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Unruh thermal hadronization and the cosmological constant

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A B S T R A C T

We use black holes with a negative cosmological constant to investigate aspects of the freeze-out temperature for hadron production in high energy heavy-ion collisions. The two black hole solutions present in the anti-de Sitter geometry have different mass and are compared to the data showing that the small black hole solution is in good agreement. This is a new feature in the literature since the small black hole in general relativity has different thermodynamic behavior from that of the large black hole solution. We find that the inclusion of the cosmological constant (which can be interpreted as the plasma pressure) leads to a lowering of the temperature of the freeze-out curve as a function of the baryochemical potential, improving the description previously suggested by Castorina, Kharzeev, and Satz.

1. Introduction

In recent years relativistic heavy-ion collisions at high energies have become a laboratory for exploring new states of matter [1–4] and for testing exciting new ideas for the description of these novel states [5–9]. It is currently understood that in these reactions a strongly interacting quark–gluon plasma (QGP) forms and behaves like a nearly perfect liquid, i.e. the shear viscosity is very small [10,8]. However, the approach to apparent local equilibrium is still under debate [11,12]. Current estimates of these effects are based on hydrodynamical modeling (mostly at vanishing baryochemical potential μ_B) [13–16], lattice QCD [17,18] or, via gauge/gravity duality, on strongly coupled dual non-Abelian plasmas with a large number of colors [19,20].

Lattice QCD is the main non-perturbative technique that can be used to study strongly interacting QCD physics. However, when $\mu_B \neq 0$, lattice approaches are affected by the sign problem of the fermion determinant. Various alternative tools have been developed to address this issue, allowing one to investigate, at least in principle, small chemical potentials on the lattice (see for instance [21–24]). It is therefore important to have other theoretical ways to study QCD phenomena in the strongly coupled regime at nonzero T and μ_B.

Gauge/gravity duality has provided relevant insights into the study of real-time non-equilibrium dynamical phenomena (for a review see [25] and references therein). – The duality allows one to calculate physical quantities describing a strongly coupled gauge theory on the boundary of a $d+1$ space with a gravitational theory. Holographic descriptions of strongly interacting systems (bottom-up models) cannot be obtained in general from top-down string theory constructions and are based on the conjectured validity of the duality under more general circumstances.

Here, however, we consider the analogy between gravity and gauge theories from another point of view, based on a conceptual framework proposed some time ago [26–28] and developed in more detail over recent years [29,30]. The analogy relies on the confinement property of QCD, i.e. the fact that QCD forbids colored constituents to exist in the physical vacuum. It resembles in some way the phenomenon of gravitational confinement of matter inside a black hole. Indeed, a black hole can be regarded as a solution to Einstein's equations defined by a confining potential. The fate of matter near a black hole (within its innermost stable circular orbit) is to inevitably fall through the event horizon in the absence of countervailing forces. The application of the quantum mechanics to black holes resulted in the discovery of their thermal emission [31]. Soon after Hawking's pioneering work, Unruh

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showed that an observer under uniform acceleration a experiences a thermal bath at temperature $T = a\hbar/2\pi$ [32].

In other words confining potentials in general lead (quantum mechanically) to an intrinsic temperature. This led to the proposal that quarks in a confining potential are also associated with an effective temperature for hadrons [33]. More specifically, following the connection between gravitational properties and particle physics, a conjecture was put forward that color confinement causes the physical vacuum to form an event horizon for quarks and gluons that can only be crossed by quantum tunneling [29,34]. In this sense hadron production corresponds to a form of Hawking–Unruh radiation in QCD.

This analogy is also supported by two additional facts in black hole physics:

(i) The metric of a system in uniform acceleration, the Rindler metric, is equivalent to the near-horizon approximation of the black hole metric if the acceleration is equal to the surface gravity κ;
(ii) Hawking radiation is a quantum phenomenon associated with pair-creation near the event horizon and the tunneling of particles [35–37], in analogy with string breaking [38–40] and pair creation in systems with uniform acceleration.

Within the context of the above conjecture, one may consequently propose the following hypotheses: (a) the hadronic freeze-out temperature at high energy is an Unruh temperature; (b) the associated Rindler horizon can be identified with a "color blind" horizon dynamically produced by the color charge confinement during the $q\bar{q}$ production.

Previous approaches toward a concrete realization of this conjecture have been restricted to a charged black hole in an asymptotically flat background [41]. However (as well shall see) the freeze-out temperature obtained by this analogy does not describe the data at low T and large μ_B [41].

In this paper we enlarge the analogy presented in [29,42] to a charged black hole in anti-de Sitter spacetime (AdS). We vary the AdS curvature radius and see if it has a particular counterpart in the description of the freeze-out. The thermodynamics of an AdS black hole has features that we will see are important in the analogy, namely a minimum temperature $T_{\min}$, which occurs when the horizon radius is of the order of the characteristic radius of the AdS space [43]. Above $T_{\min}$ there are two possible black hole solutions with different radii. We find that the freeze-out temperature is well described by the Hawking temperature of the small AdS charged black hole, providing a very favorable fit to current data.

The sections are organized as follows: in Sec. 2 we review anti-de Sitter spacetime and the hypothesis of interpreting a variable negative cosmological constant as pressure. In sec. 3 we review the connection proposed in [29,42] between black holes and QCD. Sec. 4 presents to our calculations and results. Finally, sec. 6 is dedicated to the conclusions.

2. Gravitational pressure

The study of black hole thermodynamics in the presence of a negative cosmological constant Λ (i.e. an AdS background) has exhibited very interesting properties [43], subsequently opening the way to further insights into string theory [44] and thermodynamic phase transitions [45–47]. The notion that the cosmological constant itself might be considered as a dynamical variable was initially suggested by Teitelboim and Brown in [48,49], while the relative thermodynamic term was included only later into the first law of black hole thermodynamics [50]. The idea of associating the cosmological constant with pressure was then explored in different ways [51–53]. In contrast to an asymptotically flat Schwarzschild black hole, a black hole in an AdS background with sufficiently large radius (as compared to the AdS radius ℓ) has positive specific heat and so can be in stable equilibrium at a fixed temperature (where the AdS space mimics a gravitational box). Depending on the temperature, it can also be subjected to a phase transition to pure radiation known as the Hawking–Page transition [43]. In the framework of the AdS/CFT duality, this transition was later associated with a confinement/deconfinement phase transition in the field theory on the boundary [54]. The idea of associating the cosmological constant Λ and hence the AdS radius ℓ, see Eq. (1), with a pressure (along with the notion of a conjugate thermodynamic volume) requires the generalization of the laws of black hole mechanics [53]. The pressure can be defined as

$$P = -\frac{\Lambda}{8\pi G} = \frac{(d-1)(d-2)}{16\pi G\ell^2}, \tag{1}$$

where d is the number of spacetime dimensions and G is the Newton constant. The resultant generalized first law of black hole thermodynamics is

$$\delta M = T\delta S + V\delta P + \Omega\delta J + \Phi\delta Q \tag{2}$$

where J is the black hole angular momentum and Q the charge. The quantity M is the conserved charge associated with the time-translation Killing vector of the spacetime. The entropy is related to area of the black hole event horizon according to $S = A/(4\hbar G)$ and the Hawking temperature is $T = \hbar\kappa/(2\pi)$ where κ, as mentioned before, is its surface gravity. The conjugate thermodynamic volume to the pressure is defined as $V \equiv (\partial M/\partial P)_{S,Q,J}$. From this viewpoint the confinement/deconfinement phase transition can be understood as a solid/liquid phase transition [55,56].

Because of the presence of the cosmological constant in Eq. (2), the mass M cannot be interpreted as usual as the internal energy of the system. Rather, M can be understood as the gravitational version of the chemical enthalpy [53], i.e., the total energy of a system containing both the energy PV needed to displace the vacuum energy of its environment and its internal energy E [55].

The definition of the cosmological constant as pressure will allow us to proceed with the study of the freeze-out temperature using the physical parameters M, Q, P of the extended phase space. Using the pressure in this way we introduce the corresponding thermodynamic volume. Therefore, for each value of P we will consider the corresponding volume of the (regularized) spacetime at a fixed time slice that is the volume inside the black hole.

3. QCD and black holes

Classically, a black hole just absorbs matter. On the quantum level, however, matter inside the black hole (i.e., its constituents: hadrons, leptons and photons) has a non-vanishing probability to escape by tunneling through the barrier of the event horizon. The transmitted radiation is thermal and ensures color neutrality. The thermal behavior of black holes is fully encoded in the thermodynamic description: Hawking radiation cannot give any information related to the internal state of the black hole.

In all collisions e^+e^-, pp, $p\bar{p}$, πp, etc..., including nucleus–nucleus scattering, particle production likewise exhibits thermal behavior that seems to occur at the same temperature [40,57–62] (see also [63]). This feature motivated the proposal [29] that in relativistic heavy-ion collisions at large $\sqrt{s}$, corresponding to zero baryochemical potential [61], the hadronic freeze-out temperature T is an Unruh temperature. Hadronization can be seen as the