Quantum Zeno and Zeno-like effects in nitrogen vacancy centers

Jing Qiu1,*†, Yang-Yang Wang1,** Zhang-Qi Yin2, Mei Zhang1, Qing Ai2 & Fu-Guo Deng1

We present a proposal to realize the quantum Zeno effect (QZE) and quantum Zeno-like effect (QZLE) in a proximal 13C nuclear spin by controlling a proximal electron spin of a nitrogen vacancy (NV) center. The measurement is performed by applying a microwave pulse to induce the transition between different electronic spin states. Under the practical experimental conditions, our calculations show that there exist both QZE and QZLE in a 13C nuclear spin in the vicinity of an NV center.

Quantum Zeno effect1,2 (QZE) is a very interesting phenomenon in quantum physics, in which the evolution of a quantum system can be inhibited by frequent measurements. In 1990, based on Cook’s theoretical proposal3, QZE4 was experimentally demonstrated by controlling the transition between two hyperfine levels of 9Be+ with laser pulses, and there was a good agreement between theoretical prediction and experimental results. Since then, much effort has been paid to the research on QZE5–8, quantum anti-Zeno effect9–12 and quantum Zeno-like effect (QZLE)13,14. Because of its potential application in slowing down or even freezing the dynamic evolution of a system via repeated frequent measurements, it recently has attracted considerable interest as a tool in the fields of quantum information processing15–21 and ultrasensitive magnetometer22.

QZE has been successfully demonstrated on various physical systems, such as trapped ions23, superconducting qubits24,25, cavity quantum electrodynamics7,16, nuclear magnetic resonance26,27, and Bose-Einstein condensates28–30. On the other hand, in solid-state quantum-information technology, a nitrogen vacancy (NV) center which consists of a nitrogen substituting for a carbon and an adjacent vacancy in diamond has been identified as one of the most promising candidates for qubits31–38 due to its long coherence time at room temperature39–41 and convenient manipulation under optical field, microwave field and rf field42,43. Quantum Zeno-like phenomenon was experimentally demonstrated by inhibiting coherent spin dynamics induced by the microwave driving between two ground-state electron-spin levels (\(m_s = 0\) and \(m_s = 1\)) of a single NV center44. Therein, only one measurement is performed to analyze the measurement effect on electron-spin states, i.e., the population variation between the electron-spin states \(m_s = 0\) and \(m_s = 1\) has been made by this single measurement.

In the conventional QZE, repeated instantaneous perfect measurements performed on the system will freeze the evolution of the initial state. The perfect conventional QZE requires infinite measurements with repetitive frequency approaching infinity, which might be impossible in experiment. However, it was recently discovered that perfect freezing of quantum states can also be achieved by more realistic non-projective measurements performed at a finite frequency13. According to Brouwer’s fixed-point theorem45, there always exist some quantum states which satisfy \(\Phi(\rho_0) = \rho_0\), where \(\Phi\) represents a quantum dynamical evolution process of a system with its initial state \(\rho_0\). After \(n\) identical cycle process, the system stays at the state as the same as its initial one, i.e., \(\Phi^n(\rho_0) = \rho_0\). In this way, a QZLE can be achieved with finite-frequency measurements.

In this paper, inspired by the discovery in ref. 13, we present a proposal to achieve the QZLE in a proximal 13C nuclear spin of an NV center by controlling the electron spin. In our proposal, the electron spin plays the role as a detector while the 13C nuclear spin acts as the target. Furthermore, the conventional QZE is demonstrated by modulating the measurement parameters and the external magnetic field.

1Department of Physics, Applied Optics Beijing Area Major Laboratory, Beijing Normal University, Beijing 100875, China. 2Center for Quantum Information, Institute for Interdisciplinary Information Sciences, Tsinghua University, Beijing 100084, China. *These authors contributed equally to this work. Correspondence and requests for materials should be addressed to Q.A. (email: aiqing@bnu.edu.cn)
Here, instead of projective measurements, we apply a microwave pulse to induce the transition between different electronic states, followed by initialization of electron spin. Our numerical calculation properly shows that for suitable parameters there exist the conventional QZE and QZLE in a proximal $^{13}$C nuclear spin of the NV center.

Results

The model. An NV center in diamond is composed of a nitrogen atom and a vacancy in an adjacent lattice site. It is a defect with $C_3v$ symmetry. For the negatively-charged NV center with electron spin $S = 1$, the ground state is a spin-triplet state $^3A$ with a zero-field splitting $D = 2.87$ GHz between spin sublevels $m_s = 0$ and $m_s = \pm 1$. Around NV centers there are three kinds of nuclear spins, i.e., $^{13}$C ($I = 1/2$), $^{14}$N ($I = 1$), and $^{15}$N ($I = 1/2$). They can be manipulated by microwave and rf fields.

Consider an NV center and a $^{13}$C nuclear spin which locates in the first coordination shell around the NV center, as shown in Fig. 1(a). In other words, this $^{13}$C nuclear spin is at the nearest-neighbor lattice site of the NV center. As a result, there is a strong hyperfine coupling between the nuclear and electronic spins. Figure 1(b) shows the simplified energy-level diagram of the ground-state hyperfine structure associated with the nearest-neighbor $^{13}$C nuclear spin. To demonstrate the QZE, the electron-spin states ($m_s = -1, 0$) and nuclear-spin states ($\uparrow, \downarrow$) are chosen to code qubits. The target and detector are initially uncorrelated, i.e., they are in a product state. A strong electron-spin polarization into the $m_s = 0$ sublevel can be induced by circulatory optical excitation-emission. This effect results from spin-selective non-radiative intersystem crossing to a metastable state lying between the ground and excited triplet states. Moreover, the nuclear spin could be well isolated from the electron spin, during the optical polarization and measurement of the electronic state. In other words, the state of nuclear spin could be unperturbed when the initialization and measurement are performed on the electronic spin.

Suppose that the electron spin is initially in its ground state $|0\rangle$ and the nuclear spin is in an arbitrary state. First of all, the whole system evolves freely for a time interval $\Delta t_f$. Afterwards, a microwave driving is used to perform measurement. As Fig. 1(b) shows, the microwave drives the transition between $|0, \uparrow\rangle$ and $|-1, \uparrow\rangle$ with Rabi frequency $\Omega$ and driving frequency $\omega$. In the process of measurement, the total system evolves under the Hamiltonian $H_M = H_F + H_I$ for a time interval $\Delta t_m$, where $H_F$ is the free Hamiltonian without measurement and $H_I$ is the interaction Hamiltonian describing the transition induced by microwave driving. After the measurement, by optical pumping, the electron spin is initialized in its ground state $|0\rangle$, and meanwhile the electron and nuclear spins are decoupled. Moreover, the nuclear spin could be well isolated from the electron spin, during the optical polarization and measurement of the electronic state. In other words, the state of nuclear spin could be unperturbed when the initialization and measurement are performed on the electronic spin.

The free Hamiltonian $H_F$. The general Hamiltonian of an NV center and a $^{13}$C nuclear spin which locates in the first coordination shell around the NV center is

$$
H = DS_z^2 + \gamma_e B \cdot S + \gamma_n B \cdot I + SA I
$$

$$
= DS_z^2 + \gamma_e(B_x S_x + B_y S_y + B_z S_z) + \gamma_n(B_x I_x + B_y I_y + B_z I_z)
+ (A_{xx} S_x I_x + A_{yy} S_y I_y + A_{zz} S_z I_z).
$$

(1)
Here, the first term stands for the zero-field splitting of the electronic ground state. The second term is the Zeeman energy splitting of the electron with $\gamma_e$ being the electronic gyromagnetic ratio. The third term denotes the nuclear Zeeman effect where $\gamma_n$ is the $^{13}$C nuclear spin gyromagnetic ratio. And the last term describes the hyperfine interaction between the electron spin and the nuclear spin of $^{13}$C atom.

Using a permanent magnet, an external magnetic field $B_z$ is applied parallel to the NV axis. Hence, $\gamma_e(B_zS_x + B_yS_y)$ and $\gamma_n(B_zI_x + B_yI_y)$ are removed. Under the condition of weak magnetic field strength, the difference between the zero-field splitting $D = 2.87$ GHz and the electronic Zeeman splitting is much larger than the hyperfine interaction. In this situation, the electron-nuclear-spin flip-flop processes induced by the hyperfine interaction are sufficiently suppressed. Therefore, this allows for the secular approximation and the $S_xI_x$ and $S_yI_y$ terms can be neglected. In other words, for the weak external magnetic field along the NV axis only the longitudinal hyperfine interaction needs to be taken into account, and the ground-state manifold of the NV center coupled with a proximal $^{13}$C nuclear spin is described by the Hamiltonian

$$H_F = DS_z^2 + \gamma_eB_zS_z + \gamma_nB_zI_z + A_{zz}S_zI_z,$$

where

$$I_z = \frac{1}{2}\sigma_z,$$

$$S_z = \begin{pmatrix}
1 & 0 & 0 \\
0 & 0 & 0 \\
0 & 0 & -1
\end{pmatrix},$$

and $\sigma_z$ is the Pauli-$z$ operator.

The Hamiltonian under measurement. A microwave driving is utilized to perform the measurement, as shown in Fig. 1(b). This microwave pulse drives the transition between $|0\rangle$ and $|-1\rangle$. The driving frequency is set to be resonant with the transition between $|0, \uparrow\rangle$ and $|-1, \uparrow\rangle$, and meanwhile largely detuned from that between $|0, \downarrow\rangle$ and $|-1, \downarrow\rangle$. In this way, the transition between $|0, \uparrow\rangle$ and $|-1, \uparrow\rangle$ can be induced selectively. Thus the system evolves under the whole Hamiltonian $H_M = H_F + H_I$, where the interaction Hamiltonian is

$$H_I = \Omega e^{-it[|0, \uparrow\rangle\langle -1, \uparrow|] + h.c.}$$

In order to analytically calculate the quantum dynamics under the influence of $H_M$, we transform to the rotating frame defined by the transformation $\Psi(t) = U^\dagger(t)\Psi(0)$, where $U(t) = \exp(-iH_FT)$, $\Psi(0)$ and $\Psi(t)$ are the wave functions in the static and rotating frames respectively. Therefore, using equation (23), the Hamiltonian under the rotating frame can be obtained, i.e.,

$$H_M^R = U^\dagger H_M U - H_F = \Omega|0, \uparrow\rangle\langle -1, \uparrow| + h.c.$$

Dynamic Evolution. Now, let us demonstrate the quantum dynamics of the whole system in a full cycle, which includes a free evolution followed by a measurement process. The electron spin is initially prepared in its ground state, i.e.,

$$\rho^{(D)}(0) = |0\rangle\langle 0|,$$

and the nuclear spin is in an arbitrary state

$$\rho^{(T)}(0) = \begin{pmatrix}
\alpha & \beta \\
\beta^* & 1 - \alpha
\end{pmatrix},$$

which is spanned by the basis $\{|\uparrow\rangle, |\downarrow\rangle\}$. Thus, the initial state of the total system is $\rho(0) = \rho^{(D)}(0) \otimes \rho^{(T)}(0)$.

In the free evolution, the total system evolves under its free Hamiltonian $H_F$ for a time interval $\Delta t_f$, which is described by the evolution operator

$$U_f(\Delta t_f) = e^{-iH_F\Delta t_f}.$$

Apparentely, without the driving, the evolution operator of the total system is diagonal. At the end of free evolution, the state of the total system becomes $\rho(\Delta t_f) = U_f(\Delta t_f)\rho(0) U_f^\dagger(\Delta t_f)$. Afterwards, a microwave pulse is used to drive the transition between $|0, \uparrow\rangle$ and $|-1, \uparrow\rangle$. The total system evolves under
the Hamiltonian $H^R_M$ for a time interval $\Delta t_m$. Having transformed to the rotating frame, a time-independent Hamiltonian is obtained and the corresponding evolution operator is

$$U^R_m(\Delta t_m) = e^{-iH^R_m\Delta t_m}. \quad (10)$$

After a cycle with duration $\tau = \Delta t_f + \Delta t_m$, the state of the whole system is

$$\rho^R(\tau) = U^R_m U_f \rho(0) U_f^\dagger U^R_m. \quad (11)$$

Utilizing equation (24), the final state of the whole system in the static frame reads

$$\rho(\tau) = U(\Delta t_m) U^R_m(\Delta t_m) U_f(\Delta t_f) \rho(0) U_f^\dagger (\Delta t_f) U^R_m(\Delta t_m) U_f^\dagger (\Delta t_f). \quad (12)$$

By partially tracing over the degree of the electron spin, the final state of the nuclear spin $\rho^{(T)}(\tau) = \text{Tr}_D[\rho(\tau)]$ reads

$$\rho^{(T)}(\tau) = \begin{pmatrix} \alpha & e^{-i\gamma B_z \tau} \cos(\Omega \Delta t_m) \beta^* \\ e^{i\gamma B_z \tau} \cos(\Omega \Delta t_m) \beta & 1 - \alpha \end{pmatrix}. \quad (13)$$

On the other hand, the initial state of the nuclear spin can be decomposed into its eigenbasis as

$$\rho^{(T)}(0) = C_0 I + C_1 \sigma_z + C_2 \sigma_x + C_3 \sigma_y, \quad (14)$$

where $C_0 = 1/2, C_1 = \beta, C_2 = \beta', C_3 = (2\alpha - 1)/2$, I is the identity operator, $\sigma_+ = \uparrow \downarrow \uparrow$ and $\sigma_- = \uparrow \downarrow \downarrow \uparrow \uparrow \downarrow \downarrow \uparrow$ are the raising and lowering operators respectively. After the first cycle, the nuclear spin is in the state

$$\rho^{(T)}(\tau) = C_0 \lambda_0 I + C_1 \lambda_1 \sigma_z + C_2 \lambda_2 \sigma_x + C_3 \lambda_3 \sigma_y, \quad (15)$$

where the eigenvalues are

$$\lambda_0 = \lambda_3 = 1, \quad \lambda_1 = \lambda_2^* = e^{-i\gamma B_z \tau} \cos(\Omega \Delta t_m). \quad (16)$$

After N cycles, the nuclear-spin qubit evolves into the state

$$\rho^{(T)}(N\tau) = C_0 \lambda_0^N I + C_1 \lambda_1^N \sigma_z + C_2 \lambda_2^N \sigma_x + C_3 \lambda_3^N \sigma_y. \quad (18)$$

Here, $\lambda_0 = \lambda_3 = 1$ are related to fixed points independent of all parameters. However, $\lambda_1$ and $\lambda_2$ are modulated by the parameters $(\Omega, B_z, \Delta t_{nr}, \Delta t_f)$. By adjusting these parameters, the quantum Zeno and Zeno-like effects can be observed.

Hereafter, by analyzing the dependence of the eigenvalues on the parameters, we demonstrate the existence of quantum Zeno and Zeno-like effects.

**Quantum Zeno-like effect.** In equation (15), the eigenvalues $\lambda_0 = \lambda_3 = 1$ mean that $\rho^{(T)}(0) = C_0 I + C_3 \sigma_y$ are the fixed points independent of the combination of parameters $(\Omega, B_z, \Delta t_{nr}, \Delta t_f)$ after repeated measurements. To be specific, if the initial state of the nuclear spin is of diagonal form, the state will not be changed and thus is preserved. This is a QZLE on the nuclear spin, similar to that in ref. 13.

On the other hand, the $\sigma_x$ and $\sigma_y$ components of the initial nuclear-spin state are exponentially suppressed, when $|\lambda_1| = |\lambda_2| < 1$ with appropriate parameters $(\Omega, B_z, \Delta t_{nr}, \Delta t_f)$. Therefore, the following process $\rho^{(T)}(0) = C_0 I + C_1 \sigma_z + C_2 \sigma_x + C_3 \sigma_y \rightarrow \rho^{(T)}(N\tau) = C_0 I + C_3 \sigma_y$ is achieved by sufficiently many measurements.

Furthermore, the existence of $\lambda_1 = 1$ preserves the polarization of the nuclear spin. If $\alpha = 1$ or $0$, $\rho^{(T)}(N\tau) = \rho^{(T)}(0) = \uparrow \downarrow \uparrow$ or $\rho^{(T)}(N\tau) = \rho^{(T)}(0) = \uparrow \downarrow \downarrow \uparrow$ can be obtained. Thus, the polarization of the $^{13}$C nuclear spin near the NV center is frozen. It may be a potential way to preserve the polarization of $^{13}$C nuclear spin against its hyperfine interaction with electron spin.

**Quantum Zeno effect.** For the eigenvalues $\lambda_1$ and $\lambda_2$, we consider both the ideal situation when $\Delta t_f$ and $\Delta t_{nr}$ and the realistic situation of finite $\Delta t_f$ and $\Delta t_{nr}$.

In the ideal situation, equation (17) is simplified as

$$\lambda_1 = \lambda_2^* \approx e^{-i\gamma B_z \tau} \left( 1 - \frac{\Omega^2}{2} \Delta t_m^2 \right). \quad (19)$$
From equation (18), we learn that the eigenvectors $\sigma_+$ and $\sigma_-$ contribute to the off-diagonal part of $\rho(T(N\tau))$. When $\Delta t_f$ and $\Delta t_m$ are small enough, the eigenvalues $|\lambda_1|$ and $|\lambda_2|$ can be very close to unity. Furthermore, $\gamma_n Bz N\tau = 2n\pi$ is assumed, where $N\tau = T$ is the fixed total evolution time and $n$ is an integer. Because the eigenvalues $|\lambda_1|$ and $|\lambda_2|$ approach unity quadratically in the high-measurement-frequency limit, an arbitrary nuclear-spin state is exactly preserved by infinitely-frequent measurements. Here, the conventional QZE is recovered.

On the other hand, consider the realistic condition in an NV center, e.g. non-vanishing $\Delta t_m$ due to a finite pulse width. When the Rabi frequency and the pulse width are chosen to meet the following requirement

$$\Omega \Delta t_m = 2n_1 \pi$$

with $n_1$ being positive integer, $\lambda_1 = \lambda_2 = 1$ can be obtained. In this case, arbitrary initial state is the Zeno-like fixed point which depends on the appropriate choice of parameters ($\Omega$, $B_z$, $\Delta t_m$, $\Delta t_f$). In other words, under certain measurement conditions, the QZLE is observed. Figure 2 shows the locations where QZLE will occur in the parameter space ($\Omega$, $\Delta t_m$). In the case of $|\lambda_1| = |\lambda_2| < 1$, after repeated measurements the elements of $\sigma_+$ and $\sigma_-$ in $\rho(T(T))$ may disappear due to accumulated loss. However, by tuning parameters to the vicinity of the points ($\Omega$, $\Delta t_m$) given in equation (20), equation (17) can be expanded to the second order of $\Delta t_m$ as

$$\lambda_1 = \lambda_2^* \approx 1 - \frac{1}{2}(\Omega \Delta t_m - 2n_1\pi)^2.$$  

Here, the conventional QZE happens in the neighbourhood of the QZLE points. In other words, the QZE occurs for a series of parameter combinations corresponding to finite-frequency measurements with finite coupling strengths. Since the eigenvalues $\lambda_1$ and $\lambda_2$ approach unity quadratically under the repeated measurements, arbitrary nuclear-spin state is exactly preserved by finitely-frequent measurements, even though it is affected by the free evolution.

**Discussion**

The conventional QZE and QZLE are demonstrated in a $^{13}$C nuclear spin around an NV center by controlling the electron spin. Both of the QZE and QZLE can be observed by modulating the Rabi frequency, and the magnetic field, and the free-evolution time, and the pulse width. Our numerical calculation properly shows that for suitable parameters there exist both the QZE and QZLE in an NV-center system under the experimental condition. Consequently, the conventional QZE and QZE are obtained with finite-frequency imperfect measurements.

In order to put our experimental proposal into practice, the secular approximation should be valid, i.e. the applied magnetic field strength should not be too strong$^{36}$. As a consequence, the magnetic field strength $B_z$ could be less than 200 G. Additionally, due to the resonance condition, the driving frequency $\omega$ equals to the level spacing between $|0, \uparrow\rangle$ and $|\downarrow, \downarrow\rangle$, i.e., $D - \gamma_z B_z - A_{zz}/2$. At the same time, the level spacing $\omega_z$ between $|0, \downarrow\rangle$ and $|\downarrow, \downarrow\rangle$ is $D - \gamma_z B_z + A_{zz}/2$. To selectively only induce the transition between $|0, \uparrow\rangle$ and $|\downarrow, \downarrow\rangle$, the large-detuning condition $\Delta \omega = \omega_1 - \omega = A_{zz} \gg \Omega$ should be fulfilled.
Since the hyperfine coupling between the electron spin and a $^{13}$C nuclear spin in the first coordination shell is known to be 130 MHz$^{51,59}$, the Rabi frequency $\Omega$ can be no more than 10 MHz. Furthermore, the initialization of the NV center will take approximately ~140 ns$^{42}$, and the intrinsic dephasing time of the $^{13}$C nuclear spin $T_{2n}$ was observed as around one second$^{44}$. To ignore the decoherence effect induced by the environment, we restrict the total experiment time as $T \ll T_{2n}$, i.e., the total experiment time $T$ is chosen as 100 ms. In this case, we can demonstrate the quantum Zeno and Zeno-like effects for roughly $2 \times 10^4$ cycles.

On the other hand, due to the presence of the nitrogen nucleus, $^{14}$N ($I = 1$) or $^{15}$N ($I = 1/2$), and the $^{13}$C nuclear spin bath, the dephasing time of the electron spin is 58 $\mu$s$^{59}$. The duration $\tau = \Delta t_f + \Delta t_m$ of a cycle is smaller than the dephasing time of the electron spin by one order. Because the hyperfine coupling between the electron spin and the nitrogen nuclei $A_N < 4$ MHz$^{50}$ is much smaller than $A_{zz}$, the dephasing effect induced by the nitrogen nucleus can be neglected. The dipole-dipole interactions between the electron spin and the other $^{13}$C nuclear spins are too weak. Therefore, the dephasing effect induced by all nuclear spins can also be neglected.

Last but not the least, the nuclear spin bath induces the dephasing of the $^{13}$C nuclear spin. Because the total experiment time is sufficiently short and the magnetic dipole-dipole interactions between the $^{13}$C nuclear spin and the other nuclear spins are weak enough$^{60}$, the dephasing effect induced by the spin bath can be neglected. Meanwhile, after every measurement, we decouple the electron and $^{13}$C nuclear spins and initialize the electron spin in its ground state$^{42,54}$ without perturbing the $^{13}$C nuclear spin. In this process, the nuclear spin is supposed to be completely isolated from the environment$^{42,54}$. Therefore, the nuclear spin hardly evolves during this process.

In conclusion, as shown in Fig. 2, our numerical calculation properly indicates that under practical conditions we can demonstrate the conventional QZE and QZLE in $^{13}$C nuclear spin around the NV center with finite-frequency imperfect measurements.

Methods

The rotating frame. Since the original Hamiltonian in the measurement process $H_M$ is time-dependent, the whole system is transformed to a rotating frame defined by the transformation $|\Psi(t)\rangle = U(t)|\Psi(0)\rangle$, where $U(t) = \exp(-iH_Mt)$ and $|\Psi(t)\rangle$ are respectively the wave functions in the static and rotating frames. Now, we derive the relationship between the Hamiltonian in the static frame $H_M$ and the Hamiltonian in the rotating frame $H^R_M$. Because the time evolution of $|\Psi(t)\rangle$ still fulfills the Schrodinger equation in the rotating frame, i.e.

$$i\frac{d}{dt}|\Psi(t)\rangle = \frac{d}{dt}U^\dagger \Psi(t)\rangle$$

$$= iU^\dagger \Psi(t)\rangle + U^\dagger i\Psi(t)\rangle$$

$$= iU^\dagger \Psi(t)\rangle + U^\dagger H_M U^\dagger \Psi(t)\rangle$$

$$= iU^\dagger \Psi(t)\rangle + U^\dagger H_M U^\dagger \Psi(t)\rangle$$

$$= iU^\dagger (U^\dagger H_M U^\dagger - \xi) \Psi(t)\rangle,$$

the effective Hamiltonian in the rotating frame reads

$$H^R_M = U^\dagger H_M U - \xi. \quad (23)$$

Correspondingly, the relationship between the density matrix in the static frame $\rho(t)$ and the density matrix in the rotating frame $\rho^R(t)$ is

$$\rho(t) = \langle\Psi(t)\rangle \langle\Psi(t)\rangle$$

$$= U(t)\rho(t) U^\dagger (t)$$

$$= U(t)\rho^R(t) U^\dagger (t). \quad (24)$$

References

1. Khalfin, L. A. Phenomenological theory of $K^0$ mesons and the non-exponential character of the decay. *JETP Lett.* **8**, 65–68 (1968).
2. Misra, B. & Sudarshan, E. C. G. The Zeno’s paradox in quantum theory. *J. Math. Phys.* **18**, 756 (1977).
3. Cook, R. J. What are quantum jumps. *Phys. Scr. T* **21**, 49–51 (1988).
4. Itano, W. M., Heinzen, D. J., Bollinger, J. J. & Wineland, D. J. Quantum Zeno effect. *Phys. Rev. A* **41**, 2295–2300 (1990).
5. Wang, X. B., You, J. Q. & Nori, F. Quantum entanglement via two-qubit quantum Zeno dynamics. *Phys. Rev. A* **77**, 062339 (2008).
6. Xu, D. Z., Ai, Q. & Sun, C. P. Dispersive-coupling-based quantum Zeno effect in a cavity-QED system. *Phys. Rev. A* **83**, 022107 (2011).
7. Berro, J. et al. Freezing coherent field growth in a cavity by the quantum Zeno effect. *Phys. Rev. Lett.* **101**, 180402 (2008).
8. Zhang, Y.-R. & Fan, H. Zeno dynamics in quantum open systems. *Sci. Rep.* **5**, 11509 (2015).
9. Kofman, A. G. & Kurizki, G. Acceleration of quantum decay processes by frequent observations. *Nature (London)* **405**, 546–550 (2000).
10. Facchi, P., Nakazato, H. & Pascazio, S. From the quantum Zeno to the inverse quantum Zeno effect. *Phys. Rev. Lett.* **86**, 2699–2703 (2001).
11. Ai, Q., Li, Y., Zheng, H. & Sun, C. P. Quantum anti-Zeno effect without rotating wave approximation. *Phys. Rev. A* **81**, 042116 (2010).
12. Ai, Q. et al. Quantum anti-Zeno effect without wave function reduction. *Sci. Rep.* **3**, 1752 (2013).
13. Layden, D., Martín-Martínez, E. & Kempf, A. Perfect Zeno-like effect through imperfect measurements at a finite frequency. *Phys. Rev. A* **91**, 022106 (2015).
14. Nakazato, H., Takazawa, T. & Yuasa, K. Purification through Zeno-like measurements. *Phys. Rev. Lett.* **90**, 060401 (2003).
15. Xue, Z.-Y. et al. Robust interface between flying and topological qubits. *Sci. Rep.* **5**, 12233 (2015).
16. Hua, M., Tao, M., I. & Deng, F. G. Fast universal quantum gates on microwave photons with all-resonance operations in circuit QED. *Sci. Rep.* **5**, 9274 (2015).
17. Liu, Y.-C. et al. Coupling of a single diamond nanocrystal to a whispering-gallery microcavity: Photon transport benefitting from Rayleigh scattering. *Phys. Rev. A* **84**, 011805 (2011).
18. Li, P.-B., Gao, S.-Y. & Li, F.-L. Quantum-information transfer with nitrogen-vacancy centers coupled to a whispering-gallery microresonator. *Phys. Rev. A* **83**, 054306 (2011).
19. Li, P.-B., Gao, S.-Y., Li, H.-R., Ma, S.-L. & Li, F.-L. Dissipative preparation of entangled states between two spatially separated nitrogen-vacancy centers. *Phys. Rev. A* **85**, 042306 (2012).
20. Yu, X.-C., Liu, Y.-C., Yan, M.-Y., Jin, W.-L. & Xiao, Y.-F. Coupling of diamond nanocrystals to a high-Q whispering-gallery microresonator. *Phys. Rev. A* **86**, 043833 (2012).
21. Liu, S., Li, J., Yu, R. & Wu, Y. Achieving maximum entanglement between two nitrogen-vacancy centers coupling to a whispering-gallery-mode microresonator. *Opt. Express* **21**, 3501 (2013).
22. Wang, P. F., Ju, C. Y., Shi, F. Z. & Du, J. F. Optimizing ultrasensitive single electron magnetometer based on nitrogen-vacancy center in diamond. *Chin. Sci. Bull.* **58**, 2920–2923 (2013).
23. Balzer, C., Huesmann, R., Neuhauser, W. & Toschek, P. E. The quantum Zeno effect-evolution of an atom impeded by measurement. *Opt. Comm.* **180**, 115–120 (2000).
24. Matsuzaki, Y., Saito, S., Kakuyanagi, K. & Semb, K. Quantum Zeno effect with a superconducting qubit. *Phys. Rev. B* **82**, 180518(R) (2010).
25. Zhang, T.-T. & Xue, Z.-Y. Demonstration of quantum zeno effect in a superconducting phase qubit. *JETP Letters* **93**, 349–353 (2011).
26. Xiao, L. & Jones, J. A. NMR analogues of the quantum Zeno effect. *Phys. Lett. A* **359**, 424–427 (2006).
27. Alvarez, G. A., Bhaktavatsala Rao, D. D., Frydman, L. & Kurizki, G. Zeno and anti-Zeno polarization control of spin ensembles by induced dephasing. *Phys. Rev. Lett.* **105**, 160401 (2010).
28. Streed, E. W. et al. Continuous and pulsed quantum Zeno effect. *Phys. Rev. Lett.* **97**, 260402 (2006).
29. Bar-Gill, N., Rowen, E. E., Kurizki, G. & Davidson, N. Short-time enhancement of the decay of coherent excitations in Bose-Einstein condensates. *Phys. Rev. Lett.* **102**, 110401 (2009).
30. Zhang, M. & You, L. Quantum Zeno subspace and entangled Bose-Einstein condensates. *Phys. Rev. Lett.* **91**, 230404 (2003).
31. Zhou, J. et al. High fidelity state transfer in electromechanical systems with intermediate coupling. *Sci. Rep.* **4**, 6237 (2014).
32. Yang, W. L., Yin, Z. Q., Xu, Z. Y., Feng, M. & Du, J. F. One-step implementation of multiqubit conditional phase gating with nitrogen-vacancy centers coupled to a high-Q silica microsphere cavity. *Appl. Phys. Lett.* **96**, 241113 (2010).
33. Wei, H. R. & Deng, F. G. Compact quantum gates on electron-spin qubits assisted by diamond nitrogen-vacancy centers inside cavities. *Phys. Rev. A* **88**, 042312 (2013).
34. Ren, B. C., Wang, G. Y. & Deng, F. G. Universal hyperparallel hybrid photonic quantum gates with dipole-induced transparency in the weak-coupling regime. *Phys. Rev. A* **91**, 032328 (2015).
35. Liu, Q. & Zhang, M. Generation and complete nondestructive analysis of hyperentanglement assisted by nitrogen-vacancy centers in resonators. *Phys. Rev. A* **91**, 062321 (2015).
36. Song, W. L. et al. One-step generation of multipartite entanglement among nitrogen-vacancy center ensembles. *Sci. Rep.* **5**, 7775 (2015).
37. Kost, M., Cai, J.-M. & Plenio, M. B. Resolving single molecule structures with nitrogen-vacancy centers in diamond. *Sci. Rep.* **5**, 11007 (2015).
38. Yin, Z. Q., Zhao, N. & Li, T. Hybrid opto-mechanical systems with nitrogen-vacancy centers. *Sci. China-Phys. Mech. Astron.* **58**, 050303 (2015).
39. Kennedy, T. A., Colton, J. S., Butler, J. E., Lineaes, R. C. & Doering, P. J. Long coherence times at 300 K for nitrogen-vacancy center spins in diamond grown by chemical vapor deposition. *Appl. Phys. Lett.* **83**, 4190–4192 (2003).
40. Bar-Gill, N., Pham, L. M., Jarmola, A., Budker, D. & Walsworth, R. L. Solid-state electronic spin coherence time approaching one second. *Nat. Commun.* **4**, 1743 (2013).
41. Maurer, P. et al. Room-temperature quantum bit memory exceeding one second. *Science* **336**, 1283–1286 (2012).
42. Dutt, M. V. G. et al. Quantum register based on individual electronic and nuclear spin qubits in diamond. *Science* **316**, 1312–1316 (2007).
43. Zu, C. et al. Experimental realization of universal geometric quantum gates with solid-state spins. *Nature (London)* **514**, 72–75 (2014).
44. Wolters, J., Straß, M., Schoenfeld, R. S. & Benson, O. Quantum Zeno phenomenon on a single solid-state spin. *Phys. Rev. A* **88**, 020101(R) (2013).
45. Brouwer, L. E. J. Über Abbildung von Mannigfaltigkeiten. *Math. Ann.* **71**, 97–115 (1911).
46. Maze, J. R. et al. Properties of nitrogen-vacancy centers in diamond: the group theoretic approach. *New J. Phys.* **13**, 025025 (2011).
47. Doherty, M. W., Manson, N. B., Delaney, P. & Hollenberg, L. C. L. The negatively charged nitrogen-vacancy centre in diamond: the electronic solution. *New J. Phys.* **13**, 025019 (2011).
48. Jacques, V. et al. Dynamic polarization of single nuclear spins by optical pumping of nitrogen-vacancy color centers in diamond at room temperature. *Phys. Rev. Lett.* **102**, 057403 (2009).
49. Smeltzer, B., McIntyre, J. & Childress, L. Robust control of individual nuclear spins in diamond. *Phys. Rev. A* **80**, 050302(R) (2009).
50. Felton, S. et al. Hyperfine interaction in the ground state of the negatively charged nitrogen vacancy center in diamond. *Phys. Rev. B* **79**, 075203 (2009).
51. Jelezko, F. et al. Observation of coherent oscillation of a single nuclear spin and realization of a two-qubit conditional quantum gate. *Phys. Rev. Lett.* **93**, 130501 (2004).
52. Tamarat, Ph. et al. Spin-flip and spin-conserving optical transitions of the nitrogen-vacancy centre in diamond. *New J. Phys.* **10**, 045004 (2008).
53. Manson, N. B., Harrison, J. P. & Sellars, M. J. Nitrogen-vacancy center in diamond: Model of the electronic structure and associated dynamics. *Phys. Rev. B* **74**, 104303 (2006).
54. Jiang, L. et al. Coherence of an optically illuminated single nuclear spin qubit. *Phys. Rev. Lett.* **100**, 073001 (2008).
55. van der Sar, T. et al. Decoherence-protected quantum gates for a hybrid solid-state spin register. *Nature (London)* **484**, 82–86 (2012).
56. Dréau, A., Spinicelli, P., Maze, J. R., Roch, J.-F. & Jacques, V. Single-shot readout of multiple nuclear spin qubits in diamond under ambient conditions. *Phys. Rev. Lett.* **110**, 060502 (2013).
57. Childress, L. et al. Coherent dynamics of coupled electron and nuclear spin qubits in diamond. *Science* **314**, 281–285 (2006).
58. Neumann, P. et al. Multiparticle entanglement among single spins in diamond. *Science* **320**, 1326–1329 (2008).
59. MZ, Z. 13C hyperfine interactions in the nitrogen-vacancy centre in diamond. *New J. Phys.* **13**, 025021 (2011).
60. Bermudez, A., Jelezko, F., Plenio, M. B. & Retzker, A. Electron-mediated nuclear-spin interactions between distant nitrogen-vacancy centers. *Phys. Rev. Lett.* **107**, 150503 (2011).

**Acknowledgements**

We thank C. Zu for helpful discussions. FGD was supported by the National Natural Science Foundation of China under Grant No. 11474026 and the Fundamental Research Funds for the Central Universities under Grant No. 2015KJJCA01. QA was supported by the National Natural Science Foundation of China under Grant No. 11505007, the Youth Scholars Program of Beijing Normal University under Grant No. 2014NT28, and the Open Research Fund Program of the State Key Laboratory of Low-Dimensional Quantum Physics, Tsinghua University Grant No. KF201502. MZ was supported by the National Natural Science Foundation of China under Grant No. 11475021. QZY is funded by the National Key Basic Research Program of China under Grant No. 2011CB00300 and the National Natural Science Foundation of China under Grant Nos. 11105136 and 61435007.

**Author Contributions**

Q.A., Z.Q.Y., F.G.D., M.Z., J.Q. and Y.Y.W. wrote the main manuscript text, J.Q. and Y.Y.W. did the calculations. Q.A., F.G.D., M.Z. and Z.Q.Y. designed the project. Q.A. supervised the whole project. All authors reviewed the manuscript.

**Additional Information**

**Competing financial interests:** The authors declare no competing financial interests.

**How to cite this article:** Qiu, J. et al. Quantum Zeno and Zeno-like effects in nitrogen vacancy centers. *Sci. Rep.* **5**, 17615; doi: 10.1038/srep17615 (2015).

This work is licensed under a Creative Commons Attribution 4.0 International License. The images or other third party material in this article are included in the article’s Creative Commons license, unless indicated otherwise in the credit line; if the material is not included under the Creative Commons license, users will need to obtain permission from the license holder to reproduce the material. To view a copy of this license, visit http://creativecommons.org/licenses/by/4.0/