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Nuclear Physics B 923 (2017) 458–474

NUCLEAR PHYSICS B

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Dynamics of quantum entanglement in de Sitter spacetime and thermal Minkowski spacetime

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Received 28 June 2017; received in revised form 11 August 2017; accepted 19 August 2017
Available online 24 August 2017
Editor: Stephan Stieberger

Abstract

We investigate the dynamics of entanglement between two atoms in de Sitter spacetime and in thermal Minkowski spacetime. We treat the two-atom system as an open quantum system which is coupled to a conformally coupled massless scalar field in the de Sitter invariant vacuum or to a thermal bath in the Minkowski spacetime, and derive the master equation that governs its evolution. We compare the phenomena of entanglement creation, degradation, revival and enhancement for the de Sitter spacetime case with that for the thermal Minkowski spacetime case. We find that the entanglement dynamics of two atoms for these two spacetime cases behave quite differently. In particular, the two atoms interacting with the field in the thermal Minkowski spacetime (with the field in the de Sitter-invariant vacuum), under certain conditions, could be entangled, while they would not become entangled in the corresponding de Sitter case (in the corresponding thermal Minkowski case). Thus, although a single static atom in the de Sitter-invariant vacuum responds as if it were bathed in thermal radiation in a Minkowski universe, with the help of the different dynamic evolution behaviors of entanglement for two atoms one can in principle distinguish these two universes.
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http://dx.doi.org/10.1016/j.nuclphysb.2017.08.014
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1. Introduction

Entanglement as a quantum property of compound systems means that the global states of a composite system cannot be written as a product of the states of its corresponding individual subsystems. It is the most fascinating nonclassical manifestation of quantum formalism and plays a significant role in quantum information and quantum computation [1,2]. Recently, most of the tasks such as quantum teleportation [3,4], quantum dense coding [5,6], quantum computational speedups [7], quantum error correction [8], cryptographic key distribution [9] have been implemented with entanglement. However, due to the unavoidable interaction with environment, quantum systems may be subjected to decoherence and dissipation, and correspondingly its entanglement may decrease and even experience sudden death [10–17]. Decoherence thus is one of the main obstacles to the realization of quantum information technologies. Besides, when two atoms are immersed in a common thermal bath, the indirect interactions between the otherwise independent atoms, as a result of the field correlation, may lead to some interesting phenomena, such as the revival of destroyed entanglement and the creation of entanglement in initially separable states [18–25]. The relevant investigations could guide us to effective quantum state preparation, storage and protection, effective implementation of quantum information tasks, and even the understanding of the property of external environments. Therefore, the entanglement dynamics of open quantum systems is an important issue in quantum information science and is worthy for us to study in different scenarios, e.g., relativistic framework [26–32].

On the other hand, de Sitter spacetime is a very simple curved background that has the same degree of symmetry as the Minkowski background, both having ten Killing vectors. It is also an important model of our universe in the far past and the far future, as verified by our current observations and the theory of inflation [33]. Besides, it is found that a single particle interacting with a conformally coupled massless scalar field in the de Sitter invariant vacuum state behaves exactly the same way as the one coupled to thermal bath in Minkowski spacetime [34–41]. Therefore, it is worthy to ask whether it is possible to distinguish de Sitter spacetime from the thermal Minkowski spacetime, i.e., which universe the inhabitants are exactly in. In this regard, let us note that Refs. [42–46] investigated this issue by considering different entangling power of these two universes. Moreover, it is shown that the Casimir–Polder interaction between atoms behaves quite differently in these two universes and thus one can in principle distinguish these two universes with the different behaviors of Casimir–Polder interaction [47,48].

In this paper, we study the dynamics of entanglement for two-atom system coupled with a massless scalar field in the de Sitter invariant vacuum and with a thermal bath in Minkowski universe. We first treat the two atoms as an open quantum system and obtain its master equation by tracing over the degree of freedom of quantum field. Then we discuss the evolution behaviors of entanglement between the two atoms in the de Sitter spacetime and Minkowski background. We find that for different initial states, the atomic entanglement evolves quite differently with respective to time or other parameters, such as the interatomic distance and temperature of thermal bath. Besides, the entanglement dynamics of atoms in de Sitter spacetime are also different from that of the corresponding thermal Minkowski spacetime case. We thus arrive at the conclusion that with the help of the different dynamic evolution behaviors of entanglement for two atoms one can in principle distinguish the de Sitter spacetime from the thermal Minkowski one. Note that the open quantum system approach applied in current paper is different from that in Refs. [42,45,46], and allows us to examine the entanglement dynamics, i.e., the entanglement evolution with respective to time. Besides, unlike the previous studies [42,45,43,46] where the authors only discussed the creation of entanglement for the atoms with special initial state, i.e.,

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