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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 introduced [12]. Several methods based on semigroup, divisibility, flow back of information or quantum mutual information and quantum correlations for the measurement of non-Markovianity have 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

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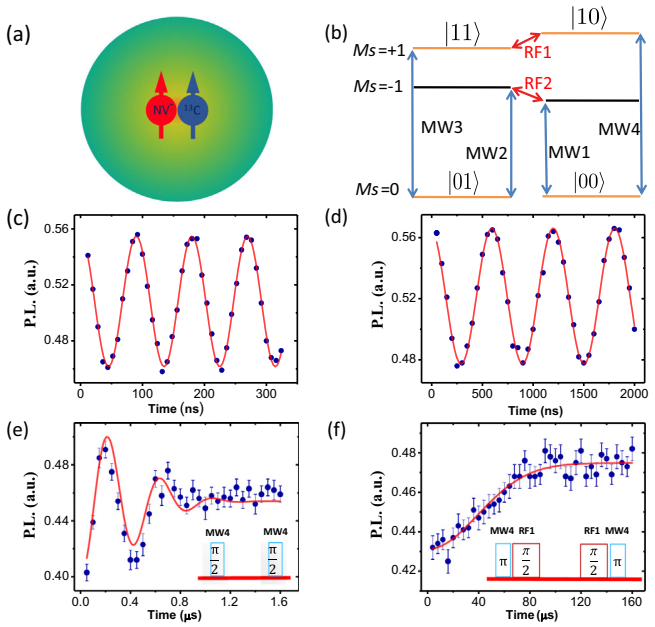

Fig. 1. Experimental system. (a) schematic of the studied quantum system composing of a NV center and nearby ^{13}C nuclei in spin bath. (b) energy level scheme of the system. The four states used here are from the subspace containing $M_s = 0$ and $M_s = 1$ states (labeled $|00\rangle, |01\rangle, |10\rangle$ and $|11\rangle$). MW1 to MW4 stand for the the transitions between electron spins, and RF1 and RF2 represent the transitions of nuclear spin. (c) and (d) are the electron and nuclear spin Rabi nutations, respectively. (e) and (f) are the free induction decays of electron and nuclear spins, respectively.

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}C nuclear spin can be described as:

$$H = \gamma_e B_z S_z + DS_z^2 + \hat{S}\tilde{A}\hat{I} + \gamma_c B_z I_z. \quad (1)$$

The zero-field splitting with $D = 2.87$ GHz, the Zeeman term with $\gamma_e = 2.802$ MHz/Gauss of the electron spin and $\gamma_c = 1.071$ kHz/Gauss of the ^{13}C nuclear spin and the hyperfine coupling tensor $\tilde{A}$ determine the energy level structure shown in Fig. 1b. The detailed hyperfine coupling tensor $\tilde{A}$ 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 IIa diamond, the environment of the NV center is mainly the surrounding ^{13}C nuclear spin bath, which brings about the loss of NV center's quantum coherence [38]. As the direct dipole-dipole coupling between two nuclear spins is weak, a ^{13}C nuclear spin on the first shell of the NV center can be adopted as an ancilla qubit for the NV electron spin to form the two-qubit system of interest depicted in Fig. 1b, with state $|M_S = 0, M_I = 1\rangle$ denoted as $|01\rangle$ and alike.

All measurements were carried out under ambient conditions on a type IIa bulk diamond sample, in which ^{13}C has the natural abundance (1.1%) and the nitrogen impurity concentration is less than 5 ppb. A single NV center was addressed by a home-built confocal microscope. The microwave fields used to control the electron spin were generated from Apsin 6000 Signal Generators passed through a switch (Mini-Circuits ZASWA-2-50R+) and a 16 W power amplifier. The radio-frequency fields for the excitation of nuclear spin were generated by a direct digital synthesis and went through a switch and a phase shifter (carefully tuned at 90°), and amplified (Mini-Circuits ZHL-20W-13+) before combining with microwave signals. The combined signals through a diplexer were transmitted to the the NV center through a coplanar waveguide beneath the diamond. Three pairs of adjustable Helmholtz coils were used to generate a 60 Gauss magnetic field to remove the degeneracy of $M_s = \pm 1$ state. In the experiment, the length of initialization laser pulse is 3 μs and the waiting time following the laser is 5 μs. The photoluminescence is measured during an integration time of 0.35 μs. To suppress the photon statistic error, each measurement is typically repeated more than 10^6 times.

Fig. 1 shows the basic control abilities and coherent properties of the system. The resonance frequency of the nuclear spin in the electron spin $M_s = 1$ subspace was obtained from electron nuclear double resonance spectrum. The experimental data is not shown here. From the sequences of free induced decay, which is depicted at the low right corner of Fig. 1e and f, we find the coherence time of NV center is $T_{2e}^* = 0.75$ μs and the coherence time of the nuclear spin in the electron spin $M_s = 1$ subspace is $T_{2n}^* = 56$ μs. The short coherence time of nuclear spin is caused by the interaction with the surrounding nuclear spins mediated by the NV center electron spin.

The main experimental process is described in Fig. 2. At the beginning, we applied cascaded MW, RF and laser pulses to polarize the population to $|00\rangle$ state. This process is mainly through the polarization transfer from the electron spin to the nuclear spin. The sequence was repeated 8 times and the degree of polarization was about 0.8. Then we applied another MW2 π pulse to transfer the rest population on $|01\rangle$ state to the $M_s = -1$ subspace, so it was the pure state in the subspace of interest. Then we applied the combined Microwave pulses to generate one of the Bell states $\frac{1}{\sqrt{2}}(|00\rangle - |11\rangle)$. Through a period of free evolution or with pulsed dynamical decoupling during evolution, the final state was readout by quantum sate tomography technique. All the population was transferred to the $M_s = |0\rangle$ state of the electron spin of the NV center, which was readout by the fluorescence.

During the experiment of entangle state preparation, the $\pi/2$ pulse was exerted to the nuclear spin to minimize the decoherence influence from the NV center. When doing the quantum state tomography, the transition between $|11\rangle$ and $|10\rangle$ is defined as the working transition, for example, when measuring the density matrix element $|11\rangle\langle 10|$, we do the Rabi nutation with two 90° phase shifted radio frequency pulses. Other elements can be measured by transferring the corresponding nutations to the working transition. The population and coherence can be calculated from the rotation curves. Fig. 3 shows the real and imaginary part of

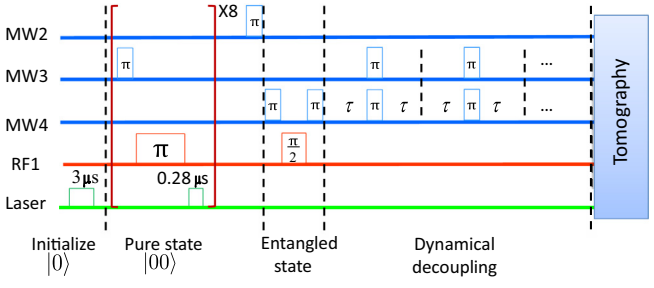

Fig. 2. Initialization, dynamical decoupling and measurement of the system. To initialize the system into the maximum entangled state $\frac{1}{\sqrt{2}}(|00\rangle - |11\rangle)$, firstly, the electron spin of NV center is transfer to $M_s = |0\rangle$ state by a laser pulse lasting 3 μs, then the system 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 π MW4 pulse with one $\pi/2$ 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.

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