magnetic moment. We found that the effects of PM field lead to the easier formation of magnetic moment at higher critical temperature. The studies were also generalized to other gravity theories. In the context of GB gravity, the phase transition of the holographic superconductors were explored in Refs.[61-69]. Their motivations are to study the effects of higher order gravity corrections on the critical temperature of holographic superconductors. They found that when GB coefficients become larger, the condensation on the boundary field theory becomes harder to be formed. In our previous work [60] we have considered the effects of PM on paramagnetic-ferromagnetic phase transition in Einstein gravity. It it also interesting to examine the effects of this kind of nonlinear electrodynamics when the higher order corrections on the gravity side such as GB terms, is taken into account. We would like to examine whether or not the holographic paramagnetic-ferromagnetic phase transition still hold in the presence of higher order gravity corrections. We shall apply the shooting method to numerically investigate the influences of both the higher order GB curvature correction terms, as well as the nonlinear PM electrodynamics on the holographic system.

This paper is organized as follows. In section II, we introduce the action and basic field equations in the presence of PM electrodynamics by considering the higher order GB curvature correction terms. In section III, we employ the shooting method to obtain numerically critical temperature and magnetic moment of the system. We investigate the effect of external magnetic field for our model and obtain the magnetic susceptibility density in section IV. In the last section, we finish with closing remarks.

II. HOLOGRAPHIC MODEL

In this section, we introduce the action of Einstein-Gauss-Bonnet in AdS spaces which is coupled to a PM field. The action of an \((n + 1)\)-dimensional Einstein-Gauss-Bonnet gravity can be written as,

\[ S = \frac{1}{16\pi G} \int d^{n+1}x \sqrt{-g} \left[ R - 2\Lambda + \frac{\alpha}{2} (R^2 - 4 R_{\mu\nu} R^{\mu\nu} + R_{\mu\nu\rho\sigma} R^{\mu\nu\rho\sigma}) + L_1(\mathcal{F}) + \lambda^2 L_2 \right], \]

with

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

where \(G\) is Newtonian gravitational constant, \(g\) is the determinant of metric and \(\alpha\) is the GB coefficient. In the above action, \(R, R_{\mu\nu}, R_{\mu\nu\rho\sigma}\) are, respectively, Ricci scalar, Ricci tensor and Riemann curvature tensor. Here \(\lambda\) and \(J\) are two real parameters. \(\lambda^2\) characterizes the back reaction of the 2-form field \(M_{\mu\nu}\) to the Maxwell field strength and to the background geometry. In addition, \(m\) is the mass of the real tensor field \(M_{\mu\nu}\), being greater than zero [38], and \(dM\) is the exterior differential 2-form field \(M_{\mu\nu}\). In the above action, when \(\alpha \rightarrow 0\), the Einstein-Maxwell theory is recovered [60]. In addition \(\Lambda = -n(n - 1)/2l^2\) is the cosmological constant of \((n + 1)\)-dimensional AdS spacetime with radius \(l\). Here \(L_1(\mathcal{F}) = -\mathcal{F}^q/4\), where \(\mathcal{F} = F_{\mu\nu} F^{\mu\nu}\) in which \(F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu\) and \(A_\mu\) is the Maxwell potential and \(q\) is the power parameter of the PM field. In the limiting case, \(q \rightarrow 1\), the PM Lagrangian will reduce to the Maxwell case, \(L_1 = -F_{\mu\nu} F^{\mu\nu}/4\). The theory is conformally invariant for \(q = (n + 1)/4\) and the energy-momentum tensor of the PM Lagrangian is traceless in all dimension [45].
$V(M_{\mu\nu})$ describes the self interaction of polarization tensor. This nonlinear potential should be expanded as the even power of $M_{\mu\nu}$. For simplicity, we take the following form for this model, \[ V(M) = (*M_{\mu\nu}M^{\mu\nu})^2 = [*(M \wedge M)]^2, \] where $*$ is the Hodge star operator. Since we consider the probe limit, the gauge and matter fields do not back react on the background metric. The line element of the metric with flat horizon is given by \[ ds^2 = -r^2 f(r) dt^2 + \frac{dr^2}{r^2 f(r)} + r^2 \sum_{i=1}^{n-1} dx_i^2, \]

with \[ f(r) = \frac{1}{2\alpha} \left[ 1 - \sqrt{1 - 4\alpha \left( 1 - \frac{r_+^n}{r^n} \right)} \right], \]

where $r_+$ is the positive real root of Eq. $f(r_+) = 0$. At large distance where $r \to \infty$, the metric function reduces to \[ f(r) \approx \frac{1}{2\alpha} \left[ 1 - \sqrt{1 - 4\alpha} \right], \]

Since $f(r)$ should be a positive definite function, it implies $0 \leq \alpha \leq 1/4$ and real, where the upper bound $\alpha = 1/4$ is called the Chern-Simon limit [62]. We can present the effective AdS radius $L_{\text{eff}}$ as \[ L_{\text{eff}}^2 = \frac{2\alpha}{1 - \sqrt{1 - 4\alpha}}. \]

The Hawking temperature associated with the black hole event horizon, which can be interpreted as the temperature of CFT on the boundary, is given by [61] \[ T = \frac{f'(r_+)}{4\pi}, \]

Varying action (3) with respect to 2-form field, $M_{\mu\nu}$, and the gauge field, $A_\mu$, we arrive at the following field equations [60] \[ 0 = \nabla^r (dM)_{\tau\mu\nu} - m^2 M_{\mu\nu} - J(*M_{\tau\sigma}M^{\tau\sigma})(*M_{\mu\nu}) - F_{\mu\nu}, \]

\[ 0 = \nabla^\mu \left( qF_{\mu\nu}(\mathcal{F})^{q-1} + \frac{\lambda^2}{4} M_{\mu\nu} \right). \]

Our aim here is to investigate the effects of the power parameter $q$ and the GB coefficient $\alpha$ on the holographic ferromagnetic-paramagnetic phase transition. We adopt the following self-consistent ansatz for the matter and gauge fields [39] \[ M_{\mu\nu} = -p(r) dt \wedge dr + \rho(r) dx \wedge dy, \]

\[ A_\mu = \phi(r) dt + B x dy, \]

where $B$ is a uniform magnetic field viewed as an external magnetic field in the boundary field theory. Here $\rho(r)$ and $p(r)$ are the components of $M_{\mu\nu}$, while $\phi(r)$ stands for the electric potential. Inserting the above ansatz into Eqs. (10) and (11), lead to the following nontrivial equations of motion,

\[ 0 = \rho'' + \rho' \left[ \frac{f'}{f} + \frac{n-3}{r} \right] - \frac{\rho}{r^2 f} \left[ m^2 + 4Jp^2 \right] + \frac{B}{r^2 f}, \]

\[ 0 = \left( m^2 - \frac{4J\rho^2}{r^4} \right) p - \rho', \]

\[ 0 = \phi'' + \frac{2\phi}{r} \left[ \frac{n-1}{2} \phi'^2 + \frac{(2q-n+3)}{2q-1} B^2 \frac{r^2}{r^2} \right] + \frac{\lambda^2}{q2^{q+1}} \left( p' + \frac{(n-1)p}{r} \right) \left[ \left( \frac{\phi'^2 - B^2}{r^2} \right)^{2-q} \right]. \]
FIG. 1: The behavior of magnetic moment $N$ and the critical temperature with different values of power parameter $q$ for $\alpha = 0, 0.1$ and $0.2$ in $(n+1=)5$-- dimensions. Here we have taken $m^2 = 1/8$ and $J = -1/8$.

FIG. 2: The behavior of magnetic moment $N$ and the critical temperature for different values of GB parameter $\alpha$ with $q = 1, 11/10, 5/4$. Here we have taken $n = 4$, $m^2 = 1/8$ and $J = -1/8$.

here a prime denotes the derivative with respect to $r$. Obviously, for Einstein gravity ($\alpha \to 0$) in the Maxwell limit where $q \to 1$ and $n = 3$, the above equations reduce to the standard holographic ferromagnetic-paramagnetic phase transition models discussed in Ref. [38]. In order to solve Eqs.(14) numerically, we should specify the boundary conditions for the fields. Imposing the regularity conditions at the horizon($r = r_+$), yields the following boundary conditions [34]

$$\phi'(r_+) = (m^2 - 4J\rho^2)p, \quad \rho'(r_+) = \frac{\rho(r_+)(m^2 + 4Jp^2) - B}{4\pi T}. \quad (15)$$

Since the behaviors of model functions are asymptotically $AdS$, thus we solve the field equations (14) near the boundary $(r \to \infty)$. We find the asymptotic solutions as

$$\phi(r) \sim \mu - \frac{\sigma}{r^{(n-1)/2}}, \quad p(r) \sim \frac{(n-2\mu)/\sigma}{r^{(n-1)/2}},$$

$$\rho(r) \sim \frac{\rho_-}{r^{\Delta_-}} + \frac{\rho_+}{r^{\Delta_+}} + \frac{B}{m^2}, \quad (16)$$

with

$$\Delta_\pm = \frac{1}{2} \left[ -(n-4) \pm \sqrt{(n-4)^2 + 4m^2L^2_{\text{eff}}} \right]. \quad (17)$$

Here $\rho_\pm$, $\mu$ and $\sigma$ are all constants. Based on the AdS/CFT correspondence, $\rho_+$ and $\rho_-$ are interpreted as the source and vacuum expectation value of the dual operator. According to Ref.[34], we consider $\rho_-$ as the source of the dual operator when $B = 0$, which plays the role of order parameter in the boundary theory. Moreover, $\mu$ and $\sigma$ are regarded as the chemical potential and charge density of dual field theory, respectively. Unlike other nonlinear electrodynamics [43], the boundary condition for the gauge field $\phi$ depends on the power parameter $q$ of the $PM$ electrodynamics. To find the restriction to this parameter, we require to confined $\phi$ near boundary($r \to \infty$), so we set $\frac{n-1}{2q-1} - 1 > 0$, which implies that the power parameter $q$ ranges as $1/2 < q < n/2$. In the next section, we solve the field equations numerically and obtain the physical properties of our holographic model.
TABLE I: Numerical results of $T_c/\mu$ for different values of $q$ and $\alpha$, in 5D.

| $q$     | 3/4 | 1 | 11/10 | 5/4 |
|---------|-----|---|-------|-----|
| $\alpha = 0$ | 3.3494 | 2.4368 | 2.3177 | 2.2604 |
| $\alpha = 0.1$ | 3.1568 | 2.3070 | 2.1938 | 2.1375 |
| $\alpha = 0.2$ | 2.8503 | 2.0982 | 1.9943 | 1.9393 |

TABLE II: The magnetic moment $N$ with different values of power parameter $q$ and GB coefficient $\alpha$ in 5D.

| $q$ | 1 | 11/10 | 5/4 |
|-----|---|-------|-----|
| $\alpha = 0$ | 1.7084$(1 - T/T_c)^{1/2}$ | 1.7095$(1 - T/T_c)^{1/2}$ | 1.7174$(1 - T/T_c)^{1/2}$ |
| $\alpha = 0.1$ | 1.6879$(1 - T/T_c)^{1/2}$ | 1.6887$(1 - T/T_c)^{1/2}$ | 1.6960$(1 - T/T_c)^{1/2}$ |
| $\alpha = 0.2$ | 1.6466$(1 - T/T_c)^{1/2}$ | 1.6467$(1 - T/T_c)^{1/2}$ | 1.6531$(1 - T/T_c)^{1/2}$ |

III. SPONTANEOUS MAGNETIZATION

In this paper, we confined our investigation to grand canonical ensemble by considering a fixed chemical potential $\mu$. Here we employ the shooting method [6] to numerically investigate the behavior of the holographic ferromagnetic-paramagnetic phase transition in GB gravity. Our system has the following scaling symmetry:

$$r \rightarrow ar, \quad f \rightarrow a^2 f, \quad \phi \rightarrow a\phi, \quad \rho \rightarrow a^2 \rho,$$

we can use these above scaling symmetry to obtain the solutions of Eqs. (14) with the same chemical potential. In the follow, we choose $m^2 = -J = 1/8$ and $\lambda = 1/2$ as a typical example in the numerical computation and determine the basic features of the model. Since the spontaneous magnetization in low temperature corresponds to order parameter $\rho$ in the absence of external magnetic field, we set $B = 0$ and solve Eqs.(14) to get these solution for the order parameter $\rho$, and then compute the value of the magnetic moment $N$, which is defined as

$$N = -\lambda^2 \int_{r_h}^{r_+} \frac{\rho}{2\pi^{n-1}} dr.$$  (18)

Now we introduce a new variable $z = r_+/r$ instead of $r$ which transforms the coordinate $r$ to dimensionless coordinate $z$. In this new coordinate, $z = 0$ and $z = 1$ correspond to the boundary ($r \rightarrow \infty$) and horizon ($r = r_+$), respectively. For convenience, we will set $l = 1$ and $r_+ = 1$ in the following calculation. In order to investigate the trend of the magnetic moment numerically, we use the shooting method and solve the Eqs.(14).

We do our numerical calculation in five spacetime dimensions with $n = 4$, for the cases of different $PM$ parameter $q$ and GB coefficient $\alpha$. We present our results in Figs. 1 when GB parameter is fixed for three different values of $q$. Fig. 2 show the behavior of this system for three allowed values of GB parameter by fixing the power parameter $q$. These figures show the behavior of magnetic moment as a function of temperature for different choices of nonlinearity and GB parameters. For all cases, it can be found that as the temperature decreases, the magnetization increases and the critical temperature. In fact, the effect of larger parameters $\alpha$ and $q$ make the magnetization harder and the ferromagnetic phase transition happen which is in a good agreement with previous works [43, 44]. When the temperature is lower than $T_C$, the spontaneous magnetization appears in the absence of external magnetic field. For all cases, by fitting this related curve for $T < T_c$, we find that the phase transition is second-order ($N \propto \sqrt{1 - T/T_C}$). The results have been presented in Table II. According to these results, neither GB or PM parameters, change the critical exponent $(1/2)$, which is the value according to mean field theory. In other words, there is a holographic ferromagnetic-paramagnetic phase transition by considering the PM electrodynamics in the GB gravity similar to the cases of nonlinear electrodynamics in Einstein gravity discussed in Refs. [43, 60]. Table I gives information about the values of critical temperature based on $\mu$ for different values of GB parameter as well as power parameter $q$. Considering the GB coefficient leads to the same effect as the larger values of power parameter $q$ on the critical temperatures. On the other hand, increasing $\alpha$ in the allowed range can cause the transition to ferromagnetic phase to be harder for any values of the power parameter $q$. We see also from Table I that by increasing the power parameter $q$, the critical temperature $T_c$ decreases for fixed value of $\alpha$. It means that the magnetic moment is harder to be formed and the phase transition is made harder in the Einstein- Gauss-Bonnet gravity. This behavior have been reported previously in Ref. [43] for nonlinear electrodynamics in Einstein gravity too.
IV. FERROMAGNETIC MATERIAL IN THE PRESENCE OF EXTERNAL MAGNETIC FIELD

In this section, we investigate the effect of external magnetic field for our model. So by turning on this external field, we examine the susceptibility density of the materials as a response to magnetic moment. This behavior is an important property of ferromagnetic materials. In order to study the static susceptibility density of the ferromagnetic materials in the GB gravity, we follow the definition

$$\chi = \lim_{B \to 0} \frac{\partial N}{\partial B}.$$  \hspace{1cm} (19)

In the presence of magnetic field, the magnetic susceptibility obtained by solving Eq.(10). We follow the previous analysis which one has been discussed in Ref. [38]. In order to study the effect of nonlinear electrodynamics and GB parameter, on the susceptibility density near the critical temperature, we plot these behaviors in Fig.3. These figures show the behavior of susceptibility density as a function of the temperature for different choices of nonlinearity and Gauss–Bonnet parameters. We see that increasing each one of these parameters, makes the susceptibility value increases when the temperature decreases. In fact, with increasing these parameters, the system will become unstable and then the ferromagnetic phase will be broken into the paramagnetic phase. In the region of $T \to T_c^+$, the susceptibility density satisfies the Curie-Weiss law of ferromagnetic and the paramagnetic phase happens,

$$\chi = \frac{C}{T + \theta}, \quad T > T_c,$$  \hspace{1cm} (20)

where $C$ and $\theta$ are two constants. The numerical results are listed in Table III. Obviously, we can see that the coefficient in front of $T/T_c$ for $1/\chi$ increases, by decreasing the power parameter($q$) and GB coefficient($\alpha$). It means that for the smaller values of these two parameters our system becomes stable.
conclude that this critical exponent is not effected by the model parameters such as the mean field value (1/2) and/or the gauge field coefficient lowers the critical temperature. Numerical calculations indicate that increasing the values of nonlinearity and GB parameters in different dimensions can make magnetization harder to be formed, since the increasing α and q always inhibit the ferromagnetic phase transition. Increasing the effect of PM parameter in GB gravity leads to the same behavior as in case of Einstein gravity [60]. We observed that the enhancement in GB parameter α causes the paramagnetic phase more difficult to appear. These results are reflected in Figs. 2. We find out that the magnetic moment behaves as (1 − T/Tc)1/2 indicating that the critical exponent has the mean field value (1/2), which seems to be a universal constant, as it is the same value for the Einstein case. We conclude that this critical exponent is not effected by the model parameters such as q, α and n.

In the presence of external magnetic field, the inverse magnetic susceptibility near the critical point behaves as (C/Tcθ) for all allowed values of the power parameter q and different values of the GB coupling α in different dimensions, and therefore it satisfies the Curie-Weiss law. The absolute value of θ increases by increasing each one of q and α. When T < Tc, the ferromagnetic phase happens, and for T > Tc, this model goes to the paramagnetic phase. As a result, our model provides a holographic description for the ferromagnetic-paramagnetic phase transition.

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**TABLE III:** The magnetic susceptibility χ with different values of q and α.

| q     | 0.9 | 1   | 11/10 |
|-------|-----|-----|-------|
| α = 0 | 0.3236(T/Tc − 1.331) | 0.2881(T/Tc − 1.5486) | 0.2683(T/Tc − 1.7039) |
| θ/μ  | 3.5675 | 3.7735 | 3.9491 |
| α = 0.1 | 0.2947(T/Tc − 1.5483) | 0.2500(T/Tc − 1.9584) | 0.2251(T/Tc − 2.2696) |
| θ/μ  | 3.9253 | 4.5182 | 4.9790 |
| α = 0.2 | 0.2635(T/Tc − 1.7828) | 0.2114(T/Tc − 2.4542) | 0.1828(T/Tc − 3.0002) |
| θ/μ  | 4.1108 | 5.1496 | 5.9833 |

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**V. CLOSING REMARKS**

We have numerically investigated the behavior of a holographic ferromagnetic model with the PM electrodynamics based on shooting method, by considering the higher order GB correction terms on the gravity side of the action. On the gauge field side, however, we have considered the effects of PM nonlinear electrodynamics on the system. We have focused on 1/2 < q < n/2 as the physical range of the parameter. We found that for this system, increasing the value of nonlinearity parameter and/or GB coefficient lowers the critical temperature. Numerical calculations indicate that increasing the values of nonlinearity and GB parameters in different dimensions can make magnetization harder to be formed, since the increasing α and q always inhibit the ferromagnetic phase transition. Increasing the effect of PM parameter in GB gravity leads to the same behavior as in case of Einstein gravity [60]. We observed that the enhancement in GB parameter α causes the paramagnetic phase more difficult to appear. These results are reflected in Figs. 2. We find out that the magnetic moment behaves as (1 − T/Tc)1/2 indicating that the critical exponent has the mean field value (1/2), which seems to be a universal constant, as it is the same value for the Einstein case. We conclude that this critical exponent is not effected by the model parameters such as q, α and n.

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