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Entropic destruction of heavy quarkonium in the quark-gluon plasma

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Abstract

The excitations of a bound state immersed in a strongly coupled system are often delocalized and characterized by a large entropy, so that the state is strongly entangled with the rest of the statistical system. If this entropy S increases with the separation r between the constituents of the bound state, $S = S(r)$, then the resulting *entropic force* $F = T\,\partial S/\partial r$ (T is temperature) can drive the dissociation process. Lattice QCD indicates a large amount of entropy associated with the heavy quark pair in strongly coupled quark-gluon plasma. This entropy $S(r)$ peaks at temperatures $0.9\ T_c \le T \le 1.5\ T_c$ (T_c is the deconfinement temperature) and grows with the inter-quark distance r. This peak in the holographic description arises because the heavy quark pair acts as an eyewitness to the black hole formation in the bulk – the process that describes the deconfinement transition. In terms of the boundary theory, this entropy likely emerges from the entanglement of a "long string" connecting the quark and antiquark with the rest of the system. We argue that the entropic mechanism results in an anomalously strong quarkonium suppression in the temperature range near T_c. This *entropic destruction* may thus explain why the experimentally measured quarkonium nuclear modification factor at RHIC (lower energy density) is smaller than at LHC (higher energy density), possibly resolving the "quarkonium suppression puzzle" – all of the previously known mechanisms of quarkonium dissociation operate more effectively at higher energy densities, and this contradicts the data.

Keywords: quark-gluon plasma, heavy quarkonium, entropy, holography

1. Introduction

The studies of heavy quarkonium at finite temperature are expected to advance the understanding of QCD plasma and to clarify the nature of the deconfinement transition. It was originally proposed [1] to use quarkonium suppression in heavy ion collisions as a way to detect the Debye screening in the quark-gluon plasma. The subsequent experimental studies of quarkonium production in nuclear collisions at different energies however revealed a puzzle – the charmonium suppression observed at RHIC [2] (lower energy density) appeared to be stronger than at LHC [3] (larger energy density). This is in contrast to both the Debye screening scenario [1] and the thermal activation [4] through the impact of gluons [5, 6]. One possible solution to this puzzle is the recombination of the produced charm quarks into charmonia [7, 8, 9].

However, recently it was argued [10, 11, 12] that an anomalously strong suppression of charmonium near the deconfinement transition can be a consequence of the nature of deconfinement. The argument put forward in [10, 11, 12] is based on the lattice QCD results [13, 14, 15, 16] indicating a large amount of entropy associated with the heavy quark-antiquark pair placed in the quark-gluon plasma. This entropy S was found to grow as a function of the distance L between the quark and antiquark on the lattice [13, 14, 15, 16]. The proposal of [10] is that this entropy should give rise to the emergent entropic force

$$F = T\,\frac{\partial S}{\partial L}, \tag{1}$$

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where T is the temperature of the plasma. It has been found that the repulsive entropic force leads to a strong suppression of charmonium states near the deconfinement transition. The leading role of the entropic force in the deconfinement transition itself has been conjectured [10, 11, 12], as well as a possible relation of the observed peak in the entropy near the deconfinement transition to the "long string" condensation [17, 18, 19, 20, 21, 22, 23].

The entropic force does not describe any additional fundamental interaction; instead, it is an *emergent* force that stems from multiple interactions driving the system, in accord with the second law of thermodynamics, towards the state with a larger entropy. The entropic force was originally introduced [24] to explain the elasticity of polymer strands in rubber. The rubber polymer strands are long, and when stretched, possess smaller entropy than in the ground state where their motions are unrestricted. The stretched polymers thus tend to contract to the ground state, and this causes a macroscopic entropic force resulting in the contraction of the stretched rubber band. The underlying fundamental interactions are of course electromagnetic, but the notion of entropic force allows to bypass the consideration of complicated microscopic dynamics.

The physical reason for the increase of the entropy of the heavy quark pair with the inter-quark distance is likely the abundance of the physical states that become available for the separating heavy quarks – while at short distances the color dipole moment of the pair is small and it decouples from the medium, at larger distances the heavy quarks may form extended bound states characterized by a larger entropy.

By (1), the increase of the entropy with the quark-antiquark distance leads to the entropic force that points outward and can induce the self-destruction of the bound state. The resulting delocalization of heavy quarks, and thus the quarkonium suppression rate, is maximal near the deconfinement transition temperature [10]. This provides a possible explanation for the puzzling energy dependence of the heavy quarkonium nuclear modification factor observed at RHIC [25] and LHC [3]: even though the density of produced matter is higher at LHC than at RHIC, the nuclear modification factor at LHC appears larger than at RHIC.

2. Entropic force and diffusion

Let us summarize the entropic approach to diffusion proposed by Neumann [26]. Consider a particle released at the origin $r = 0$. The number of states for the particle at distances between r and $r + dr$ is proportional to the volume $dV(r) = 4\pi r^2 dr \equiv \Omega(r)dr$, and the corresponding r-dependent part of the entropy is

$$S(r) = k \ln \Omega(r) = 2k \ln r + const; \tag{2}$$

where we wrote explicitly the Boltzmann constant k. The resulting entropic force is

$$F(r) = T\frac{\partial S}{\partial r} = \frac{2kT}{r}. \tag{3}$$

In a viscous fluid, the ensemble average of the entropic force is equilibrated by the average of the Stokes force that is proportional to the particle's velocity,

$$\langle F(r) \rangle = c \left\langle \frac{dr}{dt} \right\rangle; \tag{4}$$

for a spherical particle of radius R the constant c in the Stokes force is proportional to the shear viscosity of the fluid η:

$$c = 6\pi R\eta. \tag{5}$$

In using the hydrodynamical notion of viscosity, we assume that the number of interactions needed to change r substantially is very large. The ensemble average is thus performed over the continuous three-dimensional Gaussian probability distribution

$$P(r) = \frac{4\, r^2}{\sqrt{\pi}\, q(t)^3}\, \exp\left(-\frac{r^2}{q(t)^2}\right), \tag{6}$$

defined as follows: after time t the particle will be located between r and $r + dr$ with the probability $P(r)dr$ normalized by $\int P(r)dr = 1$, and $q(t)$ is the most probable value of $r(t)$. It is well known that the Gaussian distribution as a limit of Bernoullian distributions when the number of steps in a walk becomes very large [27].

Performing the averages of different powers of r over the distribution (6) and using the expression for the entropic force (3), we get the differential equation

$$qdq = 2Ddt, \tag{7}$$

where D is the diffusion coefficient that according to (5) is given by

$$D = \frac{kT}{c} = \frac{kT}{6\pi R\eta}. \tag{8}$$

The solution of (7) consistent with the initial condition $q(t = 0) = 0$ is

$$q^2(t) = 4Dt. \tag{9}$$