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The quark–gluon plasma and D6-branes on the conifold

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Abstract

We investigate the possibility of constructing a supergravity background dual to the quark–gluon plasma using D6-branes wrapping a three-cycle in the deformed conifold. The UV-completion of this setup is given by M-theory on a G_2 holonomy manifold. For the class of metrics considered we find that there are only non-extremal D-brane solutions in the limit of the singular conifold with the singularity being resolved by the D-brane horizon. The thermodynamic properties of the system show some puzzling features, such as negative specific heat at an unusual behavior of the entropy. Among the properties of the plasma studied using this holographic dual are the quark–antiquark potential, the shear viscosity and parton energy loss. While one finds the expected behavior for the potential and the viscosity – deconfinement and the universal shear-viscosity to entropy ratio – both the jet quenching parameter and the calculation of the drag force lead us to the conclusion that there is no parton energy loss in the dual plasma. Our results indicate that the background constructed is not dual to a realistic QGP, yet we argue that this should improve upon inclusion of the three-form gauge potential in the eleven-dimensional background.

1. Introduction and summary

As it is well known, the gauge/string theory correspondence relates strongly coupled gauge with weakly coupled string theories and vice versa [1–3]. Further developments in the field lead to studies of the non-perturbative quark–gluon plasma (QGP) as produced in relativistic heavy ion collisions [4–7] or as relevant to the physics of the early universe and super dense stars. Among the items that were studied using a gravity dual are the plasma's shear viscosity [8], photoproduction [9], jet-quenching [10], and drag force [11].[1]

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[1] A recent review on the uses of gauge/string duality and QGP physics is [12]. The general properties of the plasma in general and RHIC physics are summarized in [13] and [14].

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A large portion of the research conducted in this area centers on $\mathcal{N}=4$ super-Yang–Mills and AdS/CFT in its best understood form, D3-branes in type IIB theory. Apart from the fact that this is the most tractable of gravity duals, one reason for choosing $\mathcal{N}=4$ is that albeit having properties very different from those of QCD at $T=0$, the two theories start to appear more and more similar as soon as there is finite temperature. Despite these successes however a complete study of QGP physics based on string theory demands for an investigation of the $T\neq 0$ behavior of other gravity duals showing a stronger resemblance to QCD even at zero temperature. Some work in this direction was undertaken in [15–19]

In this paper we investigate the possibility of constructing a supergravity background dual to an $\mathcal{N}=1$ QGP based on D6-branes wrapping an S^3 in the deformed conifold. In order for some supersymmetry to be preserved, the field theory living on the world-volume of the branes has to be topologically twisted [20]. Apart from the usual gauge/gravity correspondence, the theory exhibits a further large N duality, the conifold transition, whose history starts with [21]. Here it was shown that topological string theory on a blown up Calabi–Yau conifold is equivalent to Chern–Simmons gauge theory on S^3 at large N. This duality reappears in the context of the AdS/CFT correspondence when considering N D6-branes wrapping an S^3 in the deformed conifold [22], as the conifold transition connects this setup to type IIA string theory on the resolved conifold without any branes but with N units of Ramond–Ramond flux through an S^2. Independently of whether one starts from the resolved or the deformed conifold, when lifting to M-theory the geometry is that of the spin bundle over S^3, a manifold with G_2 holonomy [23], and the duality takes the form of the flop transition [24]. The connection to 8-dimensional gauged supergravity was established in [25].

The duality resurfaces in the gauge-theory as follows. For $\lambda = N g_{\mathrm{YM}}^2 = N g_s \ll 1$, the gauge-theory is best described by the N D6-branes wrapping the S^3. For large 't Hooft coupling however, one needs to consider the branes' gravitational backreaction and makes therefore use of the resolved conifold. The theory is pure $\mathcal{N}=1$ super-Yang–Mills with additional massive degrees of freedom from Kaluza–Klein reduction. We will see it is not possible to fully decouple these modes. Also, as was already shown in [26] for the case of flat D6-branes, one cannot expect the gauge theory to fully decouple from gravity.

If one wants to use this gravity dual to study the QGP, one needs to add a black hole to the supergravity background. As the theory is purely gravitational when lifting to eleven dimensions, the equations of motion take the simplest form possible here,

$$R_{\mu\nu} = 0, \tag{1.1}$$

making this the best place to perform the search for a black hole solution. As we find in Section 4, if one wants to keep the ansatz for the new metric as simple as possible by making the substitutions

$$dt^2 \to f(\rho)\,dt^2, \qquad d\rho^2 \to \frac{d\rho^2}{f(\rho)}, \tag{1.2}$$

there is a non-trivial solution if and only if one makes the geometry of the G_2 manifold singular. The unique solution is then $f = 1 - \rho_h^5/\rho^5$, where the singularity at $\rho = 0$ is hidden by the horizon $\rho_h > 0$. When studying the thermodynamics of this new solution, we will see that the black hole behaves in many ways as the ordinary Schwarzschild solutions in four and eleven dimensions. I.e. the temperature is proportional to the inverse of the horizon, $T = \frac{5}{4\pi\rho_h}$, and the specific heat is negative. As the horizon of the black hole covers the six-dimensional base of the internal G_2 cone, the entropy behaves as $S \propto \rho_h^6$, leading to the surprising relation $S \propto T^{-6}$.