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Non-Markovian discrete qubit dynamics

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Abstract The study of open quantum systems is important for fundamental issues of quantum physics as well as for technological applications such as quantum information processing. The interaction of a quantum system with its environment is usually detrimental for the quantum properties of the system and leads to decoherence. However, sometimes a quantum control can lead to a coherent partial exchange of information between the system and the dynamics of the open system might become non-Markovian. In this article, we study experimentally discrete non-Markovian open quantum system dynamics. We implement a local control protocol using linear optics for controlling the information flow between the open system and the environment. We show how the transition from Markovian to non-Markovian dynamics can be controlled using only local operations for the open system.

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1 Introduction

Whenever quantum system is not perfectly isolated (up to experimental accuracy) it has to be treated as an open system [1]. The description of the open system dynamics is based on a family of completely positive and trace preserving maps (CPT), so called dynamical map, governing the evolution of the state of the open system as $\rho \mapsto \rho = \Phi\rho$ [2]. The dynamical map is a standard tool to describe dechorence and dissipation phenomena. If the family of dynamical maps has the semi-group property then its properties and structures are well known. The generator of the quantum dynamical semigroup in time continuous case is the famous Gorini–Kossakowski–Sudarshan–Lindbald (GKSL) master equation [3, 4] which is the workhorse of the open quantum systems research [5]. Open systems falling into a category where their dynamics can be described with quantum dynamical semigroup are called Markovian [6].

In general, the dynamical map is less structured, meaning the dynamical map may not necessarily be divisible, not even with positive maps [7], relistic quantum systems interact and exchange information with the environment and thus lead to open quantum non-Markovian dynamics. Recently due to efforts to quantify quantum non-Markovianity [8–15] and technological advances [16–19], non-Markovian quantum processes have become a central topic in the study of open quantum systems. In general, realistic quantum systems interact and exchange information with the environment. The possibility to engineer decoherence processes and to be able to control the information flow between the open system and its environment is the key to be able to control quantum memory effects in the open quantum system dynamics.

One form of quantum control [20–30] is the dynamical decoupling techniques, where fast pulses are applied to the open system locally and the environmental effects may be eliminated [31–34]. In this work, we study experimentally discrete open quantum system dynamics. We implement single qubit dephasing dynamics with local control protocol using linear optics. Similar method has been used in Orieux's work [27] in which they demonstrated that distributed entanglement can be fully restored on-demand by sutiable local controls on the overal dynamics. While in our work, the local control acts only on the open system (qubit) locally. We show that the transition from Markovian to non-Markovian dynamics can be controlled from the open system side locally. The environment is characterized by a spectral distribution that leads to Markovian dynamics in the absence of local control [16], which allows us to conclude that the properties of the local control are responsible for the emerging quantum memory effects.

2 Theory

We design our experiment with a single photon propagating through a sequence of half-wave plates and quartz plates. The open system is the polarization degree of freedom of a single photon and the environment is the frequency degree of freedom. Hilbert space for the system H_S is thus spanned by the polarization eigenvectors $|H\rangle$, $|V\rangle$. Environment Hilber space H_E is spanned by a continuous set of frequency states $|\omega\rangle$ by $|\chi\rangle = \int \mathrm{d}\,\omega f(\omega)|\omega\rangle$, $f(\omega)$ is a normalized amplitude. Total Hilbert space is thus $H = H_S \otimes H_E$. Local control operations are unitaries implemented by half-wave plates acting only on the polarization degrees of freedom. They are described by the following unitary

$$C_\eta = (\sqrt{\eta}|H\rangle\langle H| + \sqrt{1-\eta}|H\rangle\langle V| + \sqrt{1-\eta}|V\rangle\langle H| - \sqrt{\eta}|V\rangle\langle V|) \otimes I, \tag{1}$$

where $\eta \in [0,1]$ is controlled by the tilt angle of the half-wave plate. For each η we choose, the corresponding angle of the half-wave plate is given by $\varphi_\eta = 1/2\arccos(\eta^{\frac{1}{2}})$. Simple theoretical model for the quartz plate is given by the following unitary coupling between the qubit and the environment Hilbert spaces

$$U_{\delta t} = \sum_{k=H,V} \int \mathrm{d}\,\omega \mathrm{e}^{\mathrm{i}n_k\omega\delta t}|k\rangle\langle k| \otimes |\omega\rangle\langle\omega|, \tag{2}$$

where δt is the interaction time of the photon with the environment and n_k is the index of refraction for polarization state $|k\rangle$. Interaction time δt is related to the quartz plate thickness by $nL = c\delta t$, where c is the speed of light.

We choose the frequency distribution of the photon $\chi(\omega,\omega) \equiv |\chi(\omega)|^2$ to be a single Gaussian with standard deviation σ. Evolution of the initial state of the total system $\rho_0^{\mathrm{T}} = \rho_0 \otimes \chi$ through a n-fold sequence of pairs of half-wave plates and quartz plates is $(U_{\delta t} \cdot C_\eta)^n \rho_0^{\mathrm{T}}((U_{\delta t} \cdot C_\eta)^\dagger)^n$. We describe a single step operation as $U \equiv U_{\delta t}(C_\eta \otimes \mathbb{1}_E)$. We obtain the dynamics of the open system after n steps by tracing out the environment

$$\rho_n = \mathrm{tr}_E\{U^n(\rho_0 \otimes \chi)(U^\dagger)^n\}. \tag{3}$$

We prepare two initial states and measure their trace distance, which can be used as a measure for the distinguishability of quantum states [35], after every step of evolution. The trace distance between two quantum states ρ_1, ρ_2 is defined as $D(\rho_1,\rho_2) = \frac{1}{2}||\rho_1 - \rho_2||$ where $||\cdot||_1$ is the trace norm. It is a monotonically decreasing function under Markovian quantum dynamical maps. Here we define the non-Marokvianity as the sum of the postive temporal increments of the trace distance between the two quantum states after every step of their evolution under the same dynamical map [9]. The increment of the trace distance evolution is defined as $\varDelta_{1,2}(n) = D(\rho_1(n),\rho_2(n)) - D(\rho_1(n-1),\rho_2(n-1))$, where $\rho_1(n)$ and $\rho_2(n)$ are the two final states corresponding to the pair of initial states after n steps of evolution. We obtain a measure for non-Markovianity after n steps with a chosen pair of initial states $\rho_{1,2}(0)$ as $\mathcal{N}_{1,2}(n) = \sum_{\varDelta_{1,2}(n)>0} \varDelta_{1,2}(n)$. A lower bound for the measure is obtained just with a single pair that shows non-monotonic trace distance evolution. In this experiment the initial state pairs were taken to be $\rho_1(0) = |H\rangle\langle H|$ and $\rho_2(0) = |V\rangle\langle V|$.

The above theoretical model includes the local control of the open system and also the interplay of the local controls and the correlations between the open system and the environment. We know from earlier studies that when frequency distribution is a single Gaussian it will lead to Markovian dynamics without the local control [16, 36]. Specifically we can explain how we get non-Markovian dynamics with a Markovian dephasing environment by adding suitable local controls.

3 Experimental

The experimental setup is shown in Fig. 1. A femtosecond pulse (with a duration of about 150 fs, the operation wavelength at $\lambda_0 = 800$ nm and a repetition rate of about 76 MHz) generated from a Ti sapphire laser is used to generate attenuated single-photons and the average number