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Dynamics and quantum entanglement of two-level atoms in de Sitter spacetime

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ABSTRACT

In the framework of open quantum systems, we study the internal dynamics of both freely falling and static two-level atoms interacting with quantized conformally coupled massless scalar field in de Sitter spacetime. We find that the atomic transition rates depend on both the nature of de Sitter spacetime and the motion of atoms, interestingly the steady states for both cases are always driven to being purely thermal, regardless of the atomic initial states. This thermalization phenomenon is structurally similar to what happens to an elementary quantum system immersed in a thermal field, and thus reveals the thermal nature of de Sitter spacetime. Besides, we find that the thermal baths will drive the entanglement shared by the freely falling atom (the static atom) and its auxiliary partner, a same two-level atom which is isolated from external fields, to being sudden death, and the proper time for the entanglement to be extinguished is computed. We also analyze that such thermalization and disentanglement phenomena, in principle, could be understood from the perspective of table-top simulation experiment.

1. Introduction

One of the amazing effects predicted by the relativistic quantum field theory is the Unruh effect [1–3]. It is represented as that a uniformly accelerated observer can view an extraordinary

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phenomenon, thermal particles, in Minkowski vacuum, which is completely contrary to the inertial status. Usually, the Unruh effect, in theory, can be read from the excitation rate, i.e., the probability per unit time of a spontaneous transition from the ground state to one of its excited states, of a uniformly accelerated DeWitt detector [3,4] due to the appearance of Planck factor in it. This factor is considered as the concrete embodiment of thermal effect, because it indicates that the equilibrium between the accelerated detector and the external field is the same as that which would have been achieved had the detector remained unaccelerated, but immersed in a bath of thermal radiation at a temperature associated with its proper acceleration, which is the exact Unruh temperature [3]. Similar analysis also can be done to discuss Hawking effect [5], one of the famous predicted phenomena in curved spacetime.

Besides the detector method, a wonderful alternative scheme to study the Unruh effect and Hawking effect is the open quantum system method. This method involves many important areas in physics, such as quantum mechanics, quantum field theory and relativistic theory. Therefore, it has attracted much attention recently [6–9]. A system, such as a uniformly accelerated two-level atom, which couples with the external field in Minkowski vacuum, is considered as an open quantum system. Through studying its evolution, we will find that the density matrix corresponding to the quantum system is eventually driven to a purely thermal equilibrium state, and exhibits a nonvanishing probability of spontaneous excitation. This phenomenon is usually referred to as the Unruh effect. It is needed to note that this approach has been extended to understanding Hawking effect [7] in curved spacetime by assuming a two-level atom in the interaction with vacuum fluctuations. Besides, this method has also been used to analyze the geometric phase of a two-level atom to detect the Unruh temperature [9] and reveal the nature of de Sitter spacetime [8]. In this regard, let us note that the theory of open quantum system has been fruitfully applied to studying relativistic effects [6–10].

A two-level atom, which interacts with quantized conformally coupled massless scalar field in de Sitter-invariant vacuum, can be thought of as an open quantum system, and the massless scalar field it interacts with is equivalent to the external environment. One may expect that the evolution of the atom, e.g., transition rates between energy levels and the thermalization process, will be influenced by the spacetime curvature which backscatters the fluctuating scalar field the atom is coupled to. Indeed, further study shows that both the freely falling atom and static atom in weak interaction with a massless scalar field in de Sitter spacetime feel a thermal bath and will be subjected to dissipation [8]. Moreover, by introducing an auxiliary system (the same two-level atom, we call it the auxiliary partner), which is initially entangled with our freely falling atom or static atom and isolated from external field, we can discuss how the nature of de Sitter spacetime affects the dynamic evolution of bipartite atomic entanglement, a very important quantum resource, which plays a key role in the quantum information tasks such as quantum teleportation [11,12] and computation [12]. It is needed to note that this model is in structural similarity to a bipartite quantum system in quantum information theory, with one subsystem in interaction with external environment, and the other isolated from that. In this regard, let us note that this model has been used to discuss the loss of spin entanglement for accelerated electrons in electric magnetic fields [10], and the entanglement of two qubits in a relativistic orbit [13].

It is well known that entanglement is observer dependent [14], incorporating the concepts of quantum information into relativistic settings can produce new and surprising effects [15]. For example, from the perspective of the accelerated observer the entanglement shared no matter by the Bosonic fields or by the Dirac fields decreases with the increase of acceleration. Furthermore, because of different statistics, the entanglement for the Bosonic fields will disappear in the limit of infinity acceleration, while it is not so for the Dirac fields [16,17]. Recently, the generation of quantum entanglement for both the Bosonic fields and Dirac fields has been investigated due to the expansion of the universe [18,19], and Martín-Martínez et al. gave a review on the cosmological quantum entanglement [20]. It is needed to note that the entanglement studied in previous articles [16–19] is the entanglement of the free field modes, and these free field modes are spatially delocalized, which cannot be measured and processed. So it is remains interesting to see what happens to the spatially localized entangled quantum system when it is subjected to the spacetime effect, such as Gibbons–Hawking effect [21], due to being placed in a curved spacetime. To aim at that, we, in this paper, study the dynamics and entanglement for two-level atoms in de Sitter spacetime. The reason for our special attention to de Sitter spacetime stems from the fact that de Sitter space is the unique maximally symmetric curved