Short Communication

Observation of non-Markovianity at room temperature by prolonging entanglement in solids

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Abstract

Open quantum systems are always exposed to an external environment, which result in interacting and exchanging information between quantum systems and their surroundings. The dynamics of real open quantum systems are often expected to deviate from the idealized Markovian process of losing information to their surrounding environment and to exhibit non-Markovian behaviour with information flowing back to the quantum system from the environment [1–3]. Non-Markovian dynamics is responsible for a wide variety of interesting systems including quantum optics [4], solid systems [5–8], and even some problems in quantum chemistry [9] and biology systems [10]. In recent years, more and more attentions have been paid to non-Markovian processes in theory [11–20], with some experimental characterization on quantum optics [21–23]. Due to the ability of regaining lost information and recovering coherence, the Markovian dynamics also show important application prospects in quantum metrology [18,24] and quantum key distribution [19].

In order to clearly distinguish the regimes of Markovian and non-Markovian quantum evolutions and to quantify memory effects in the open system dynamics, the measure for the degree of quantum non-Markovianity has been developed recently [13–15,17,25]. And some experiments have been done in quantum optics systems according to these methods through changing the mimic external environment with the knowledge of model of environment [21–23,26]. Under the situation of the absent of an accurate microscopic model of the system-bath interaction, which may actually be unfeasible especially in many body systems, and in order to avoid the definition of an optimization problem [13], entanglement was introduced to measure deviations from Markovianity [14]. However, in real quantum systems, especially in solids, entanglement are fragile and influenced by decoherence due to the inhomogeneous noise in the surrounding environment, so the non-Markovianity is usually concealed in the Markovian behaviour and has not been observed yet with entanglement. Nowadays dynamical decoupling [27,28] has been used to suppress the inhomogeneous noise and prolong the entanglement coherence time in realistic solid systems [29], which makes it feasible to observe and study the degree of non-Markovianity of the quantum system evolution.

In recent years, Nitrogen Vacancy (NV) center system in diamond has attracted more and more attentions due to its promising potential in quantum metrology [30–33] and quantum information processing [34–36] at room temperature. As an open quantum system in solids, it is interesting itself to gain a clear knowledge of its quantum dynamical evolution and it is also very important to know the quantum dynamical properties of the NV center quantum system for its application in quantum control and quantum metrology. Here we present an experimental study of non-Markovianity in diamond solid system. With the entanglement of single electron spin of NV center in diamond and its nearby ancillary nuclear spin, we observed the concurrence revival of these two qubits entanglement which reveals the non-Markovianity of the NV center quantum evolution. By applying dynamical decoupling pulses on the single electron spin, we observed the non-Markovianity and obtained more detailed information of the environment memory effect influencing the quantum non-Markovianity.

In the experiment, a single NV center coupled to a first shell $^{13}$C nuclei in diamond was chosen to study the non-Markovianity of...
quantum evolution. The diagram of the system is shown in Fig. 1a. The direction of the external magnetic field to adjusted to be along the symmetry axis, and the Hamiltonian of the NV center electron spin with a $^{13}\text{C}$ nuclear spin can be described as:

$$H = \gamma_e B_S S_z + D S_z^2 + \hat{A} I_z + \gamma_i B_I I_z.$$  

The zero-field splitting with $D = 2.87$ GHz, the Zeeman term with $\gamma_e = 2.802$ MHz/Gauss of the electron spin and $\gamma_i = 1.071$ kHz/Gauss of the $^{13}\text{C}$ nuclear spin and the hyperfine coupling tensor $\hat{A}$ determine the energy level structure shown in Fig. 1b. The detailed hyperfine coupling tensor $\hat{A}$ can be found in Ref. [37]. The hyperfine coupling term between the NV center electron spin and the intrinsic Nitrogen nuclear spin is not shown here. During the experimental process, we mainly considered the entanglement of the electron spin and nuclear spin in the subspace of $M_s = 0$ and $M_s = 1$ of the electron spin, which is shown in Fig. 1b by orange lines. In type Ia diamond, the environment of the NV center is mainly the surrounding $^{13}\text{C}$ nuclear spin bath, which brings about the loss of NV center's diamond, the environment of the NV center is mainly the surrounding $^{13}\text{C}$ nuclear spin bath. (b) energy level scheme of the system. The four states used here are from the subspace containing nuclear spins, respectively. (c) and (d) are the electron and nuclear spin Rabi transitions of nuclear spin. (e) and (f) are the free induction decays of electron and nuclear spins, respectively.

![Fig. 1. Experimental system. (a) schematic of the studied quantum system composing of a NV center and nearby $^{13}\text{C}$ nuclei in spin bath. (b) energy level scheme of the system. The four states used here are from the subspace containing nuclear spins, respectively. (c) and (d) are the electron and nuclear spin Rabi transitions of nuclear spin. (e) and (f) are the free induction decays of electron and nuclear spins, respectively.](image1)

![Fig. 2. Initialization, dynamical decoupling and measurement of the system. To initialize the system into the maximum entangled state $\frac{1}{\sqrt{2}}(|00\rangle - |11\rangle)$, firstly, the electron spin of NV center is transfer to $M_s = 0$ state by a laser pulse lasting 3 μs, then the system is transfer into $|00\rangle$ state by a pulse sequence of 8 times of cycling followed by a MW2 π pulse, and finally the combination of two X MW4 pulse with one π/2 RF1 pulse in between completes the preparation of the entangled state. Periodic pulsed dynamical decoupling sequence is then exerted to the electron spin through MW3 and MW4 simultaneously. Measurement of the system is done by quantum tomography.](image2)
The initial state density matrix. The fidelity is estimated by the equation $F - \text{tr}(\sqrt{\rho} \sqrt{\sigma})$, where $\rho$ is the initial state density matrix and $\sigma$ is the ideally expected one, the obtained result is 0.94, while the concurrence is about 0.67. Here, the concurrence is calculated by the formula $C(\rho) = \max\{0, \lambda_1 - \lambda_2 - \lambda_3 - \lambda_4\}$, where the $\lambda_i$ s are the square roots of the eigenvalues of $\rho \rho^\dagger$ in descending order. Here, $\rho = \sigma_i \rho \sigma_j$, where $\sigma_i$ is the standard Pauli matrix. The error bars of concurrence were estimated through Monte Carlo method. The error bars for the measured data set bounds for the quantity with a certain confidence. We randomly generated parallel data within the bonds to calculate concurrence and the process was repeated $10^5$ times. Then we set error bars to be the maximum and minimum value of this set of concurrence.

In Fig. 4, we present the non-Markovianity of the quantum evolution with entanglement. From the simple way to quantify the degree of non-Markovianity of quantum evolution introduced in Ref. [14], the non-Markovianity within a selected interval $[t_0, t_{\text{max}}]$ can be calculated by:

$$F_E = \int_{t_0}^{t_{\text{max}}} \left| \frac{dE(\rho(t))}{dt} \right| dt - \Delta E. \quad (2)$$

Here, $\Delta E = E(\rho(t_{0})) - E(\rho(t_{\text{max}}))$, and $E$ denotes some entanglement measure. In this paper, $E$ means the entanglement concurrence. From the simple formula, we can see that the non-Markovianity can be gained through the height of the entanglement concurrence revival. The free evolution of the entangled state in Fig. 4a clearly shows the concurrence oscillation during the evolution. This is attributed to the strong coupling between the NV center and N nuclear spin which obviously deviates the Markovian process assumption. The decay is mainly caused by the thermal noise of the surrounding $^{13}$C nuclear spin bath. In Fig. 4a, the initial concurrence less than a perfect Bell state is mainly caused by the imperfection of the entanglement preparation pulses. The simulation results match the experimental results by considering these errors. From the non-Markovianity of the free entanglement evolution we obtain the coupling strength of N nuclear spin with the quantum system and the thermal noise strength of the nuclear spin bath. By using dynamical decoupling methods, this noise has been suppressed and the entanglement is prolonged. Fig. 4b shows the experimental results of entanglement evolution under PDD2 sequences working only on the NV’s electronic spin qubit through MW3 and MW4 simultaneously. The entanglement is obviously prolonged and the concurrence of entanglement firstly decays to zero, remains zero and then suddenly revives. The horizontal axis is the total entanglement evolution time. This revival is caused by the environmental nuclear spins collective evolution due to the very weak coupling between nuclear spins in the environment, the nuclear spin bath evolution is mainly influenced by the NV center state and the external static magnetic field. By using the PDD2 pulse on NV center, the coupling of the environmental nuclear spin with the NV center is suppressed. Then the nuclear spin bath evolution is mainly subject to the external magnetic field, which induces the collective evolution of the nuclear spin bath. So the entanglement is recovered when the nuclear spins simultaneously evolve to their initial states. However, the concurrence of the entanglement did not reach its initial value. One reason is the remaining decoherence of the electron spin under PDD2 caused by the nuclear spin-spin interaction within the environment, which can lead to incomplete recovery of the environmental nuclear spins to their collective initial state; and another reason is due to the limited ancillary nuclear spin coherence time. Here, it is mainly caused by the latter, as usually the nuclear spin-spin interaction is too weak to take effect in the considering time scale [41]. The ancillary nuclear spin interacts with the environment mediated by the NV center that induced the main decay. By excluding this reason, the non-Markovianity in Fig. 4b mainly reflects the interaction strength inside the nuclear spin bath which concern with the bath memory time. Comparison of Fig. 4a with Fig. 4b shows that more non-Markovianity is revealed by dynamical decoupling, which is helpful to understanding the detail origin of non-Markovianity. This method is expected to be useful in quantum control and quantum metrology in non-Markovian environment [18,24].

In summary, we have studied the non-Markovian characteristics of quantum evolution in diamond experimentally by using the entanglement method. We find different non-Markovianity of the entanglement evolutions and provide corresponding explanations. By using the dynamical decoupling, more non-Markovianity is revealed that otherwise is hiding in the environment. From such an experimental non-Markovianity study, we can obtain much more detail interaction information of the environment with the NV center in the diamond. This will be helpful for making non-Markovianity as a resource for quantum technology applications and also would be expected useful in other open quantum systems like transport processes in biological aggregates and complex nano-structures [42].

**Conflict of interest**

The authors declare that they have no conflict of interest.
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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.scib.2018.02.017.

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