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Effect of two-qutrit entanglement on quantum speed limit time of a bipartite V-type open system

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ABSTRACT

In the present paper, quantum speed limit (QSL) time of a bipartite V-type three-level atomic system under the effect of two-qutrit entanglement is investigated. Each party interacts with own independent reservoir. By considering two local unitarily equivalent Werner states and the Horodecki PPT state, as initial states, the QSL time is evaluated for each of them in the respective entangled regions. It is counterintuitively observed that the effect of entanglement on the QSL time driven from each of the initial Werner states are completely different when the degree of non-Markovianity is considerable. In addition, it is interesting that the effect of entanglement of the non-equivalent Horodecki state on the calculated QSL time displays an intermediate behavior relative to the cases obtained for the Werner states.

1. Introduction

Quantum speed limit (QSL) is of particular interest and has attracted much attention in tremendous areas of quantum physics and quantum information, such as nonequilibrium thermodynamics [1], quantum metrology [2–5], quantum optimal control [6–11], quantum computation [12–14], and quantum communication [1,15]. In these fields, QSL time is a key concept, defined as the minimum

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evolution time in which a system evolves from an initial state to a target state. In the other hand, the QSL time sets a bound on the minimal time a system which needs to evolve between two distinguishable states, and it can be understood as a generalization of the time-energy uncertainty principle. For isolated systems, the QSL time under unitary evolution is determined by the Mandelstam–Tamm bound [16] and Margolus–Levitin bound [17]. Because of the inevitable interactions with the environments, quantum systems should be generally regarded as open systems. Therefore, it is necessary to determine a QSL time for open systems. Recently, Taddei et al. developed a method to investigate the QSL problem in open systems described by positive non-unitary maps by using of quantum Fisher information for time estimation [18]. While, for the case of the initial mixed states, a Hermitian operator is required to minimize the Fisher information in the extended system–environment space, which is generally a hard task. Afterwards, Campo et al. exploited the concept of relative purity to derive an analytical and computable QSL time for open systems undergoing a completely positive and trace preserving evolution [19]. It should be noted that relative entropy can perfectly make a distinction between an initial pure state and its target state, however it may fail to distinguish an initial mixed state to its target state. Also, a tight bound on the minimal evolution time of an arbitrarily driven open system has been formulated by Deffner and Lutz [20]. However, their time bound is derived from pure initial states and cannot be directly applied into the mixed initial states. Motivated by the recent studies above, the authors in Ref. [21] employed an alternative fidelity definition different from relative entropy in order to derive an easily computable QSL time bound for open systems whose initial states can be chosen as either pure or mixed states and this QSL time is applicable to either Markovian or non-Markovian dynamics. Alongside these efforts, several attentions have been devoted to investigate the effects of entanglement on the QSL time in multiqubit systems (for instance, see [18,22]).

In this paper, we consider a bipartite system composed of two identical V-type three-level atoms as a two-qutrit system where each atom interacts with own independent reservoir. We use the QSL time bound obtained in [21] to evaluate the speed of evolution of the system under the effects of two-qutrit entanglement exhibited in the system. To this aim, we choose two local unitarily equivalent Werner states [23] and the Horodecki PPT (partial positive transpose) state [24] which is not equivalent to the Werner states, as initial states, and obtained the QSL time for each of them in the respective entangled regions. When the degree of non-Markovianity in the system dynamics is considerable, surprisingly distinct behaviors for the QSL time are obtained for the equivalent Werner states in the entangled regions. In other words, under the condition of considerable non-Markovianity, effect of the same two-qutrit entanglement related to equivalent Werner states are completely different on the respective QSL times. It is interesting to note that for the non-equivalent Horodecki state, the calculated QSL time has an intermediate behavior relative to the cases obtained for the Werner states. We see that, although any local unitary operation does not increases the degree of entanglement (in the case of Werner states discussed in the present paper, the introduced local unitary operator does not change the degree of entanglement) but, as illustrated in the text, it is observed that the related QSL time changes under the mentioned local unitary operator effect.

The paper is organized as follows: In Section 2, we describe dynamics of a V-type three-level atomic system as an open system along with giving a quantitative description of non-Markovian behavior of that system. Also, we extend the dynamics of the V-type three-level system to a bipartite case. Section 3 is devoted to the obtaining of QSL time for the bipartite system and discussing about the connection between two-qutrit entanglement and the related QSL time. Finally, in Section 4, we present our conclusions.

2. Dynamics of V-type three-level open systems

In this section, we study at first, Markovian and non-Markovian dynamics of a V-type three level atom, as a qutrit, coupled to a dissipative environment. Each atom has two excited states each of them spontaneously decays into ground states such that the respective dipole moments of transitions may have interaction with each other. We then extend the scheme into a two-qutrit case which each of them coupled to independent reservoirs as depicted in Fig. 1. For a V-type atom, under the interaction with the same environment, the two upper levels $|2\rangle$ and $|1\rangle$ are coupled with the ground one, $|0\rangle$,