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Holographic entanglement entropy close to crossover/phase transition in strongly coupled systems

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Abstract

We investigate the behavior of entanglement entropy in the holographic QCD model proposed by Gubser et al. By choosing suitable parameters of the scalar self-interaction potential, this model can exhibit various types of phase structures: crossover, first order and second order phase transitions. We use entanglement entropy to probe the crossover/phase transition, and find that it drops quickly/suddenly when the temperature approaches the critical point which can be seen as a signal of confinement. Moreover, the critical behavior of the entanglement entropy suggests that we may use it to characterize the corresponding phase structures.

1. Introduction

In the past two decades, AdS/CFT [1–3] or the more generic gauge/gravity duality has attracted lots of attention and efforts, which relates a quantum field theory (QFT) in $(d+1)$ dimensions to some gravitational theory in $(d+2)$ dimensions. As a strong/weak duality, it provides a powerful tool to deal with strongly coupled field systems for which traditional methods of perturbative QFT confront great challenge or even break down. It has been applied on various areas of modern theoretical physics, including QCD [4–6], condensed matter physics [7–11] and cosmology [12], and achieved great successes.

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On the other hand, experiments of heavy ions collisions on RHIC [13–16] have opened a novel window into the physics of strongly interacting hadronic matters. The existing data suggest the following evolution picture: After collision, the hot QCD matters undergo a very fast thermalization process to reach thermal equilibrium where a ball of quark–gluon plasma (QGP) forms; And subsequently, the QGP expands to cool down until the temperature falls below the QCD transition (or crossover) point where it finally hadronizes. The QGP can be described very well by relativistic hydrodynamics with a very small η/s [17], where η/s is the ratio of shear viscosity to entropy density. This implies that the QGP is strongly coupled, and thus a treatment beyond the perturbative QCD is called for. With the help of the most well-established example of the AdS/CFT correspondence, namely the duality between $N = 4$ superconformal Yang–Mills (SYM) theory in four-dimensional Minkowski spacetime and type IIB supergravity in $AdS_5 \times S^5$, η/s of $N = 4$ SYM is produced which is very close to the hydrodynamic result [18,19]. This remarkable result shows the validity and powerfulness of the holographic method. However, $N = 4$ SYM is a conformal field theory and thus does not exhibit crossover behavior or any kind of phase transition which is very different from QCD. Moreover, lattice data indicates that the QGP is not a fully conformal fluid in the relevant RHIC energy range $1 \leq T/T_c \leq 3$, and the deviation from conformality may play an important role near the crossover/phase transition [20–22]. Therefore, it is interesting to seek more realistic holographic models to model non-conformal field theories such as QCD.

Now there are various ways to construct holographic models dual to non-conformal field theories, either following a top–down approach by studying a specific gravitational theory which has a string theory construction or a bottom–up approach in which the gravitational background is phenomenologically fixed to fit the lattice QCD (lQCD) data. Recently, in Refs. [23,24] Gubser and his collaborators proposed an interesting bottom–up holographic model intending to mimic the equation of state of QCD. In their model, beyond the Einstein gravity sector, a nontrivial massive scalar field as well as a judicious choice of its self-interaction potential are introduced in the bulk to break the conformal symmetry. The scalar potential has several parameters. By choosing appropriate values of these parameters, the model can exhibit a crossover behavior at some critical temperature and the equation of state generated agrees well with the result from lQCD [25]. Moreover, this simple model can also realize various types of phase transitions by choosing other values of the parameters in the scalar potential, for example the first and second order phase transitions. Thus, in additional to mimic properties of QCD, this model provides us a good background to study various phase structures of strongly coupled field systems. Many efforts have been devoted to investigate properties of this model. Various first and second order hydrodynamic transport coefficients have been calculated in Ref. [26]. In Refs. [27,28], quasinormal modes are used to probe the crossover/phase transition and a number of novel features are observed which were not present in the conformal case. In Ref. [29], this model is extended to include the effect of finite chemical potential and a more complete phase diagram of QCD is thus studied. Other models are also proposed, see Refs. [30–34] for the improved holographic QCD model (IHQCD), Refs. [35,36] for a top–down model and Refs. [37,38] for a semi-analytical holographic QCD model.

In this paper, based on Gubser's model, we aim to use one of non-local observables, the entanglement entropy, to probe the crossover/phase transition. Typically, there are three important non-local observables—the two-point function, the Wilson loop and the entanglement entropy—one can consider as probes to track the number of degrees of freedom and reflect non-local information (correlations between parts for example) of the system. However, they are difficult to calculate in the field theory side. AdS/CFT correspondence makes the calculations easier by