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Heavy Mesons Moving in Plasmas at Finite Chemical Potential via Holography

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We study the qualitative behavior of heavy quarks and mesons moving in strongly coupled plasmas with a nonzero chemical potential by means of deformations of the gauge/gravity (AdS/CFT) duality. Here, we report on our studies of the quark-antiquark screening distance and free energy. These observables show some insensitivity as to which model and deformation is used, which appears to point to strong-coupling universal behavior that depends only weakly on the microscopic details. By this token, the results may be relevant for modeling heavy quarkonia traversing a quark-gluon plasma at finite net baryon density, and their suppression by melting.

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The simplest incarnation of gauge/gravity duality ([1]; see *e. g.* [2] for a review) is the duality between classical supergravity (SUGRA) on AdS_5 and $\mathcal{N}=4$ supersymmetric Yang–Mills theory (SYM) with gauge group $SU(N_c)$ in the limit of infinite number of colors, $N_c \to \infty$, and large 't Hooft coupling $\lambda \equiv g_{YM}^2 N_c$. A thermal bath for the gauge theory is dual to a black hole in AdS_5. Having a charge on the black hole corresponds to a chemical potential in the gauge theory.

To come closer to real-world physics, we study models in which *conformality is broken* by deforming the AdS space, namely the *CGN model* proposed by Colangelo, Giannuzzi, and Nicotri [3], as well as a family of *1-parameter models*. We derive the latter from the action used by [4], which adds to 5-dimensional gravity with metric $g_{\mu\nu}$ a scalar field ϕ and a $U(1)$ gauge field A_μ whose boundary value is dual to the chemical potential in the gauge theory. Our ansatz with deformation parameter κ is

$$g_{\mu\nu}\mathrm{d}x^\mu \mathrm{d}x^\nu = \mathrm{e}^{2A(z)}\left(-h(z)\mathrm{d}t^2 + \mathrm{d}\vec{x}^2\right) + \frac{\mathrm{e}^{2B(z)}}{h(z)}\mathrm{d}z^2\,, \tag{1}$$

$$A(z) = \log\left(\frac{R}{z}\right), \qquad \phi(z) = \sqrt{\frac{3}{2}}\kappa z^2, \qquad A_\mu \mathrm{d}x^\mu = \Phi(z)\mathrm{d}t\,, \tag{2}$$

where R is a constant and $h(z)$ is the redshift factor induced by the black hole. The solutions are too complicated to reproduce them here [5]. Depending on the interpretation of ϕ, the model has two variants, called 'string frame' and 'Einstein frame' models. These, solving equations of motion, are more consistent models than the CGN model, in which the deformation is put into the metric 'by hand'. This leads to some—in our opinion—unphysical artifacts at low temperatures and chemical potentials, which reveal themselves only when investigating moving probes [6] and which are absent in the 1-parameter models.

Let us consider a dipole made of an infinitely heavy quark and its antiquark (as a model for heavy quarkonia like J/ψ or Υ), separated by a distance L in the deconfined plasma of the gauge theory. Its holographic description proceeds via the analysis of a macroscopic string connecting the quarks in the 5-dimensional bulk (see *e. g.* [2]). It turns out that there is a distance L_s, such that for $L < L_s$ there are two string configurations connecting the dipole, while no such solution exists for $L > L_s$. Thus, L_s is called the *screening distance* of the $Q\bar{Q}$ interaction in the thermal medium. The free energy $F(L)$ of the $Q\bar{Q}$ system is encoded in the extremal string action.

We analyze the behavior of these observables with special emphasis on differences and commonalities of their behavior in the different models under consideration. Fig. 1 shows the changes of the screening distance and the free energy as we vary the deformation in the 1-parameter models, and hence switch to a different theory on the dual side. In the studies [7], which worked at $\mu = 0$, it was found that at any temperature T the screening distance is bounded from below by $L_s^{\mathcal{N}=4\,\mathrm{SYM}}(T)$ under all consistent deformations (in the sense of solving equations of motion of a suitable 5-dimensional (super-)gravity action). As is illustrated in Fig. 1 (right), this bound is violated at finite chemical potential μ if the deformation κ is sufficiently small such that $\mu \gtrsim \sqrt{\kappa}$. (Additionally, in the 'string frame' model the $Q\bar{Q}$ velocity has to be sufficiently large.) Conversely, at *any* κ, there is a μ so large that the bound will be violated. However, even at maximal deformation, the amount of the violation of the bound is relatively small such that there might exist a slightly lower, improved bound. Especially in the 'Einstein frame' model, both the free energy and the screening distance depend only weakly on the deformation, and hence on the model.

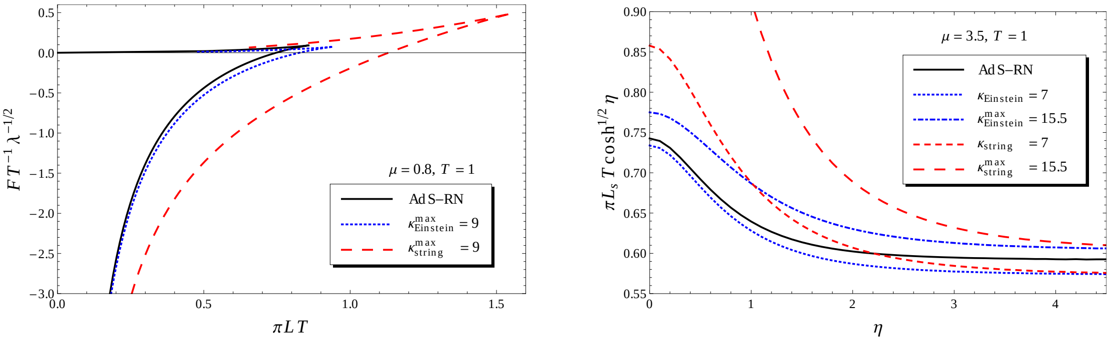

Figure 1: Evolution of observables at finite temperature T and chemical potential μ in the 1-parameter models, from the conformal case ('AdS-R(eissner)N(ordström)') to the maximal deformation κ consistent with a black hole solution providing the given (μ, T) (given in arbitrary units). **Left:** $Q\bar{Q}$ free energy at finite temperature and chemical potential. The tips of the curves represent the respective screening distances. The free energy of the stable branch is Coulomb-like, $F(L) \propto -1/L$, for small L. The deviations from this form can be ascribed to the presence of the thermal medium for L of order the thermal scale $L_{\text{th}} \sim 1/T$, and to the non-conformality introduced by the deformation for intermediate L. **Right:** Screening distance in the 1-parameter models under variations of the $Q\bar{Q}$ rapidity $\eta = \tanh(v)$. The asymptotic behavior $L_s \propto \cosh^{-1/2}(\eta)$ [8] is scaled out. At large η, the differences between the two 1-parameter models vanish.

We highlighted some results from our studies of classes of deformed gauge/gravity models of strongly coupled plasmas at nonzero chemical potential. The robustness of the behavior of heavy quark-antiquark dipoles under deformations of $\mathcal{N} = 4$ SYM theory indicates that this 'toy' model may be used to qualitatively analyze the physics in the QCD medium produced in heavy ion collisions at RHIC and LHC, as well as in future FAIR experiments, where the ability to theoretically handle nonzero chemical potential becomes crucial. Improvements are possible by using deformed non-conformal models. A more comprehensive description of our studies is in preparation.

Acknowledgments

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