Physics Letters B 712 (2012) 272–278

Contents lists available at SciVerse ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

On entropic gravity: The entropy postulate, entropy content of screens and relation to quantum mechanics

M. Chaichian *, M. Oksanen, A. Tureanu

Department of Physics, University of Helsinki, P.O. Box 64, 00014 Helsinki, Finland

ARTICLE INFO

Article history:
Received 20 November 2011
Accepted 26 April 2012
Available online 30 April 2012
Editor: T. Yanagida

Keywords:
Entropic gravity
Entropic force
Emergent gravity
Emergent space
Quantum mechanics

ABSTRACT

We consider the controversial hypothesis that gravity is an entropic force that has its origin in the thermodynamics of holographic screens. Several key aspects of entropic gravity are discussed. In particular, we revisit and elaborate on our criticism of the recent claim that entropic gravity fails to explain observations involving gravitationally-bound quantum states of neutrons in the GRANIT experiment and gravitationally induced quantum interference. We argue that the analysis leading to this claim is troubled by a misinterpretation concerning the relation between the microstates of a holographic screen and the state of a particle in the emergent space, engendering inconsistencies. A point of view that could resolve the inconsistencies is presented. We expound the general idea of the aforementioned critical analysis of entropic gravity in such a consistent setting. This enables us to clarify the problem and to identify a premise whose validity will decide the faith of the criticism against entropic gravity. It is argued that in order to reach a sensible conclusion we need more detailed knowledge on entropic gravity. These arguments are relevant to any theory of emergent space, where the entropy of the microscopic system depends on the distribution of matter in the emergent space.

1. Introduction

We consider the entropic gravity (EG) hypothesis proposed by Verlinde [1], where gravity is an emergent phenomenon driven by the second law of thermodynamics: entropy increases until a thermodynamic equilibrium is reached. In EG, space, inertia and gravity are postulated to emerge from the thermodynamics of an unknown microscopic theory of holographic screens. This proposal was preceded by a considerable amount of research on the relation between gravity and thermodynamics, and by various attempts to give gravity a thermodynamic reinterpretation. These studies have been heavily motivated by the advent of black hole thermodynamics [2–6]. The idea of holography was originally introduced in Refs. [7,8]. In the seminal paper [9], the Einstein equation was derived locally on Rindler causal horizons as a thermodynamic equation of state (see also Refs. [10]). Other major contributions to the study of holographic and thermodynamic aspects of gravity were made in Refs. [11,12]. Among other things, the (holographic) relation of bulk and surface terms in gravitational actions were extensively studied in these latter works, arguing that the field equations of any diffeomorphism invariant theory of gravity have a thermodynamic reinterpretation and showing that the equipartition of energy in the microscopic degrees of freedom of a Rindler horizon can be used to derive gravity. These results suggest that gravity and spacetime might be emergent concepts which may have a thermodynamic origin. The new insight of Ref. [1] is to recognize that the entropy of a holographic screen can change due to the displacement of matter that is located far away from the screen. When a particle moves closer to a screen, the entropy density of the screen increases. In the presence of a nonzero temperature on the screen, this leads to an attractive entropic force that can be identified as gravity. Thus, in addition to storing the information that describes the world inside a screen, holographic screens also have to contain some information about the world outside. Clearly, the EG hypothesis is still heuristic at the moment.

In Ref. [13], we analyzed critically the treatment of neutron states in Ref. [14], where it was argued that EG fails to explain the observation of gravitationally-bound quantum states of neutrons. Extremely fine observations of the two lowest energy states of neutrons in a quantum bouncer formed by the Earth's gravitational field and a neutron mirror were performed in the GRANIT experiment [15,16] (for further analysis of the experiment, see also Refs. [17–20]). A method for observing magnetically-induced resonance transitions between gravitationally-bound quantum states of neutrons in the GRANIT spectrometer has been presented in Ref. [21], which could provide a way to measure the higher energy levels. An experiment that realizes resonance transitions between

* Corresponding author.
E-mail addresses: masud.chaichian@helsinki.fi (M. Chaichian), markku.oksanen@helsinki.fi (M. Oksanen), anca.tureanu@helsinki.fi (A. Tureanu).

0370-2693/$ – see front matter © 2012 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.physletb.2012.04.065

the gravitationally-bound neutron states by introducing a mechanically vibrating neutron mirror has been reported recently [22]. We concluded that EG does not necessarily contradict the results of the GRANIT experiment, since it is conceivable that the holographic description assumed in EG could produce not only gravity but quantum mechanics as well. Indeed the idea of holography is that everything inside a screen is an image of the data that is stored and processed on the screen.

In this Letter, we elaborate on the point of view of our criticism [13] and discuss the recent communication [23], where the conclusion of [14] is restated and it is also argued that the coherence and interference of quantum states is destroyed in EG, so that EG not only fails to explain the results of the GRANIT experiment but also, for example, the gravitationally-induced quantum interference [24].[1] The result of Refs. [14,23] is based on the argument that the size of the state space that describes a particle necessarily changes with the distance to another particle. We argue that a premise of the analysis of Refs. [14,23] is based on a misinterpretation concerning the relation of the microstates of a holographic screen and the state of a particle in the emergent space. This premise is the assumption that the state of a particle at position $\vec{r}$ is described by the density operator that consists of fragments of the microstates of the holographic screen that includes the point $\vec{r}$. This assumption leads to at least two inconsistencies, which we have briefly pointed out in Ref. [13]. We hope this observation will help us find a consistent way to accomplish such an important analysis.

First we discuss the interpretation of the fundamental entropy postulate of EG in Section 2 and the entropy content of screens in Section 3. In these two sections we expose the two inconsistencies that are implied by the aforementioned assumption concerning the description of the state of a particle in Refs. [14,23]. In Section 4 we elaborate on the arguments of our paper [13] and confirm that the description of the state of a particle used in Refs. [14,23] indeed leads to two inconsistencies. We also give detailed answers to the counterarguments presented in Ref. [23]. In Section 5 we discuss a point of view where the inconsistencies concerning the state of a particle can be avoided. The general idea of the argument in Refs. [14,23], and the decisive premise (see (13)) behind it, are expounded and discussed. We also consider the meaning of this argument in a generic theory of emergent space. Section 6 contains the conclusions.

We note that in addition to the papers [14,23], EG has also been criticized by other authors. Arguments against EG together with some clarifying comments and plausible ways out have been presented, e.g., in Refs. [25–29,13].

2. Interpretation of the entropy postulate

First we briefly review the EG hypothesis [1]. Consider the fundamental entropy postulate of EG [1]:

$$\Delta S = 2\pi m \Delta r. \tag{1}$$

We assume units in which $\hbar = c = k_B = 1$. What does the formula (1) mean? In (1), ΔS is the increase in the entropy of a holographic screen $\mathcal{S}$ when a test particle, which has the mass m and is located at the distance Δr from $\mathcal{S}$, moves to the immediate vicinity of $\mathcal{S}$. It is assumed that the information stored on the screen is somehow affected due to the approaching particle, so that its entropy changes according to (1). Finally the particle m merges into $\mathcal{S}$, essentially becoming a part of the information and energy on the screen. This interpretation of the entropy postulate (1) has some similarities with Bekenstein's famous thought experiment on black hole entropy [2]. Because of the increase in entropy (1) associated with the displacement Δr of the particle towards $\mathcal{S}$, there is a statistical tendency for the particle to be closer to $\mathcal{S}$. This leads to an attractive entropic force F that is defined by

$$F\Delta r = T\Delta S, \tag{2}$$

where T is the temperature of $\mathcal{S}$. This entropic force can be identified as gravity. From (1) and (2) we see that the gravitational acceleration is defined by the temperature of $\mathcal{S}$ as $g = 2\pi T$. In other words, T is equal to the Unruh temperature $T = g/2\pi$. More generally, the particle m can be located at any distance from the screen. Then an infinitesimal displacement $\delta\vec{r}$ of the particle m is associated with a change δdS in the entropy density of the screen $\mathcal{S}$, and the resulting entropic force $\vec{F}$ is defined by [1,25]

$$\vec{F}\cdot\delta\vec{r} = \int_{\mathcal{S}} T\delta\, dS, \tag{3}$$

where the integral is taken over a screen that does not contain the particle at $\vec{r}$.

The number of microscopic degrees of freedom N on a screen is proportional to the area A of the screen as

$$N = \frac{A}{G}, \tag{4}$$

where G is the gravitational constant, i.e. Planck length squared. The average energy of a microscopic degree of freedom is assumed to be defined by the temperature on the screen according to the equipartition rule[2] $\langle E_{\text{d.o.f.}}\rangle = \frac{1}{2}T$. Hence, the total energy E of the screen, which is equal to the mass M it contains, is given by

$$M = E = \frac{1}{2}NT, \tag{5}$$

assuming the energy is evenly distributed over the microscopic degrees of freedom. In the more general description one writes

$$\int_{(\mathcal{S})} \varrho\, dV = \frac{1}{2}\int_{\mathcal{S}} T\, dN = \frac{1}{2G}\int_{\mathcal{S}} T\, dA, \tag{6}$$

where ϱ is the mass density and $\int_{(\mathcal{S})} dV$ denotes the integral over the volume enclosed by $\mathcal{S}$.

Consider a system that consists of a particle of mass M at the origin and a spherical holographic screen $\mathcal{S}_r$ of radius r around M and a test particle of mass m at $r + \Delta r$. The temperature of the screen $\mathcal{S}_r$ can be obtained from (4) and (5) as:

$$T = \frac{2M}{N(r)} = \frac{GM}{2\pi r^2}, \tag{7}$$

where the number of microscopic degrees of freedom on $\mathcal{S}_r$ is

$$N(r) = \frac{4\pi r^2}{G}. \tag{8}$$

Now let us compare our understanding of the entropy postulate (1) to the interpretation of Refs. [14,23]. In Ref. [23], it is stated that the test particle m at position r is described by a statistically

[1] This claim was already present in Ref. [14] implicitly, where it is argued that the coherence of any state that extends in the direction of gravity is destroyed in EG.

[2] It has been pointed out that the equipartition rule needs to be corrected at very low temperatures due to the quantization of the energy of the microscopic degrees of freedom [30,31]. It has also been argued that Newton's gravitational law is dramatically altered for high gravitational fields if the energy of the microscopic degrees of freedom is bounded [32].