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Subvacuum effects of the quantum field on the dynamics of a test particle

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ABSTRACT

We study the effects of the electromagnetic subvacuum fluctuations on the dynamics of a nonrelativistic charged particle in a wavepacket. The influence from the quantum field is expected to give an additional effect to the velocity uncertainty of the particle. In the case of a static wavepacket, the observed velocity dispersion is smaller in the electromagnetic squeezed vacuum background than in the normal vacuum background. This leads to the subvacuum effect. The extent of reduction in velocity dispersion associated with this subvacuum effect is further studied by introducing a switching function. It is shown that the slow switching process may make this subvacuum effect insignificant. We also point out that when the center of the wavepacket undergoes non-inertial motion, reduction in the velocity dispersion becomes less effective with its evolution, no matter how we manipulate the nonstationary quantum noise via the choice of the squeeze parameters. The role of the underlying fluctuation–dissipation relation is discussed.

1. Introduction

Manipulating the quantum field may give rise to suppression of its vacuum fluctuations, leading to a subvacuum phenomenon. One of the known examples is the existence of negative energy density. It has been shown [1] that the renormalized expectation value of the energy density operator can become negative in some spacetime region. This negative energy density may imply exotic phenomena such as the traversable wormholes [2] and the warp drive [3]. It is also known [4–7] that the renormalized local energy density/flux cannot be arbitrarily negative for an arbitrarily long period of time. Similar to the uncertainty principle, there exists an inequality, constraining negativeness

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and duration that might violate the second law of thermodynamics [8,9] and the cosmic censorship hypothesis by creating naked singularities [4]. The squeezed vacuum state of the electromagnetic field is an example that may cause subvacuum phenomena.

In the laboratory, squeezed light is produced by a nonlinear-optics technique of "squeezing" [9]. In the early universe the squeezed vacuum state of the quantum matter field may be evolved from its initial vacuum state by amplification of the vacuum fluctuations through the processes of particle creation, for example, during an inflation epoch [10].

Detection of the subvacuum fluctuations of the quantum scalar field has been studied by considering the response of a static particle detector, whose monopole moment couples to the field [11]. Various switching functions are introduced, but only one single time scale is used to characterize the processes of switching on/off and measuring. This switching process results in excitations of the detector via interaction with the quantum field. In particular, the coupling to the squeezed vacuum state of the field may suppress the rate of excitations of the detector to a level less than what would be caused by a normal vacuum state. The quantum inequality associated with this subvacuum effect is then discussed. Some other subvacuum phenomena have been proposed in laboratory experiments [12–14].

Here we would like to study the subvacuum effects of the quantized electromagnetic field, so a natural choice of the detector is a charged particle since it has a well-defined particle–field interaction. More specifically, we wish to explore the effects of electromagnetic squeezed vacuum on the dynamics of the charged particle, which is prepared in a wavepacket. The charged particle is considered as the system of interest, and the degrees of freedom of the fields as the environment. The linear coupling with the electromagnetic gauge potential allows us to integrate out the field variables exactly. Within the context of the closed-time-path formalism [15–24], we will obtain the influence functional that encodes all effects from the fields upon the particle.

The influence of the electromagnetic field fluctuations is expected to give an additional effect to the dynamics of the particle. Since the charged particle is never observed without being affected by the electromagnetic zero-point fluctuations, the observed velocity dispersion should already include the additional effect due to normal vacuum fluctuations. Thus we define the renormalized velocity dispersion of the free particle by absorbing the normal vacuum contributions into the intrinsic velocity dispersion due to the finite wavepacket size. Then, we investigate how this renormalized velocity dispersion can be possibly reduced by the squeezed vacuum fluctuations so that it is smaller than its counterpart in normal vacuum fluctuations of the fields. This leads to the subvacuum phenomenon. Our approach of treating a nonrelativistic charged particle quantum-mechanically should give leading-order results when the cutoff energy scale of radiation fields is consistently set at the inverse of the width of the wavepacket, much smaller than the rest mass energy of the particle. It is no doubt that a more precise quantitative evaluation certainly requires the full QED study. This, in spirit, follows a similar treatment of the Lamb shift, proposed by Weldon in a more heuristic way [25], as well as by Bethe in terms of the time-dependent perturbation theory [26]. There the associated energy shift of hydrogen states can be understood mainly arising from the influence of the quantum fluctuations of electromagnetic fields on nonrelativistic quantum-mechanical, bound electrons. Their approach turns out to yield an estimated energy shift with the correct order of magnitude as compared with the results from the full QED calculations [25].

Next, for a more detailed analysis of the subvacuum phenomena, we incorporate the switching function, as a consequence of the finite-time switching-on/off process of interaction between the charged particle and electromagnetic squeezed modes. We first consider a sudden switching-on process, and then generalize the switching process to the case with a finite switching time by introducing a suitable switching function. We can derive an inequality associated with this subvacuum phenomenon. Finally, we consider that the center of a wavepacket undergoes non-inertial motion where the electromagnetic self-force will give rise to a weak damping effect on the evolution of the trajectory. We find that non-trivial motion tends to modify the result of the velocity dispersion in such a way that it becomes less effective to suppress the environmental noise than the case of inertial motion.

Our presentation is organized as follows. In Section 2, we briefly introduce the closed-time-path formalism in order to describe the evolution of the reduced density matrix of a nonrelativistic