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Spontaneous excitation of a circularly accelerated atom coupled to electromagnetic vacuum fluctuations

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HIGHLIGHTS

- We study the spontaneous excitation of a circularly accelerated atom.
- Contribution of radiation reaction to the excitation is affected by acceleration.
- The radiation perceived by a circularly orbiting observer is no longer thermal.
- An effective temperature can be defined in terms of atomic transition rates.
- Effective temperature is larger than Unruh temperature and frequency-dependent.

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ABSTRACT

We study, using the formalism proposed by Dalibard, Dupont-Roc and Cohen-Tannoudji, the contributions of the vacuum fluctuation and radiation reaction to the rate of change of the mean atomic energy for a circularly accelerated multilevel atom coupled to vacuum electromagnetic fields in the ultrarelativistic limit. We find that the balance between vacuum fluctuation and radiation reaction is broken, which causes spontaneous excitations of accelerated ground state atoms in vacuum. Unlike for a circularly accelerated atom coupled to vacuum scalar fields, the contribution of radiation reaction is also affected by acceleration, and this term takes the same form as that of a linearly accelerated atom coupled to vacuum electromagnetic fields. For the contribution of vacuum fluctuations, we find that in contrast to the linear acceleration case,

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terms proportional to the Planckian factor are replaced by those proportional to a non-Planck exponential term, and this indicates that the radiation perceived by a circularly orbiting observer is no longer thermal as is in the linear acceleration case. However, for an ensemble of two-level atoms, an effective temperature can be defined in terms of the atomic transition rates, which is found to be dependent on the transition frequency of the atom. Specifically, we calculate the effective temperature as a function of the transition frequency and find that in contrast to the case of circularly accelerated atoms coupled to the scalar field, the effective temperature in the current case is always larger than the Unruh temperature.

1. Introduction

A uniformly accelerated observer perceives the Minkowski vacuum as a thermal bath of Rindler particles [1,2], and this is the well-known Unruh effect. One way to study the Unruh effect is to examine the response of a Unruh–DeWitt particle detector which can be taken as a point-like atom weakly coupled to external quantum fields. The detector (atom) transitions from the ground state to some excited state if a quantum is detected, giving rise to a spontaneous excitation. Let us note that spontaneous excitation is one of the important radiative properties of atoms caused by the interactions between atoms and fields, and its physical origin, which has long been discussed, may be attributed to vacuum fluctuations [3,4], or radiation reaction [5], or a combination of them [6]. The freedom in choosing the ordering of commuting operators of the atom and field in a Heisenberg picture leads to different physical interpretations. The ambiguity was removed by Dalibard, Dupont-Roc and Cohen-Tannoudji (DDC) who suggested a symmetric operator ordering [7,8], which makes both the contributions of vacuum fluctuations and radiation reaction to the rate of change of an atomic observable separately Hermitian and able to possess an independent physical meaning. Recently, the DDC formalism has been used to study the spontaneous excitation rates and radiative energy shifts of an accelerated two-level atom interacting with a scalar field in the Minkowski vacuum [9–11], where it has been found that the contribution of radiation reaction remains the same as that of the inertial case, while the vacuum fluctuation part is modified by the acceleration of the atom. As a result, the balance between the two contributions that exist in the inertial case is broken. This leads to spontaneous excitation of ground-state atoms even in vacuum, which is a manifestation of the Unruh effect. However, a two-level atom interacting with a scalar field is more or less a toy model. Recently, the radiative energy shifts [12] and spontaneous excitation rate [13] of a uniformly accelerated multilevel atom coupled to quantized electromagnetic fields have been studied, and it is found that unlike the scalar field case, the contribution of radiation reaction is also corrected by acceleration and a nonthermal term proportional to a^2 appears in both the radiative energy shifts and spontaneous excitation rate of the atom. Therefore the equivalence between uniform acceleration and the thermal bath is lost when the scalar field is replaced by the electromagnetic field [14].

However, the acceleration needed to observe the Unruh effect is extremely large, and it is difficult to realize in linear acceleration. As a result, there has been some interest to study the acceleration effects in the circular acceleration case, since very large centripetal acceleration can be obtained in some circumstances, for instance, for ultrarelativistic electrons in a storage ring. The field quantization in rotating coordinates was first investigated by Letaw and Pfautsch [15], and the response of a circularly moving Unruh–DeWitt detector was evaluated in Refs. [16,17]. Using the model of circulating electrons in a storage ring, the circular acceleration effect on the polarization of an electron, which is determined by the population of electron's energy state has been extensively studied [18–24]. It is worth to note here that the DDC formalism has also been applied in Ref. [11] to investigate