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Entanglement rules for holographic Fermi surfaces

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Abstract

In this paper, based on the notion of Gauge/Gravity duality, we explore the laws of entanglement thermodynamics for most generic classes of Quantum Field Theories with hyperscaling violation. In our analysis, we note that for Quantum Field Theories with compressible *quark* like excitation, the first law of entanglement thermodynamics gets modified due to the presence of an additional term that could be identified as the entanglement chemical potential associated with *hidden* Fermi surfaces of the boundary theory. Most notably, we find that the so called entanglement chemical potential does not depend on the size of the entangling region and is purely determined by the quark d.o.f. encoded within the entangling region.

1. Overview and motivation

In the recent years, the holographic models for non-relativistic Quantum Field Theories with hyperscaling violation [1–12] has been found to provide an excellent theoretical framework in order to describe compressible states of quark matter (distributed over the so called *hidden* Fermi surfaces) at strong coupling [13–15]. It turns out that for theories with holographic metals [16,17], the total charge density (associated with the boundary theory) largely dominates over that of the volume enclosed by the Fermi surfaces. In [18,19], the authors argue that such a deficit could be made up by considering hidden Fermi surfaces of fractionalized *deconfined* charged fermionic excitation known as *quarks*.

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In a recent paper [13], the authors first pointed out that the presence of such compressible states of quark matter could be identified by computing the holographic entanglement entropy (HEE) [20,21] for the boundary theory, which instead of showing the usual area divergence, exhibits the so called *logarithmic* divergence. These arguments were further sharpened by the authors in [14], who showed that an emerging infra-red geometry with arbitrary dynamic exponent (z) and hyperscaling violating parameter (θ) precisely characterizes the presence of such compressible quark matter excitation distributed over the hidden Fermi surfaces of the boundary theory.

The most natural question that arises in this context is whether there exists any notion of so called entanglement thermodynamics [22–29] for small subsystems associated with these hidden Fermi surfaces of compressible quark excitation. In other words, whether one could possibly write down some version of the first law of entanglement thermodynamics in the presence of these fractionalized charged fermionic excitation. Now, in the presence of these additional quantum numbers (fermionic d.o.f.), the first law of entanglement thermodynamics must be modified in order to include a term which should be analogous to that of the chemical potential term associated with the standard first law of thermodynamic. The question therefore turns out to be whether one could define such an entity (which we call entanglement chemical potential) associated with hidden Fermi surfaces that leads to a modified first law of entanglement thermodynamics and if such an entity exits then whether it is universal in the same sense as that of the entanglement temperature. The purpose of the present article is to provide a systematic answer to these questions based on some concrete holographic computations.

The organization of the paper is the following: In Section 2, we provide details regarding the gravitational set up in the bulk. In Section 3, we explore the modified first law of entanglement thermodynamics and compute the entanglement chemical potential associated with compressible states of quark matter. Finally, we conclude in Section 4.

2. The background

We start our analysis with a formal description to the gravitational solution in the bulk spacetime. The action that typically one considers is of the following form [30],

$$\begin{aligned} S &= S_{EH} + S_M \\ S_{EH} &= \frac{1}{16\pi G_N}\int_{\mathcal{M}} d^{d+2}x\sqrt{-g}R + \frac{1}{8\pi G_N}\int_{\partial\mathcal{M}} d^{d+1}x\sqrt{-h}K \\ S_M &= \frac{1}{16\pi G_N}\int_{\mathcal{M}} d^{d+2}x\sqrt{-g}\left[-\frac{1}{2}(\partial\Phi)^2 + V(\Phi) - \frac{e^{\lambda_1\Phi}}{4}H^2 + \frac{e^{\lambda_2\Phi}}{4}(-F^2)^s\right] \end{aligned} \tag{1}$$

where, $H^2 = H_{mn}H^{mn}$ and $F^2 = F_{mn}F^{mn}$ are the field strength tensors corresponding to two Abelian one forms B_m and A_m respectively. The first Abelian two form (H_{mn}) coupled with the dilaton (Φ) generates the desired asymptotic solution of the Lifshitz type. On the other hand, the second Maxwell field (F_{mn}) gives rise to the non-linear charged Lifshitz black brane configuration. Here, $V(\Phi)(= -2\Lambda e^{\gamma\Phi})$ is the so called exponential potential for the dilaton.