Using black hole physics to compute the energy loss of a quark in strongly coupled QCD

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Abstract. The AdS/CFT duality can be applied to study strongly coupled regimes of QCD, such as the quark-gluon plasma. Gravity is a key factor in the understanding of the duality and an intriguing correspondence between the gravitational properties of higher-dimensional black holes and quark/gluon physics can be established. In this context, I will show that the dual theory allows us to identify a new mechanism for the energy loss of a deconfined quark in this plasma, which can be described as Cherenkov radiation of vectorial mesons. The corresponding results might be observed in heavy-ion collision experiments.

1. Introduction
The purpose of this work is to study an experimental situation: The emission of meson Cherenkov radiation when a quark goes through a quark-gluon plasma. This is a phase of QCD which exists at extremely high temperature and density. It consists basically of free, deconfined quarks and gluons. Current heavy-ion collision experiments at the RHIC of Brookhaven are studying the properties of the quark/gluon plasma, and future experiments at the LHC will continue this effort.

2. New mechanism of energy loss
The classical phenomenon known as Cherenkov radiation is an electromagnetic radiation emitted when a charged particle, such as an electron, passes through an insulator faster than the speed of light in that medium. An analogous phenomenon is expected to happen in the context of quantum chromodynamics. The quark, in this case, would radiate mesons.

As a consequence of this radiation, the quark loses energy. Therefore, it represents a new mechanism of energy loss, “new” in the sense that it has not been studied before. But, because the plasma is a strongly-coupled phase of QCD, its theoretical study remains a challenge. There are no systematic methods with which we can analyze its non-perturbative properties. This is why the gauge/string duality, so-called AdS/CFT, is a useful tool to treat the problem, providing at the same time a theoretical understanding. In this case, it will allow us to identify the mechanism of this loss of energy.

3. String theory background
In the dual string theory, a deconfined quark corresponds to an open string stretching between D-branes, in the 10-dimensional spacetime. D-branes are solitonic solutions of the equations of
And to be precise, our framework involves $N_c$ coincident black D3-branes and also $N_f$ coincident D7-branes. The D3-branes are surrounded by a horizon, like a black hole. This is required because we are interested in studying the plasma at temperature different from zero, and the temperature of the dual gauge theory corresponds to the Hawking temperature of this black hole (By considering $T > 0$ we will extend the analysis considered in [1]).

The metric sourced by the black branes is asymptotically flat, but in the neighboring region it develops a throat geometry described by 5-dimensional Anti-DeSitter spacetime (plus a 5-sphere at each point: $AdS_5 \times S^5$). And, since the number of flavors is considered to be much smaller than the number of colors, $N_f << N_c$, the D7-branes can be considered as probes in this geometry, neglecting their gravitational effect. Besides, the D7-branes, so-called flavor branes, introduce new degrees of freedom in the theory, corresponding to strings stretching between them and the D3, which would be matter in the fundamental representation in the dual gauge theory (such as quarks). And also, there are open strings with both ends on the flavor branes, which correspond to bound states of quarks and antiquarks; mesons.

These open string excitations are represented by fields, which live on the worldvolume of the branes, and their spectrum can be found by computing the brane fluctuations. The full spectrum of meson excitations includes scalar and vector modes. These meson fields will couple to the external quark, that is why they are interesting for us.

I will not go into the details of the calculations here, but they involve the embedding of the D7-branes which bend towards the black hole (see figure 1), and the corresponding induced metric. Physically, the scalar fields have a geometrical interpretation, in terms of the
deformations of the shape of the branes along the transverse directions.

4. Mesons on the brane
First, we extremize the action of the brane to find the solution for the embedding. The solutions fall into two classes: “Black hole” embeddings, if the brane falls into the horizon, and “Minkowski” embeddings, if the brane closes-off smoothly outside (see figure 2). The presence of one or the other depends on the size of the horizon, which is related to the temperature. In the dual theory, this corresponds to a phase transition exemplified by discontinuities in some observable quantities. For instance, in the Minkowski phase, the mesons are stable and the spectrum is discrete with a mass gap; whereas in the black hole phase, stable mesons cease to exist and instead we find a continuous gapless spectrum of excitations. Hence the phase transition is characterized by the dissociation or “melting” of the mesons (see the discussion in [2]).

In the next step, we consider fluctuations around this background embedding, and obtain the linearized equations of motion for the scalar fields. In the case of vector mesons, this is a little more complicated because we need to consider the contribution of non-Abelian gauge fields. For each choice of the three-momentum $\vec{q}$, we tune the frequency $\omega$ in order to find solutions that vanish asymptotically. Thus, by selecting normalizable solutions, we can find the dispersion relations for the modes of the meson fields (see figure 3).

For the vector fields, there is a decomposition into two transverse modes and one longitudinal mode. Each one has a different dispersion relation, although they converge to the same value at zero momentum, because in that case there is no distinction between these modes. There is a set of normalizable solutions, indexed by $n$. We can also solve numerically the equations and plot their radial profiles (see figure 4). Note that the profiles of $n > 0$ cross the axis, and the number of crossings is precisely $n$.

And notice also that the profiles corresponding to greater $q$ are more peaked around the origin. The intuitive explanation is that greater frequency means greater energy, and the gravitational pull of the black hole has a greater effect over those more energetic mesons. The most important characteristic of these plots is that examining the regime of large $q$, we get a linear relation, and
the slope is the same for all the modes. Its value is given by the local speed of light, which is affected by the redshift of the black hole:

\[ c = \sqrt{-\frac{g_{tt}}{g_{xx}}} \]  

(1)

The intuitive explanation is that the radial profiles of the mesonic fields are very peaked around the origin, which is the point of maximum curvature of the embedding of the D7-branes. So we can roughly think of them as excitations propagating along the bottom of the branes, and the speed of these signals is therefore set by the speed of light. Actually, this is a clear and beautiful result that supports the physics behind the duality: Basically, the phase velocity of the mesons is given by the redshift of a black hole.

5. Phenomenology

The mesonic Cherenkov radiation will be produced when the quark exceeds this limiting velocity of the mesons. Just in the same way as its classical counterpart were produced when the electron surpassed the limiting velocity of light.

Hopefully, we will be able to study the coupling between the quark and the meson fields and calculate the energy loss of the quark. This is work in progress, recent results can be found in [3]. The aim is to obtain results which might be contrasted with results from real experiments.

Although we should draw into attention that the correspondence we are working with relates the 10-dimensional physics to \( \mathcal{N} = 4 \) SYM gauge theory, not QCD. However, finite temperature breaks both the supersymmetry and the conformal invariance of the SYM theory, and this encourages us to think that some properties of the SYM plasma may be shared by the real-life QCD plasma.

References

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