Regular black holes in isothermal cavity

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**A B S T R A C T**

We examine the thermodynamic behavior of a static neutral regular (non-singular) black hole enclosed in a finite isothermal cavity. The cavity enclosure helps us investigate black hole systems in a canonical or a grand canonical ensemble. Here we demonstrate the derivation of the reduced action for the general metric of a regular black hole in a cavity considering a canonical ensemble. The new expression of the action contains quantum corrections at short distances and concludes to the action of a singular black hole in a cavity at large distances. We apply this formalism to the noncommutative Schwarzschild black hole, in order to study the phase structure of the system. We conclude to a possible small/large stable regular black hole transition inside the cavity that exists neither at the system of a classical Schwarzschild black hole in a cavity, nor at the asymptotically flat regular black hole without the cavity. This phase transition seems to be similar with the liquid/gas transition of a Van der Waals gas.

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1. Introduction

Black holes are probably among the most fascinating topics in Physics. They are not only mysterious astrophysical objects but also a theoretical laboratory where one can study fundamental physics. Indeed, at their center general relativity brings about its own downfall by predicting singularities. This issue can be overcome by fully quantizing gravity. However, the already existing candidates of quantum gravity are not helping that much to overcome such a problem. As a result, a literature of effective regular and ultraviolet complete black holes has been proposed [1–11], replacing the curvature singularity of the black hole with a regular core, while recovering general relativity at large distances.

On the top of that, a variety of thermodynamic phenomena have been noticed for black holes during the years following the derivation of the black hole temperature [12] and the related thermodynamics [13]. Of particular interest is the discovery of the Hawking-Page transition [14] between pure thermal radiation and a stable anti-de Sitter (AdS) black hole. Moreover, charged AdS black holes have an intriguing phase structure [15,16], in contrast to the uncharged ones, which is recently identified with the phase structure of a Van der Waals gas [17]. This result is possible if we consider an extended phase space for the black hole, where the cosmological constant is treated as the thermodynamic pressure of the system [18,19]. Similar phase structures have also been noticed for the known Bardeen black hole in AdS spacetime [20]. Another interesting issue is the enclosure of classical black hole systems, uncharged [21,22] or charged [23,24], inside an isothermal cavity that acts as a reservoir. This can be realized by placing a heat bath around the cavity that fixes the temperature at its surface, allowing for thermodynamically stable black holes to exist. Such a system is in analogy with the known canonical ensemble in statistical mechanics. The cavity enclosure appears similarities with the properties of AdS spacetime, which also stabilizes the black hole by acting as a reflecting box. For instance, Carlip and Vaidya [25] found the same phase structure between pure AdS black holes and asymptotically flat cases in a cavity, as well as de Sitter cases. More recently, new phase transitions and critical phenomena have been discovered for both neutral and charged de Sitter black holes with a Born-Infeld gauge field inside an extended phase space [26,27].

So far, a model of a regular black hole surrounded by an isothermal cavity has not been discussed in the scientific literature. For this reason, it is the goal of this paper to study the thermodynamics and the phase structure of such a system. The structure of the paper is as follows: In Sec. 2 we choose as our regular black hole candidate the noncommutative Schwarzschild black hole [1], which is a non-singular black hole solution of the Einstein equations, and we review its basic geometrical and thermodynamic features. In addition, we provide the basic boundary conditions/constraints for the general system black hole-cavity. In Sec. 3 we assume the cavity enclosure for any generic regular black hole solution, resulting from the existence of an anisotropic fluid with two pressure terms, and we perform the derivation of the re-
duced action. The new action is a generalization of the action characterizing the classical system Schwarzschild black hole-cavity [28] (see also the uncharged version in [23]), containing extra quantum correction terms at short scales, due to the existence of the minimal cut-off length that regularizes the spacetime geometry at the center. The action of the regular case concludes to the singular case at the large distance regime. In Sec. 4 we consider the model of the noncommutative Schwarzschild black hole and we examine the phase structure of the system noncommutative black hole-cavity. In contrast to the classical Schwarzschild black hole, which appears a Hawking-Page-like phase transition inside the cavity [28], the regular black hole undergoes a phase transition between a small and a large stable black hole similar to the liquid/gas transition of a Van der Waals gas. Similar behavior has also been noticed for noncommutative [29] and Reissner-Nördstrom [17] black holes inside the AdS space. Here the role of the negative cosmological constant has been replaced by the cavity, indicating that the cavity acts to the system the same way as the AdS space does. Sec. 5 is devoted to conclusions. Throughout the paper we use Planck units (c = ℏ = G = ℏ₀ = 1) and we consider a canonical-like ensemble, where the boundary radius and the temperature of the cavity wall are held fixed and the only variable which is allowed to fluctuate is the event horizon.

2. Basic review

2.1. Noncommutative Schwarzschild black hole

A basic feature of noncommutative geometry [3] is the presence of a minimal cut-off length that makes gravity ultraviolet self-complete below this scale. The meaning of a smooth classical manifold breaks down when approaching this length because quantum fluctuations are expected to appear, making spacetime "fuzzy" at short distances. These fluctuations can be encoded in the commutator

\[ [x^\mu, x^\nu] = i \theta^{\mu\nu}, \]

where \( \theta^{\mu\nu} \) is an anti-symmetric tensor that discretizes the spacetime vectors \( x^\mu \) in the same way the Planck constant discretizes the phase space. The quantity \( \sqrt{\theta} \) has dimensions of length and can be interpreted as the minimal cut-off length, very close to the Planck length, i.e., \( \sqrt{\theta} \sim 10^{-33} \) cm, below which there is no physically meaningful length.

It can be shown that noncommutativity implies the replacement of point-like structures, that are described by Dirac-delta functions, with very narrow Gaussian distributions [30–32]. This feature has been used to improve the Schwarzschild singularity [1] by imposing that the black hole mass is diffused throughout the center, just like a Gaussian distribution of minimal width \( \sqrt{\theta} \), instead of being a vacuum Dirac-delta function. The mass density of the anisotropic fluid-source is chosen to be then

\[ \rho(r) = \frac{M}{(4\pi\theta)^{3/2}} \exp(-r^2/\theta). \]

We make the following ansatz for the line element

\[ ds^2 = -b^2(r) dt^2 + a^2(r) dr^2 + r^2 d\Omega^2, \]

with \( d\Omega^2 = d\theta^2 + \sin^2 \theta d\phi^2 \),

\[ b^2(r) = 1 - \frac{2m(r)}{r} = \frac{1}{a^2(r)}. \]

Then we have to solve the Einstein equations with a stress-energy tensor \( T^{\mu\nu}_v \) that can be specified from the Schwarzschild-like prop-
an ultraviolet divergence at short wavelengths of the black-body radiation. Quantum mechanics cures this pathology much in the same way noncommutativity cures the ultraviolet divergence of the Hawking radiation.

2.2. The black-hole-cavity system

Following the seminal paper of Braden et al. [23], as well as similar works mentioned in the introduction, we have to take into account certain conditions that can be applied to any black-hole-cavity system:

1. We consider a spherically symmetric Euclidean line element of the form

\[ ds^2 = b(r)^2 d\tau^2 + a(r)^2 dr^2 + r^2 d\Omega^2 , \]  

(11)

which is the same as in the aforementioned papers of the introduction but slightly simplified (this form has also been used in [28]). The Euclidean time \( \tau \) comes after the analytical continuation \( \tau = i t \), providing us with a positive-definite Euclidean metric.

2. The event horizon \( r_+ \) is the inner boundary of the system with topology of a two-sphere \( S^2 \) and two constraints:

\[ b(r_+) = 0 \quad \text{and} \quad \frac{b'(r)}{a(r)} \bigg|_{r_+} = 1 , \]  

(12)

where the prime symbol (’') denotes from now on differentiation with respect to \( r \). The second constraint is a regularity condition, arising from the fact that we wish the geometry of the \( \tau - r \) plane to look like a flat disk near \( r_+ \), in order to avoid conical singularities.

3. The cavity wall is the outer boundary of the system with topology \( S^1 \times S^2 \). The wall is located at distance \( r_c \) and has an \( S^2 \) component with an area of \( 4\pi r_c^2 \). In addition, heat can flow in either direction of the wall maintaining the temperature fixed. This way the black hole can be in thermal equilibrium with the cavity. The temperature of the boundary equals with the inverse of the period \( \beta \), which is simply the proper length of the circle \( S^1 \) of the boundary:

\[ T^{-1} = \beta = \int_0^{2\pi} d\tau b(r_c) = 2\pi b(r_c) . \]  

(13)

We have chosen the periodicity of \( \tau \) to be \( 2\pi \) for convenience.

4. Applying the Gauss-Bonnet-Chern theorem, we find that the Euler number of the manifold should be \( \chi = 2 \). That gives us one more constraint:

\[ \frac{1}{a^2(r)} \bigg|_{r_+} = 0 . \]  

(14)

Now that we have given the above boundary conditions, we can proceed to the calculation of the reduced action for the desired system.

3. The reduced action

The starting point is the Euclidean version of the known Einstein-Hilbert action with the Gibbons-Hawking-York boundary term:

\[ I = - \int_{\mathcal{M}} d^4x \sqrt{g} \left( \frac{R}{16\pi} + \mathcal{L}_m \right) - \frac{1}{8\pi} \int_{\partial\mathcal{M}} d^3x \sqrt{h} (K - K_0) , \]  

(15)

where \( g \) and \( h \) are the determinants of the Euclidean metric of our manifold \( \mathcal{M} \) and the induced metric on the boundary \( \partial \mathcal{M} \) respectively, \( R \) is the Ricci scalar, \( \mathcal{L}_m \) is the matter Lagrangian, \( K \) is the trace of the extrinsic curvature on the boundary and \( K_0 \) is a term of our reference choice, analogous to \( K \), that is needed to regulate the boundary action. For notational convenience, we split the above action into 3 pieces (gravitational, matter and surface action)

\[ I_g = - \frac{1}{16\pi} \int_{\mathcal{M}} d^4x \sqrt{g} R , \]  

(16)

\[ I_m = - \int_{\mathcal{M}} d^4x \sqrt{g} \mathcal{L}_m , \]  

(17)

\[ I_s = - \frac{1}{8\pi} \int_{\partial\mathcal{M}} d^3x \sqrt{h} (K - K_0) , \]  

(18)

so that \( I = I_g + I_m + I_s \). The major difference from the classical system singular black hole-cavity is that the matter action (17) is no longer zero for the regular case. We evaluate first the gravitational action \( I_g \). For a metric of the form (11), the quantity \( \sqrt{g} R \) is calculated to be

\[ \sqrt{g} R = \left[ - \frac{2b}{a} + 2ba - \frac{4rb'}{a} - 4b \left( \frac{1}{a} \right)' - 2r^2 \left( \frac{b'}{a} \right)' \right] \sin \theta , \]  

(19)

where \( a = a(r) \) and \( b = b(r) \). Plugging (19) into the action (16) and integrating over the imaginary time and over the two angles \( \theta \) and \( \phi \), we get

\[ I_g = \pi \int_{r_c}^{r_+} dr \left( \frac{1}{a} - a - \frac{2ra'}{a^2} \right) b + \left( \pi r^2 \frac{b'}{a} \right) \bigg|_{r_c}^{r_+} - \pi r_+^2 , \]  

(20)

where we have performed integration by parts and used the boundary conditions (12). Proceeding a bit further, we use the Hamiltonian constraints

\[ C^c_t = C^t_c = -8\pi \rho , \]  

(21)

where \( \rho = \rho(r) \) is the matter density profile of the regular black hole. The components of the Einstein tensor read

\[ C^t_t = \left( a - a^3 - 2ra' \right) \frac{1}{r^2 a^3} \quad \text{and} \quad C^r_r = \frac{b - a^2 b' + 2rb'}{r^2 a^2 b} . \]  

(22)
From the relation $G'_r/G'_t = 1$, we conclude to $b = C/a$, where the integration constant $C$ can be specified, if the profile $\rho(r)$ of the regular black hole is specified. For now we can use the condition (13) to write $C = \frac{\alpha_0(r_c)}{\pi^2}$. Under these circumstances, the gravitational action can be written as

$$I_g = \frac{\beta \alpha(r_c)}{2} \left[ r \left( \frac{1}{a^2} - 1 \right) \right]_{r_c}^{r_+} - \frac{\beta}{2} \left[ r^2 \frac{d}{da^2} \right]_{r_c}^{r_+} - \pi r_+^2.$$  

(23)

Next we shift our interest to the matter action (17). Following the reasoning of [34], our effective fluid-like approach takes leading order quantum geometry effects, while letting us formally work in a classical framework. This allows us to connect our matter Lagrangian with the "on shell" action of an anisotropic fluid that reads

$$S(\on shell) = \int d^4x \sqrt{-g} \left( 2pf - p_\perp \right).$$

(24)

identifying our matter Lagrangian with

$$L_m = 2p_\perp - p_\perp = -\rho + \frac{r}{2} \rho'.$$

(25)

Plugging (25) into the action (17) and performing the integration, we get

$$I_m = 8\pi^2 \int_{r_c}^{r_+} dr \, abr^2 (\rho - \frac{r}{2} \rho').$$

(26)

From the Hamiltonian constraint $G'_t/G'_r = \frac{1}{\pi^2} \left[ r \left( \frac{1}{a^2} - 1 \right) \right]_{r_c}^{r_+} = -8\pi \rho$, we can extract an expression for the integral $\int dr \, r^2 \rho$:

$$\int_{r_c}^{r_+} dr \, r^2 \rho = -\frac{1}{8\pi} \left[ r \left( \frac{1}{a^2} - 1 \right) \right]_{r_c}^{r_+}.$$  

(27)

Thus using (27), the relation $ab\beta = C\frac{\alpha(r_c)}{\pi^2}$, and integrating by parts the $\rho'$-term in (26), we conclude to

$$I_m = 4\pi \beta \alpha(r_c) \left[ \frac{5}{16\pi} \left( \frac{r - r_c}{a^2} \right)_{r_c}^{r_+} - \frac{1}{2} r^2 \rho \right]_{r_c}^{r_+}. $$

(28)

We continue with the derivation of the surface action (18). Our boundary is a timelike surface at $r_c = \text{const}$., described by a radial spacelike normal unit vector $\eta^\mu = \frac{\delta^\mu}{\sqrt{\gamma}} (\eta^\mu \eta_\mu = 1)$ perpendicular to the boundary. Thus the induced metric on the boundary can be written as $h_{\mu\nu} = g_{\mu\nu} - \eta_\mu \eta_\nu$ and is described by a line element of the form

$$ds^2 = b(r_c)^2 dt^2 + r_c^2 d\Omega^2.$$

(29)

This allows us to define the trace of the extrinsic curvature $K$ as the divergence of the normal unit vector $\eta^\mu$, giving

$$K = \nabla_\mu \eta^\mu \left( \frac{br^2}{abr^2} \right)_{r_c}^{r_+}.$$  

(30)

As for $K_0$, we can choose any space we wish as the reference point from which the energy is measured. In our case, we choose $K_0$ such that $I = 0$ when $M = 0$, corresponding to an asymptotically flat spacetime that gives

$$K_0 = \frac{2}{r_c}.$$  

(31)

Using the above expressions for $K$ and $K_0$, the surface action becomes

$$I_s = \beta \left[ \frac{r^2 a'}{2a^2} - \frac{r}{a} + r \right]_{r_c}^{r_+}. $$

(32)

Finally, from the sum $I_g + I_m + I_s$ we obtain the reduced action $I$ that reads

$$I = \beta \left[ \frac{a(r_c)}{2} \left( \frac{r}{a} - r \right)_{r_c}^{r_+} + 4\pi a(r_c) \left[ \frac{5}{16\pi} \left( \frac{r - r_c}{a^2} \right)_{r_c}^{r_+} - \frac{1}{2} r^2 \rho \right]_{r_c}^{r_+} \right]_{r_c}^{r_+} - \pi r_+^2.$$  

(33)

For large distances relative to the minimal cut-off length, the mass density profile of the black hole becomes proportional to the Dirac delta function, i.e., $\rho(r) \sim M \delta(r)$, meaning that $\rho(r_+) = \rho(r_c) = 0$ since $r_+, r_c \neq 0$. Then the Hamiltonian constraints give $\frac{\alpha(r_c)}{\pi^2} \approx 1 - \frac{r_c}{r_+}$, implying the relation $(\frac{r}{a^2} - r)_{r_c}^{r_+} \approx 0$. Therefore, in this limit the matter action (28) vanishes and the reduced action (33) reduces to the action of the classical uncharged system singular black hole-cavity [28]:

$$I \approx \beta r_c \left[ 1 - \sqrt{\frac{1 - \frac{r_c}{r_+}}{r_c}} \right] - \pi r_+^2.$$  

(34)

4. The phase structure

In this last section we apply the reduced action formalism to the case of a noncommutative Schwarzschild black hole as an example. Then we derive the desired thermodynamic quantities and we study possible phase transitions that take place inside the cavity. For the noncommutative case, the profile of the density is given by (2). Solving the Hamiltonian constraints for this profile, the metric functions $a$ and $b$ of the line element (11) are evaluated to be

$$\alpha(r) = \frac{1}{\sqrt{1 - \frac{4M}{r_c \sqrt{\gamma}} \gamma(r)}}$$  

and

$$\beta(r) = C/a(r) = \frac{\beta}{2\pi \sqrt{1 - \frac{4M}{r_c \sqrt{\gamma}} \gamma(r)}} \sqrt{1 - \frac{4M}{r_c \sqrt{\gamma}} \gamma(r)}, $$

(35)

where $\gamma(r) = \gamma(3/2, r^2/4\theta)$. Moreover, the boundary condition (14) implies the relation $M = \frac{r_c}{2\sqrt{\gamma(r_c)}}$. Plugging these expressions into the general form of the reduced action (33), we get the form of the noncommutative reduced action $I_c$:

$$I_c = \beta r_c \left( 1 - \sqrt{1 - \frac{r_c^2}{r_+^2}} \right) + \frac{\beta}{2} r_c \left( \frac{1 - \gamma'(r_c)}{\gamma'(r_c)} \right)^{-1} \gamma'(r) + \frac{4\pi \beta}{\sqrt{1 - \frac{r_c^2}{r_+^2}}} \gamma(r) \left[ \gamma'(r) \gamma''(r) - \frac{1}{2} r_c^2 \rho(r_c) \right]_{r_c}^{r_+} - \frac{1}{2} r_c^2 \rho(r_c) - \pi r_+^2.$$  

(36)

As discussed in [35], thermodynamic quantities can be derived from the reduced action. The canonical partition function $Z$, evaluated in the zero-loop approximation, is connected to the Euclidean action through the relation $Z = e^{-\beta F} \approx e^{-I}$, where $F$ is
The noncommutative black hole temperature $T$ inside the cavity vs $r_+$ in $\sqrt{\sigma}$ units, for $r_c = 17\sqrt{\sigma}$ (red solid curve), for $r_c = r_i \simeq 10.913\sqrt{\sigma}$ (black dashed curve) and for $r_c = 9\sqrt{\sigma}$ (blue solid curve).

The heat capacity $C$ of the noncommutative black hole inside the cavity vs $r_+$ in $\sqrt{\sigma}$ units, for $r_c = 17\sqrt{\sigma}$ (red solid curve), for $r_c = r_i \simeq 10.913\sqrt{\sigma}$ (black dashed curve) and for $r_c = 9\sqrt{\sigma}$ (blue solid curve).

The Helmholtz free energy. The inverse temperature can be derived by extremizing the action with respect to $r_+$ and solving for $\beta$:

$$\frac{\partial I_s(\beta, \theta, r_+, r_c)}{\partial r_+} = 0 \quad \rightarrow \quad \beta(\theta, r_+, r_c) = T^{-1}. \quad (37)$$

Then the entropy of the system can be found from the relation

$$S = \beta \left( \frac{\partial I_s}{\partial \beta} \right)_{\theta, r_c} - I_s = \beta \left( \frac{\partial I_s}{\partial r_+} \right)_{\theta, r_c} \left( \frac{\partial I_s}{\partial r_+} \right)_{\theta, r_c}^{-1} - I_s = \pi r_+^2, \quad (38)$$

giving the known area law. The expression of the temperature is omitted here since it is rather lengthy but its plot is illustrated in Fig. 2 for different horizons inside the cavity. Depending on the fixed distance $r_c$ of the cavity wall relative to the minimal length $\sqrt{\sigma}$, the temperature may appear two (red curve in Fig. 2), one (black dashed curve in Fig. 2) or no extrema (blue curve in Fig. 2).

For $r_c = r_i$ the two extrema of the temperature merge at one inflexion point, while for $r_c > r_i$ the system appears always a local maximum and a local minimum temperature. The cavity has already changed the picture relative to the pure asymptotically flat regular case [10], where there is only one extremum for the temperature, as can be seen in Fig. 1. Inside the cavity there is a strong indication of a different phase transition when $r_c \geq r_i$. This can be checked by calculating the heat capacity

$$C = T \left( \frac{\partial S}{\partial T} \right) = -\beta^2 \left( \frac{\partial^2 I}{\partial \beta^2} \right)_{\theta, r_c}, \quad (39)$$

whose form is also omitted here but its shape is plotted in Fig. 3. For $r_c > r_i$ (red curve in Fig. 3) the heat capacity appears two divergent regions where $dT = 0$. In this case, there exists a small locally stable black hole with $C > 0$ when $r_+$ is smaller than the first divergent region. Then it turns to a locally unstable intermediate black hole with $C < 0$ when $r_+$ lies between the two divergences and finally it turns into a locally stable large black hole with $C > 0$ when $r_+$ is bigger than the second divergent region. Hence, a phase transition seems to take place between a small and a large stable black hole inside the cavity, in contrast to the asymptotically flat case of Sec. 2 without a cavity, where the transition occurs between background radiation and a small stable black hole. This small/large stable black hole transition seems to be similar with the liquid/gas transition of a Van der Waals gas [17], in contrast to the Hawking-Page-like transition of the singular black hole-cavity system [28]. For $r_c = r_i$ (black dashed curve in Fig. 3) the two stable black holes coexist at one inflexion point, while for $r_c < r_i$ (blue curve in Fig. 3) there exists a single thermally stable black hole with no phase transitions and with a temperature which is monotonically increasing with the horizon.

Similar phase structure appears also regular black holes [20,29] inside an AdS background without a cavity. In other words, either confining the regular black hole in a cavity, or placing it inside an AdS space, the black hole appears a small/large black hole phase transition, mimicking the liquid/gas transition of a Van der Waals gas. This indicates that AdS holography might not depend on some properties of AdS spacetime, but rather on the confinement characteristic, as has also been noticed in [28].

Last but not least, the Helmholtz free energy $F$ is the thermodynamic potential governing our system and is identified to be $F = I_s/\beta$. Its form is illustrated in Fig. 4. For $r_c > r_i$ the free energy appears two extrema (red curve in Fig. 4) with an unstable middle branch of an increasing $F$ due to the phase transition. These extrema correspond to the two divergences of the heat capacity, as can be seen from the above plots. For $r_c < r_i$ the free energy is a monotonically decreasing function of $r_+$ (blue curve in Fig. 4) with no indication of a phase transition, signalling this way the local and global stability of the system. For $r_c = r_i$ the two extrema of $F$ merge at one inflexion point (black dashed curve in Fig. 4).

5. Conclusions

We have presented a geometric and a thermodynamic analysis of a regular black hole enclosed by a cavity. The temperature at the walls and the radius of the cavity are held fixed, allowing us to work in a canonical ensemble. Based on the assumption that any regular black hole solution is described by a source of anisotropic fluid with two pressure terms, we performed the derivation of the reduced action. The new action is a generalization of the one describing a singular black hole, since it contains an extra matter action-piece that vanishes in the classical limit.
Applying this formalism to the profile of the noncommutative case, we derived through the reduced action all the necessary thermodynamic quantities, in order to study the phase structure of the system. The conclusion is that, above a certain value of the position of the cavity wall, i.e., $r_c \geq r_i$, the black hole can undergo a phase transition between a small/large stable black hole, similar to the liquid/gas transition of a Van der Waals gas, while for $r_c < r_i$ there exists always a thermally stable remnant. The enclosing cavity provides similar phase structure with the system of a regular black hole placed in AdS space without a cavity.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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