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Spontaneous excitation of a circularly accelerated atom coupled with vacuum Dirac field fluctuations

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HIGHLIGHTS

- Spontaneous excitation of a circularly accelerated atom is studied.
- The atom interacts with the Dirac field through nonlinear coupling.
- A cross term involving vacuum fluctuations and radiation reaction contributes.
- The atom in circular motion does not perceive pure thermal radiation.
- The contribution of the cross term changes as the atomic trajectory varies.

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ABSTRACT

We study the spontaneous excitation of a circularly accelerated atom coupled with vacuum Dirac field fluctuations by separately calculating the contribution to the excitation rate of vacuum fluctuations and a cross term which involves both vacuum fluctuations and radiation reaction, and demonstrate that although the spontaneous excitation for the atom in its ground state would occur in vacuum, such atoms in circular motion do not perceive a pure thermal radiation as their counterparts in linear acceleration do since the transition rates of the atom do not contain the Planckian factor characterizing a thermal bath. We also find that the contribution of the cross term that plays the same role as that of radiation reaction in the scalar and electromagnetic fields cases differs for atoms

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in circular motion from those in linear acceleration. This suggests that the conclusion drawn for atoms coupled with the scalar and electromagnetic fields that the contribution of radiation reaction to the mean rate of change of atomic energy does not vary as the trajectory of the atom changes from linear acceleration to circular motion is not a general trait that applies to the Dirac field where the role of radiation reaction is played by the cross term.

1. Introduction

Recently, a new physical picture for the Unruh effect [1] in terms of the spontaneous excitation of a uniformly accelerated two-level atom has emerged [2–8]. In this picture, the spontaneous transition of an atom in vacuum is attributed, in an approach proposed by Dalibard, Dupont-Roc, and Cohen-Tannoudji (DDC) [9,10], to two competing mechanisms: vacuum fluctuations and radiation reaction. It has been demonstrated, in this approach, that for uniformly accelerated two-level atoms coupled with quantum vacuum scalar fields [2,3], the balance between vacuum fluctuations and radiation reaction that ensures the stability of inertial ground-state atoms in vacuum is disturbed as the contribution of vacuum fluctuations is modified from its inertial value while the contribution of radiation reaction remains unchanged, making atomic transitions from the ground state to the excited state possible even in vacuum, and this spontaneous excitation can be regarded as a physical manifestation of the Unruh effect. In the case of the atomic coupling with scalar fields, one can even show that radiation reaction is generally not altered by any stationary acceleration whereas the contribution of vacuum fluctuations differs for all stationary trajectories from its inertial value [3]. Although this conclusion of radiation reaction immune to the acceleration does not hold when boundaries appear [4] or the scalar fields are replaced by electromagnetic fields [5,6], the presence of boundaries or the replacement of scalar fields by electromagnetic fields conspires to modify the vacuum fluctuations and radiation reaction in such a way that the delicate balance between the vacuum fluctuations and radiation reaction that ensures the stability of inertial ground-state atoms in vacuum in the absence of boundaries in the case of scalar fields remains, while for the uniformly accelerated ground-state atoms the balance is again broken so that the spontaneous excitation still occurs.

The above studies are concerned with atoms in interaction with bosonic fields, e.g., scalar and electromagnetic fields, where the coupling between the atom and the field is linear. Recently, these studies have been extended to fermionic fields, Dirac fields for example, where the simplest coupling one can introduce between the atom and the field is nonlinear [7]. In this case, one finds that a cross term involving both vacuum fluctuations and radiation reaction appears which dominates over the sole radiation reaction at the same order of perturbation. As a result, the evolution of the atom is governed in the leading order by vacuum fluctuations and the cross term rather than by vacuum fluctuations and radiation reaction as in the scalar and electromagnetic fields cases where the coupling is linear. Explicit calculations show that now the cross term plays the same role as that of the radiation reaction in the scalar and electromagnetic field cases and its contribution to the mean rate of change of the atomic energy for inertial ground-state atoms in vacuum cancels that from vacuum fluctuations. However, both the cross term and vacuum fluctuations are affected by uniform acceleration and they add up making atomic transitions from the ground-state to the excited states possible for accelerated atoms in vacuum [7]. This is again in contrast to the scalar field case where only vacuum fluctuations are affected by acceleration [3].

On the other hand, there has also been interest to study the acceleration effects in circular motion since an extremely large linear acceleration, which is needed for the Unruh effect to be appreciable for experimental detection, is hard to realize for linear acceleration. The quantization of scalar fields in rotating coordinates was first investigated by Letaw and Pfautsch [11]. Then the response of an Unruh–DeWitt detector in circular orbit was examined in Refs. [12,13]. By using the model of circulating