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Probing Planckian physics in de Sitter space with quantum correlations

Jun Feng [a,*], Yao-Zhong Zhang [a], Mark D. Gould [a], Heng Fan [b], Cheng-Yi Sun [c], Wen-Li Yang [c]

[a] School of Mathematics and Physics, The University of Queensland, Brisbane, QLD 4072, Australia
[b] Institute of Physics, Chinese Academy of Sciences, Beijing 100190, PR China
[c] Institute of Modern Physics, Northwest University, Xian 710069, PR China

HIGHLIGHTS

- Quantum correlation and quantum channel in de Sitter space are studied.
- Gibbons–Hawking effect causes entanglement degradation for static observer.
- Planckian physics causes extra decrement on quantum correlation.
- Convergent feature of negativity relies on the choice of alpha-vacua.
- Link between negativity convergence and quantum channel capacity is given.

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ABSTRACT

We study the quantum correlation and quantum communication channel of both free scalar and fermionic fields in de Sitter space, while the Planckian modification presented by the choice of a particular α-vacuum has been considered. We show the occurrence of degradation of quantum entanglement between field modes for an inertial observer in curved space, due to the radiation associated with its cosmological horizon. Comparing with standard Bunch–Davies choice, the possible Planckian physics causes some extra decrement on the quantum correlation, which may provide the means to detect quantum gravitational effects via quantum information methodology in future. Beyond single-mode approximation, we construct proper Unruh modes admitting general α-vacua, and find a convergent feature of both bosonic and fermionic entanglements. In particular, we show that the convergent points of fermionic entanglement negativity are dependent on the choice

* Corresponding author.
E-mail address: j.feng1@uq.edu.au (J. Feng).

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of α. Moreover, an one-to-one correspondence between convergent points H_c of negativity and zeros of quantum capacity of quantum channels in de Sitter space has been proved.

1. Introduction

Quantum information processing, based on principles of quantum mechanics, promises algorithms surpassing their classical counterparts and unconditional secure for quantum communication. Combined with relativity which is another cornerstone of modern physics, a new fast-growing field called Relativistic Quantum Information (RQI) has attracted much attentions in recent years (see Ref. [1] for a recent review). Besides its importance in probing extremely sensitive gravitational effects [2], it can also shed lights on study of black hole information paradox [3] and cosmological evolution [4]. Experimental realizations of RQI process in laboratory systems like atomic interferometry [5] and circuit QED [6] have also been proposed.

A novel phenomenon in RQI is that quantum correlations of a mostly entangled physical system are highly observer-dependent. For a bipartite entangled system in flat space, it was shown [7] that an accelerated observer, having no access to information beyond his acceleration horizon, would experience some decrement of the quantum correlations he shared initially with an inertial partner. Therefore the information-loss results in the celebrated Unruh effect [8] which claims the detection of a thermal bath for an accelerated detector in flat space. Such decoherence phenomena should exist for any other kinds of causal horizons related with thermal radiation, e.g., the event horizon of black hole [9]. By a process akin to teleportation but without the classical information transmitted [3,10], quantum information can even escape from a black hole. While above studies focus on entangled global modes, recently, entanglement between fields or systems localized in spacetime has also attracted much attention [11–15]. These entangled localized systems can in principle be measured and exploited for real quantum information tasks [16].

As an idealization of inflation regime in cosmology, de Sitter space possesses a cosmological event horizon, from which a thermal spectrum with temperature $T = H/2\pi$ could be detected by a static observer [17]. This so-called Gibbons–Hawking effect results from the highly non-trivial definition of a vacuum state in a time-dependent background where no global timelike Killing vectors could be found. The unique Bunch–Davies vacuum for a comoving observer, matching with Minkowskian vacuum at *arbitrary* short distance, appears as thermal state for a static partner who defines a distinct static vacuum and has no access to the field modes beyond the cosmological horizon [18]. This information loss with Gibbons–Hawking radiation should certainly cause a decoherence phenomenon for an inertial observer in de Sitter space. Since the thermal spectrum described by a same formula as for the temperature of Hawking radiation and Unruh effect, it is wildly believed [19] that, for RQI in de Sitter space, nothing would change in essentially but only the Hubble parameter H replacing the surface gravity of black hole or the acceleration of Unruh detector. However, as we show in this paper, it is *not* the whole story.

The main point is that the definition of Bunch–Davies vacuum, which relies on an ability to follow a field mode to infinitesimal scales, should be broken near some fundamental scale of quantum gravity. Effectively, this means a boundary condition on the vacuum of comoving observer must be imposed when the momentum of field mode $\vec{k}$ cutoff at Planck scale Λ. Such constraint can also be interpreted as choosing a harmonic oscillator vacuum at the earliest time $\eta_0(\vec{k}) = -\Lambda/H|\vec{k}|$, which eventually results a robust anisotropy signal in CMBR [20]. Therefore, in de Sitter space, any quantum information processing with a particular choice of initial vacuum should include those modifications from Planck scale, since it has a directly consequence on the behaviors of quantum correlations [21–26]. Even without a complete knowledge about quantum gravity, such investigation on RQI processing may provide a new typical signature to probe Planckian physics [27].