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Finite-time response function of uniformly accelerated entangled atoms

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We examine the transition probability from the ground state to a final entangled state of a system of uniformly accelerated two-level atoms weakly coupled with a massless scalar field in Minkowski vacuum. Using time-dependent perturbation theory we evaluate the finite-time response function and we identify the mutual influence of atoms via the quantum field as a coherence agent in each response function terms. The associated thermal spectrum perceived by the atoms is found for a finite time interval. By considering modifications of specific parameters of our setup, we also analyze how the transition probabilities are affected by the smoothness of the switching of the atom–field coupling. In addition, we study the mean life of the symmetric maximally entangled state for different accelerations. Our calculations reveal that smooth switching is more efficient than sudden switching concerning the reduction of the decay of the entangled state. The possible relevance of our results is discussed.

1. Introduction

A detector moving with a constant proper acceleration a will perceive the Minkowski vacuum state of a quantum field as a thermal bath with the following temperature: $T = \hbar a/(2\pi c k_B)$, where $\hbar$, k_B, c are the reduced Planck's and Boltzmann's constants and the speed of light, respectively [1,2].

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Using perturbation theory in first-order approximation it can be shown that the transition rates of the Unruh–DeWitt detector [3] interacting with a scalar field in the Minkowski vacuum is given by the Fourier transform of the positive frequency Wightman function evaluated on the world line of the detector [4]. In the case of an uniformly accelerated detector, it is found that, if it is initially prepared in its ground state, it can be excited by the thermal radiation perceived by it [5].

Quantum entanglement is considered as one of the key features of quantum information processing. Several sources of entangled quantum systems have been discussed in literature, for instance, in solid-state physics, quantum optics, and also atoms in cavity quantum electrodynamics [6]. Some examples of generation of entangled systems of two-level atoms interacting with a bosonic field can be found in Refs. [7,8]. Aside from production of those entangled systems, quantum-information processing requires the presence of a strong coherent coupling between the entities of the system. Nevertheless, under realistic experimental conditions, entanglement is degraded through uncontrolled coupling to environment [9].

In recent years the field of relativistic quantum information has emerged as an important research topic and is generating increasing interest within the scientific community. The mutual influence of atoms through their interaction with quantum fields is an important stimulating issue in order to analyze decoherence properties [10–12]. Moreover, an important aspect that has been witnessing a vigorous scrutiny in the recent literature is the possibility of entanglement harvesting. This is the phenomenon in which atoms are able to extract entanglement from the vacuum state of a quantum field. In other words, since quantum vacuum fluctuations are entangled (regarding the state space of local observables), they can act as a source of entanglement for atoms which are coupled with such a quantum field. This is particularly interesting for the case of uniformly accelerated atoms, since it is well known that the Minkowski vacuum state can be expressed as an entangled state between the left and right Rindler wedges when formulated on the Rindler vacuum [13]. Some works studying relativistic quantum entanglement in different setups are given by Refs. [12,14–24]. In turn, for a wide set of results in this area and special issues of performing satellite experiments, we refer the reader the Ref. [25]. Many of such works demonstrate that entanglement is an observer-dependent quantity. In addition, recent works point towards the importance of considering explicitly the contributions of vacuum fluctuations and radiation reaction in the radiative processes of entangled atoms [26,27]. Within such a context, we also refer the reader the Refs. [28,29].

In the present work we wish to address different issues in comparison with the aforementioned papers. Here we are interested in studying the transition probability to entangled states for uniformly accelerated two-level atoms due to the vacuum fluctuations of a quantum scalar field when the atoms are initially prepared in the ground state. We are not attempting to present a full analysis concerning the entanglement contained in the final state of the atoms since this would require more general tools, such as the procedure proposed by Reznik in Ref. [18], or even the master equation approach, with a suitable characterization of an entanglement monotone. Instead, given that the uniformly accelerated atomic system is initially prepared in the ground state, we formulate a simple question on the probability that the atomic system can be found in a specific entangled state in a later time due to its coupling to a quantum field. For this investigation we employ a straightforward calculation within a quantum mechanical time-dependent perturbation theory analysis. Furthermore we investigate in detail the transition probability under different description perspectives, encoded in different choices for the coupling between atoms and fields. We remark that this simplified situation contains all the important ingredients to study radiative processes involving entangled states. On the other hand, an important issue that naturally arises in this context is whether these recently formed entangled states could persist for long time intervals. In order to pursue an answer to this question, one may investigate the mean life of the entangled states, which is one of the topics of the present work. In this way we propose to afford an answer as broad as possible for the query of how radiative processes of entangled states are impacted by effects of acceleration in a perturbative framework.

The aim of this paper is to study radiative processes of a pair of uniformly accelerated two-level atoms interacting with a quantum massless scalar field. We evaluate the transition rates within time-dependent perturbation theory in a finite time interval. Refs. [30–32] present investigations on the excitation probability evaluated in a finite time interval for Unruh–DeWitt detectors. The paper is organized as follows. In Section 2 we discuss the Hamiltonian of two identical two-level