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Quantum parameter estimation in the Unruh–DeWitt detector model

Xiang Hao [a,b,*], Yinzhong Wu [a]

[a] School of Mathematics and Physics, Suzhou University of Science and Technology, Suzhou, Jiangsu 215011, People's Republic of China

[b] Pacific Institute of Theoretical Physics, Department of Physics and Astronomy, University of British Columbia, 6224 Agriculture Rd., Vancouver B.C., Canada V6T 1Z1

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ABSTRACT

Relativistic effects on the precision of quantum metrology for particle detectors, such as two-level atoms are studied. The quantum Fisher information is used to estimate the phase sensitivity of atoms in non-inertial motions or in gravitational fields. The Unruh–DeWitt model is applicable to the investigation of the dynamics of a uniformly accelerated atom weakly coupled to a massless scalar vacuum field. When a measuring device is in the same relativistic motion as the atom, the dynamical behavior of quantum Fisher information as a function of Rindler proper time is obtained. It is found out that monotonic decrease in phase sensitivity is characteristic of dynamics of relativistic quantum estimation. The origin of the decay of quantum Fisher information is the thermal bath that the accelerated detector finds itself in due to the Unruh effect. To improve relativistic quantum metrology, we reasonably take into account two reflecting plane boundaries perpendicular to each other. The presence of the reflecting boundary can shield the detector from the thermal bath in some sense.

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* Corresponding author at: School of Mathematics and Physics, Suzhou University of Science and Technology, Suzhou, Jiangsu 215011, People's Republic of China.

E-mail address: xhao@phas.ubc.ca (X. Hao).

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1. Introduction

The study of the interface between relativity and quantum theory has led to many interesting researches which in particular include relativistic quantum information theory [1–10]. In information processing, particle detectors or observers moving along relativistic trajectories, can send and receive signals which are relevant to internal degrees of freedom of detectors. The role of detectors is to locate and label events in curved spacetimes. Recently, the use of non-inertial motions to perform quantum computing has been investigated by means of accelerated optical cavities [2,3] or atoms in relativistic regimes [4,5]. The relativistic technology contributes to ultra-fast quantum computation which can overcome some obstacles from decoherence. In this Letter, we employ this idea to study the relativistic effects of accelerated qubits on the precision of parameter quantum estimation.

The selection of a physically implementable model is a key to our scenario. For many years, the Unruh–DeWitt (UdW) model [11–14] has been extensively applied to the study of aspects of quantum field theory in curved spacetimes. This model is referred to as a particle detector, like a two-level atom, which is linearly coupled to a quantum scalar field with simple monopole interactions. In comparison of QED, the model characterizes adequately light–matter interactions [15] in some specific settings. One great success of the model lies in the demonstration of Unruh effect. It was shown that a uniformly accelerated detector behaves as an inertial detector in a thermal bath, with a characteristic temperature, i.e., Unruh temperature, proportional to its proper acceleration. This open quantum system approach is applied to quantum gravity on some spacetimes [16,17]. The phenomenological model can be simulated in trapped ion systems or superconducting circuit experiments [18,19]. Our scheme is to explore quantum metrology by the UdW model.

As we know, quantum Fisher information (QFI) is thought of as one efficient measure for parameter quantum estimation [20,21]. Recently, QFI has been widely studied in various fields involving the investigation of uncertainty relations [22,23], the estimation of quantum speedup limit time [24], the characterization of quantum phase transition [25], and the detection of entanglement [26]. Until now, some interesting works have considered the Unruh effect on quantum metrology in the non-inertial frame [27–31]. The authors have found that Fork states can achieve the maximal QFI in the presence of scalar fields in a $1+1$-dimensional Minkowski spacetime [27]. Dirac fields in non-inertial frames were investigated in [28]. Additionally, relativistic effects were considered as one resource for performing quantum metrology [30]. The Fisher information for population measurement has been evaluated by the use of the open quantum system method [31]. When a measuring device is in a relativistic motion, observation occurs in a non-inertial frame. Our aim is to determine some common features of relativistic quantum metrology. We try to find some controllable conditions that contribute to the enhancement of relativistic quantum metrology.

In this paper, the dynamics of QFI with respect to phase is investigated under the condition that a uniformly accelerated atom is weakly coupled to a massless quantum scalar field in the presence of reflecting boundaries. The paper is organized as follows. First, the UdW model and one calculation method of QFI are presented. We choose a pure state with a phase parameter as an initial state, and describe the evolution of the accelerated atom by means of open quantum system approach in the non-inertial frame. Second, in accordance with motions of a measuring device, the calculations of QFI as a function of the proper time in the non-inertial frame are demonstrated in detail. The effects of reflecting boundaries on phase quantum estimation are considered. Finally, a conclusion depicts key findings about relativistic parameter quantum estimation and some possible physical realizations.

2. Model and dynamics

What we are interested in is the dynamical behavior of parameter quantum estimation related to a uniformly accelerated particle detector, such as a two-level atom. In this scenario, we present the Unruh–DeWitt detector model to characterize the atom coupled to a massless quantum scalar field. In the weak coupling limit, atomic transitions with no exchange of angular momentum are reasonably considered [5]. Without loss of generality, the Hamiltonian of the model can be expressed as

$$H = H_0^{(d)} + H_0^{(f)} + H_I. \tag{1}$$

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