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Environment-induced uncertainties on moving mirrors in quantum critical theories via holography

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ABSTRACT

Environment effects on a n-dimensional mirror from the strongly coupled d-dimensional quantum critical fields with a dynamic exponent z in weakly squeezed states are studied by the holographic approach. The dual description is a $n+1$-dimensional probe brane moving in the $d+1$-dimensional asymptotic Lifshitz geometry with gravitational wave perturbations. Using the holographic influence functional method, we find that the large coupling constant of the fields reduces the position uncertainty of the mirror, but enhances the momentum uncertainty. As such, the product of the position and momentum uncertainties is independent of the coupling constant. The proper choices of the phase of the squeezing parameter might reduce the uncertainties, nevertheless large values of its amplitude always lead to the larger uncertainties due to the fact that more quanta are excited as compared with the corresponding normal vacuum and thermal states. In the squeezed vacuum state, the position and momentum of the mirror gain maximum uncertainties from the field at the dynamic exponent $z = n + 2$ when the same squeezed mode is considered. As for the squeezed thermal state, the contributions of thermal fluctuations to the uncertainties decrease as the temperature increases in the case $1 < z < n + 2$, whereas for $z > n + 2$ the contributions increase as the temperature increases. These results are in sharp contrast with those in the environments of the relativistic free field. Some possible observable effects are discussed.

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1. Introduction

Macroscopic quantum phenomena often refer to collective quantum behavior in objects, consisting of a large number of particles in atomic scales [1,2]. The best known examples are superconductivity and superfluidity. Additionally, experimental realizations of Bose–Einstein condensation in dilute gases certainly provide a more fruitful venue, in which various macroscopic quantum phenomena are explored under experimental controls. Moreover the progress in electro- and opto-mechanical techniques makes it possible to prepare macroscopic or mesoscopic mechanical objects in nearly pure quantum states (See [3–6]) where the center of mass of a object obeys a quantum mechanical equation of motion. Recently experiments to demonstrate quantum interference between the macroscopic objects have been proposed in [7,8]. In those experiments it is essential that a macroscopic system like the mirror is prepared in the quantum superposition state.

Because of a large number of the degrees of freedom in macromechanical systems, the observability of the quantum behavior will be strongly influenced by interactions with the environment and the experimentally accessible quantum region will also depend on the decoherence dynamics due to the presence of the environment [5]. A viable microscopic approach to investigate the environmental effects on the system would start with a specific system–environment model. Then the environmental degrees of freedom are integrated out by the method of Feynman–Vernon influence functional. This approach consistently and systematically accounts for the influence of the environment on the system of interest [9–11]. The influence functional can be exactly derived if the environment variables are Gaussian and their coupling with the system is linear [12,13]. In particular, the effects from the quantized electromagnetic fields on a point charge in the dipole approximation have been studied extensively by [14–17].

In the work [18], the environment is modeled by a free massless scalar field in vacuum and thermal states, and its coupling to the system of the particle, which is a harmonic oscillator, is linear in particle's position. They focused on the evolutions of particle's reduced density matrix which initially is in vacuum and squeezed states, and explored the uncertainties of particle's position and momentum due to the interaction with the environment. What they found is that if the system is prepared in a pure state, the loss of quantum coherence can happen as a result of the coupling to the environment. In particular, when the environment field is in zero temperature, the off-diagonal terms of the reduced density matrix in the position representation decrease more rapidly than in the momentum representation, resulting in relatively small position uncertainty. This comes from the fact that the system is coupled to the environment by its position variable. They also discussed the changes in these uncertainties by varying the squeeze parameters of the system and the temperature of the environments. Here we would like to explore these effects from the environments of strongly coupled fields and also allow the dimensions of probe objects and environments to be arbitrary. The purpose is to make possible comparisons with various cases in weakly coupled environments.

In quantum field theory, the correlators of weakly interacting quantum fields are normally computed perturbatively in terms of the small coupling constant. As for strongly coupled fields in high dimensions, the holographic correspondence is among very few known nonperturbative ways to calculate their correlators. Thus in this paper, we will extend the results in [18] by considering the strongly coupled environment that admits a holographic description. The idea of holographic duality is originally proposed as the correspondence between 4-dimensional conformal field theory (CFT) and gravity theory in 5-dimensional anti-de Sitter (AdS) space [19]. Other backgrounds and field theories are soon to be generalized with the possibility to study the strong coupling problems in the condensed matter systems (see [20] for a review). Considerable efforts also have been focused on using the holography idea to explore the Brownian motion of a particle moving in a strongly coupled environment [21–41]. A review on the holographic Brownian motion can be found in [28].

Here we will apply a bottom-up holographic method, proposed in our earlier work [38], to find the uncertainties of a n-dimensional mirror in the environment of d-dimensional quantum critical theories at zero and finite temperature. The holographic dual for such quantum critical theories has been proposed in [42] where the gravity theory is in the Lifshitz background (See [29,30] for details). Several physical phenomena have been studied in this theory, including linear DC conductivity, power-law AC conductivity, and strange fermion behaviors [30,43–46]. In our set-up, the bulk

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