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Geometric phase of an accelerated two-level atom in the presence of a perfectly reflecting plane boundary

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ABSTRACT

We study the geometric phase of a uniformly accelerated two-level atom coupled with vacuum fluctuations of electromagnetic fields in the presence of a perfectly reflecting plane. We find that the geometric phase difference between the accelerated and inertial atoms which can be observed by atom interferometry crucially depends on the polarizability of the atom and the distance to the boundary and it can be dramatically manipulated with anisotropically polarizable atoms. In particular, extremely close to the boundary, the phase difference can be increased by two times as compared to the case without any boundary. So, the detectability of the effects associated with acceleration using an atom interferometer can be significantly increased by the presence of a boundary using atoms with anisotropic polarizability.

1. Introduction

The Unruh effect, which is intrinsically related with the Hawking radiation of a black hole, tells us that a uniformly accelerated observer in vacuum feels as if it were immersed in a bath of thermal radiation and it has attracted an enduring deal of interest since its discovery by Unruh in 1976 [1].

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However, up to now, there is no direct experimental observation for both the Unruh effect and the Hawking radiation. The main difficulty lies in the extreme physical conditions required for a direct test which are currently inaccessible. Take the Unruh effect for an example, the acceleration required to achieve a temperature of ~ 1 K, is as large as $\sim 10^{21}$ m/s^2. As a result, a lot of effort has been directed to exploring alternative means which may relax the extreme conditions [2]. It is interesting to note that recently the geometric phase has been suggested as a possible way to observe the Unruh effect at an acceleration orders of magnitude lower than that required by a direct test [3,4]. These proposals of using geometric phase to test the Unruh effect are based upon the generalizations of the concept of geometric phase to mixed states [5–9], non-unitary evolution and open quantum systems [10–17] from pure states, adiabatic and cyclic evolution of a closed system first studied by Berry [18].

By treating an accelerated two-level atom as an open system in a reservoir of fluctuating vacuum electromagnetic fields and calculating the geometric phase acquired by the atom coupled to all vacuum field modes and undergoing nonunitary evolution because of the environment induced decoherence and dissipation, it has been shown in Ref. [4] that the phase variation due to the acceleration can be in principle observed via atomic interferometry between the accelerated atom and the inertial one, thus providing an evidence of the Unruh effect. In a sense, the Unruh effect is a result of the distortion of vacuum fluctuations caused by the acceleration of an observer on one hand, and on the other hand, it is well-known that vacuum fluctuations may also be modified by the presence of boundaries and the resulting distortions can in general produce novel observable effects, such as the Lamb shift [19] and the Casimir effect [20–22], for two well-known examples. Other examples include but not limited to the light-cone fluctuations when gravity is quantized [23], the Brownian motion of test particles in an electromagnetic vacuum [24], and modifications of radiative properties of atoms in cavities such as the natural lifetimes and energy-level shifts which have been demonstrated in experiments [25]. Recently, it has been demonstrated that the changes in vacuum fluctuations generated by the presence of a boundary can produce a position-dependent correction to the geometric phase of an inertial atom which might be observable [26]. Therefore, questions naturally arise as to what happens to the geometric phase if the atom is accelerated, how the presence of a boundary affects the geometric phase acquired by the accelerated atom and whether the influence can be exploited for an experimental test of the Unruh effect. These are what we plan to address in the present paper.

This paper is structured as follows. In Section 2, the basic equations governing dynamical evolution of an accelerated two-level atom coupled to the electromagnetic field are given in the framework of open quantum systems and the formula for the geometric phase is obtained. In Section 3, we study the geometric phase difference between the accelerated and inertial atoms in the presence of a perfectly reflecting plane. Finally, the conclusions and discussions are given in Section 4.

2. The Basic formula and the dynamics of a two-level system coupled with electromagnetic field

The open quantum system we consider is a two-level atom coupled with vacuum fluctuations of electromagnetic fields. The total Hamiltonian of the system(atom plus bath of vacuum fluctuations) can be written as $H = H_s + H_\phi + H'$. Here, the Hamiltonian of the two-level atom is given by $H_s = \frac{1}{2}\hbar\omega_0\sigma_3$ with σ_3 being the Pauli matrix and ω_0 the energy level spacing. H_ϕ denotes the Hamiltonian of the free fluctuating electromagnetic field, of which the details are not needed here. The Hamiltonian that describes the interaction between the atom and the electromagnetic field in the multipolar coupling scheme [27] is given by $H'(\tau) = -e\mathbf{r}\cdot\mathbf{E}(x(\tau)) = -e\sum_{mn}\mathbf{r}_{mn}\cdot\mathbf{E}(x(\tau))\sigma_{mn}$, where $\sigma_{mn} = |m\rangle\langle n|$ with $|m\rangle$ being the atomic states, and $e\,\mathbf{r}$ denotes the atomic electric dipole moment with the electron electric charge e. The electric field strength is denoted by $\mathbf{E}(x)$ here.

In the framework of open quantum systems, the evolution of the reduced density matrix of the atom $\rho(\tau)$ in the limit of weak coupling can be written in the Kossakowski–Lindblad form [28,29]

$$\frac{\partial\rho(\tau)}{\partial\tau} = -\frac{i}{\hbar}\big[H_{\text{eff}},\ \rho(\tau)\big] + \mathcal{L}[\rho(\tau)], \tag{1}$$