Quantum Zeno effect in an unstable system with NMR

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We theoretically propose a scheme for verification of quantum Zeno effect (QZE) to suppress a decay process with Nuclear Magnetic Resonance (NMR). Nuclear spins are affected by low frequency noise, and so one can naturally observe non-exponential decay behavior, which is prerequisite in observing QZE. We also describe that a key component for QZE, namely measurements on the nuclear spin, can be realized with NMR in the current technology by using non-selective architecture of a measurement process.

Quantum Zeno effect (QZE) is one of the interesting phenomena of quantum mechanics. By performing frequent measurements to confirm whether it decays or not, one can slow or even freeze the decay dynamics of unstable system. This counterintuitive phenomena has received many attention since mathematical foundation of QZE was established by Misra and Sudarshan \([1]\). Besides such academic interest, QZE has many potential applications for quantum information processing if realized. QZE is expected to control several decoherence \([2]\). Furthermore, there are theoretical proposals to prepare pure states \([3]\) and generate an entanglement \([4,5]\) via QZE. Also, it would be possible to increase a success probability for logic gates by using QZE \([6,8]\). It is worth mentioning that, although pulse techniques such as a spin echo approach \([7]\) are commonly used to suppress decoherence, they are different from QZE. Such pulse techniques rely on implementing unitary evolutions while QZE uses non-unitary evolution, namely projective measurements. Therefore, verification of QZE still has a fundamental importance to understand the quantum mechanics and to realize quantum information processing.

In order to observe quantum Zeno effect, it is essential to perform such measurements when the unstable system shows a non-exponential decay such as a quadratic decay \([9]\). Projective measurements can easily affect the dynamics of an unstable system with non-exponential decay, while quantum Zeno effect does not occur for an exponential decay system via projective measurements \([9]\). Although such a quadratic decay is a consequence of general features of the Schrodinger equation, it is difficult to observe such a decay in the experiment. The time region to show the quadratic decay is usually much shorter than the typical time resolution of an experimental apparatus, and after showing a quadratic decay, the unstable system typically shows an exponential decay \([9]\).

Due to the difficulty of observing non-exponential decay, there was only one experimental demonstration of QZE for an unstable system \([10]\) where the number of trapped cold sodium atoms are frequently measured to suppress an escaping rate of the atoms from the trap. It is worth mentioning that, other than this experiment, not decay process but unitary evolution is suppressed in previous demonstration of QZE \([11-14]\). Although it is experimentally easier to change the behavior of unitary evolution by measurements, such approach is different from the original proposals to suppress irreversible decay process \([11,15,16]\). Moreover, QZE in a two-level system to suppress decoherence has not been experimentally demonstrated yet. For the realization of quantum information processing, the use of well-defined two-level systems, namely qubits, is essential. So the demonstration of QZE for decoherence by using such two-level systems would be crucial for the application of QZE to the quantum information processing \([2,4,6,8]\).

Recently, it has been shown that a system affected by low frequency noise is suitable to observe QZE for an unstable system \([17]\). Due to a long correlation time of low frequency noise, the decay process naturally shows non-exponential behavior. The quadratic decay has been observed experimentally \([18,19]\) in a superconducting qubit affected by $1/f$ noise.

As suggested in \([17]\), a superconducting qubit affected by $1/f$ noise is one of candidates to observe QZE for an unstable system. However, the challenge is that a coherence time of the superconducting qubit is relatively short such as a few micro seconds even at the optimal points \([18,19]\). Also, due to the short coherence time, a high fidelity single qubit rotation is difficult to be achieved in the current technology. These imperfections result in a significant degradation of a signal of QZE \([17]\). Therefore, it is preferable to use a system with a longer coherence time and a better controllability.

In this paper, to verify QZE of decay process, we suggest a way to use Nuclear Magnetic Resonance (NMR). Nuclear spins have a long coherence time such as a few milli seconds or more and so they are one of the candidates to provide qubits for quantum information processing. Also, an excellent control of nuclear spins can be achieved by using a sequence of radio frequency pulses where the fidelity of the rotation can be more than 99% in the current technology \([20]\). These properties make NMR a strong candidate to demonstrate quantum information processing in a small number of qubits \([21]\). Moreover, NMR is affected by a low frequency noise and therefore naturally shows a non-exponential decay behavior, which is prerequisite in observing QZE.

To verify QZE with NMR, one of the key components is a realization of projective measurements on a single qubit. In spite of many effort, a projective measurement on a single nuclear spin with NMR has not been constructed yet. Recently, a scheme called spin amplification has been suggested where the amplitude of a single spin is magnified by using an ensemble of other spins \([22,24]\), and a gain of 140 in a nuclear system have been experimentally demonstrated \([23]\). However, the minimum number of nuclear spins for detection is the...
order of $10^6$ and so a projective measurement of a single nuclear spin is not feasible in the current technology. In stead of projective measurements, we here suggest to use non-selective measurements with NMR for the verification of QZE, as is utilized to stop Rabi oscillations in NMR in a previous research [13]. If a pure state is coupled with the other classical system, non-diagonal terms of the density matrix disappear due to a decoherence, and this process can be interpreted as a measurement process without postselection [25, 27]. This kind of non-selective architecture of measurement process makes our proposal feasible even in the current technology.

We summarize the QZE. A fidelity $F = \langle \psi_{\text{fin}} | \rho | \psi_{\text{ini}} \rangle$ is utilized to measure the distance between the decohered state $\rho$ and an initial pure state $|\psi_{\text{ini}}\rangle$, and we suppress the degradation of the fidelity via frequent measurements. We perform projective measurements $|\psi_{\text{ini}}\rangle\langle\psi_{\text{ini}}|$ on the unstable system with an interval of $\tau = \frac{2}{q}$ where $t$ and $N$ denote a total time and the number of measurements, respectively. If the fidelity shows a non-exponential decay without measurements such as $F \approx 1 - \lambda t^n$ ($1 < n \leq 2$), one can project the state into $|\psi_{\text{ini}}\rangle$ with a probability $P(N) \approx (1 - \lambda^n t^n)^N \approx 1 - \frac{\lambda^n t^n}{N}$ by performing $N$ measurements. As a result, by increasing the number of the measurements, one can project the state into $|\psi_{\text{ini}}\rangle$ with almost unity success probability, which is called QZE. On the other hand, if the dynamics shows an exponential decay, we have $F \approx 1 - \lambda t$ for the initial stage of the decay. So we obtain $P(N) \approx (1 - \lambda \tau)^N \approx 1 - \lambda \tau$. Since this success probability has no dependency of the number of measurements, one cannot increase the success probability and therefore cannot observe QZE for an exponential decay system.

Let us study a general decoherence dynamics of quantum system. Although a decay behavior of unstable system has been studied [28], we introduce a simpler solvable model to consider the effect of dephasing induced by classical noise. Typically, the relaxation time is much longer than the dephasing time for the osytem. For example, a typical dephasing time in NMR is an order of milli seconds while a phasing time in NMR is an order of milli seconds. For example, a typical dephasing time in NMR is an order of milli seconds while a phasing time in NMR is an order of milli seconds. For example, a typical dephasing time in NMR is an order of milli seconds while a phasing time in NMR is an order of milli seconds. For example, a typical dephasing time in NMR is an order of milli seconds while a phasing time in NMR is an order of milli seconds. For example, a typical dephasing time in NMR is an order of milli seconds while a phasing time in NMR is an order of milli seconds. For example, a typical dephasing time in NMR is an order of milli seconds while a phasing time in NMR is an order of milli seconds. For example, a typical dephasing time in NMR is an order of milli seconds while a phasing time in NMR is an order of milli seconds. For example, a typical dephasing time in NMR is an order of milli seconds while a phasing time in NMR is an order of milli seconds. For example, a typical dephasing time in NMR is an order of milli seconds while a phasing time in NMR is an order of milli seconds. For example, a typical dephasing time in NMR is an order of milli seconds while a phasing time in NMR is an order of milli seconds. For example, a typical dephasing time in NMR is an order of milli seconds while a phasing time in NMR is an order of milli seconds. For example, a typical dephasing time in NMR is an order of milli seconds while a phasing time in NMR is an order of milli seconds. For example, a typical dephasing time in NMR is an order of milli seconds while a phasing time in NMR is an order of milli seconds. For example, a typical dephasing time in NMR is an order of milli seconds while a phasing time in NMR is an order of milli seconds. For example, a typical dephasing time in NMR is an order of milli seconds while a phasing time in NMR is an order of milli seconds. For example, a typical dephasing time in NMR is an order of milli seconds while a phasing time in NMR is an order of milli seconds. For example, a typical dephasing time in NMR is an order of milli seconds while a phasing time in NMR is an order of milli seconds. For example, a typical dephasing time in NMR is an order of milli seconds while a phasing time in NMR is an order of milli seconds.

\[
\eta(t) = \frac{\sum_{n=1}^{\infty} (-i)^n \int_0^t \int_0^{t_1} \cdots \int_0^{t_{n-1}} dt_1 dt_2 \cdots dt_n}{\int_0^t \int_0^{t_1} \cdots \int_0^{t_{n-1}} dt_1 dt_2 \cdots dt_n}
\]

where $\rho_0 = |\psi_{\text{ini}}\rangle\langle\psi_{\text{ini}}|$ denotes a pure initial state. Since the classical noise $\eta(t)$ is Gaussian, one can decompose $\eta(t_1)\eta(t_2)\cdots\eta(t_n)$ into a product of two point correlation functions [29], and so we obtain

\[
\rho(t) = \sum_{s, s' = \pm 1} e^{-\frac{1}{2} \Gamma_{s, s'}^2 t^2} |s\rangle\langle s| |s'\rangle\langle s'|
\]

\[
\Gamma(t) = \frac{1}{2t} \int_0^t \int_0^{t_1} \int_0^{t_2} \eta(t_1)\eta(t_2) dt_1 dt_2
\]

where $\Gamma(t)$ denotes a time dependent decoherence rate. So, for an initial state $|+\rangle = \frac{1}{\sqrt{2}} |1\rangle + \frac{1}{\sqrt{2}} |-\rangle$, the density matrix and the fidelity for this free induction decay (FID) are calculated as $\rho_{\text{FID}}(t) = e^{-\Gamma(t) t} |+\rangle\langle+| + e^{-\Gamma(t) t} |-\rangle\langle-|$ and $F_{\text{FID}}(t) = \frac{1}{2} (1 + e^{-\Gamma(t) t})$, respectively. Note that, if this decoherence rate is constant for time, the dynamics here shows an exponential decay, and therefore a time dependency is necessary in this decoherence rate to observe QZE.

Typically, nuclear spins are affected by $1/f^\alpha$ noise where $0 < \alpha < 2$, and one of the ways to treat $1/f^\alpha$ noise is to sum up power spectrum density of several Lorentz distributions [30, 33]. The spectrum density of a Lorentz distribution is characterized as $S_\xi(f) = \sum_{k=1}^{\infty} \xi_k(t)\xi(k) e^{-2\pi f f dt}$

\[
\eta(t_1)\eta(t_2) = \sum_{k=1}^{M} \frac{2\gamma k t - 1 + e^{-2\gamma k t}}{4(\gamma k)^2} (\frac{M}{\sum_{k=1}^{M} (\gamma k)^2})
\]

where $\gamma_k = \gamma_1 + (k - 1) \delta$, and the power spectral can be approximated to $1/f^\alpha$ noise for $\gamma_1 < \pi f < \gamma M$ [30, 33].

Since we obtain a general form of decoherence rate under the effect of classical noise, we can analyze the decoherence dynamics with NMR by substituting the noise spectrum into (1) and (2). By using the power spectrum density explained above, we obtain an analytical solution for the time dependent decoherence rate for $1/f^\alpha$ noise as follows.

\[
\Gamma(t) = \Delta^2 \sum_{k=1}^{M} \frac{1}{(\gamma k)^2} \frac{2\gamma k t - 1 + e^{-2\gamma k t}}{4(\gamma k)^2} (\frac{M}{\sum_{k=1}^{M} (\gamma k)^2})
\]

Recently, it has been found that the power spectrum density in NMR is $1/f^{1.5}$ for $1 \text{Hz} < \pi f < 1000 \text{Hz}$, and therefore we use the sum of Lorentz distributions to model this noise [34]. In FIG 1, we plot the power spectrum density of a sum of one thousand Lorentz distributions and compare this with the power spectrum density of $1/f^{1.5}$, which shows that this approximation is quite accurate in this frequency range. Also, we have plotted the decoherence rate in FIG 2. The plot shows a clear time dependency of the decoherence rate, and so the decay dynamics here is non-exponential, which is prerequisite in observing QZE as explained before.

We explain how to observe QZE with NMR. Firstly, one prepares an equally superposition of $|1\rangle$ and $|-1\rangle$, namely
Lorentz distributions can approximately describe \( \frac{1}{f^{1.5}} \) noise for a measurement about \( \hat{e}_z \) on a single nuclear spin. However, in this simple scheme, there are two difficulties to be overcome. The first difficulty is that, in spite of many effort, a projective measurement on a single nuclear spin with NMR has not been realized yet. The second difficulty is that it is usually much harder to perform a measurement about \( \hat{e}_z \) than a measurement about \( \hat{e}_x \). We will discuss how to relax these required conditions.

Fortunately, to observe QZE, it is possible for us to replace the projective measurement with a non-selective measurement which is less demanding technology. A non-selective measurement denotes a process of a measurement without postselection, and this occurs when a principal system interacts with other classical systems such as environment but the observer does not obtain information about the system \([25, 27]\). When one performs a measurement about \( \hat{e}_x \) on a state \( \alpha |1\rangle + \beta |1\rangle \) and postselects the measurement result, the system is projected into one of the pure states \( | - 1 \rangle \) or \( |1\rangle \). However, in the non-selective measurements, one discards (or loses) information of the measurement result so that the state should be a classical mixture of possible states obtained by the measurements as \( \rho = |\alpha|^2 |1\rangle \langle 1| + |\beta|^2 | - 1\rangle \langle - 1| \), which is called von Neumann mixture \([25, 26]\). Since it is not necessary to know the measurement result but necessary just to interact the principal system with the measurement apparatus, this non-selective measurement is much easier to be realized than a projective measurement.

A pulsed magnetic field gradient is one of the ways to perform non-selective measurements \([13]\). Depending on the position of the spins, different phases are embedded which causes a suppression of the Rabi oscillations \([13]\) in NMR, and it should be possible to use such magnetic field gradients to suppress decoherence in our scheme. Performing a spin amplification technique \([22, 24]\) is also a way for non-selective measurements. A pure state of the nuclear spin \( \alpha |1\rangle + \beta | - 1\rangle \) interacts with the other ancillary nuclear spins and evolves into an entangled state as \( \alpha |1\rangle |1\cdots1\rangle_{\text{ancilla}} + \beta | - 1\rangle |1\cdots1\rangle_{\text{ancilla}} \) which generates a signal much larger than a single nuclear spin. Although experimentally demonstrated gain of the signal with NMR via the amplification is still \( 140 \) \([23]\) which is much smaller than the minimum number of nuclear spins for detection, this amplification is enough to realize the non-selective measurement. Since the entangled state is much more fragile than the state of the single spin \([35]\), the entangled state quickly decoheres into a mixed state and one obtains the target mixed state as \( \rho = |\alpha|^2 |1\rangle \langle 1| + |\beta|^2 | - 1\rangle \langle - 1| \). This means that the environment effectively observes the nuclear spin and therefore the non-selective measurement is induced.

Another way to perform a non-selective measurement is to adopt a composed system of a nuclear spin and an electron spin as suggested in \([13]\), which can be entangled in the current technology \([36]\). By performing a controlled-not gate on electron nuclear double resonance (ENDOR), an initial state \( \alpha |1\rangle_n + \beta | - 1\rangle_n \) evolves into a Bell state \( \alpha |1\rangle_e |1\rangle_n + \beta | - 1\rangle_e | - 1\rangle_n \) where \( |a\rangle \langle i| \) denotes the state of the nuclear (electron), so that the information of the nuclear is effectively transferred to the electron. Since highly sensitive and local magnetic field sensors have already been realized and these have potential to perform a projective measurement on a single electron spin \([37, 39]\), it might be possible in the future to perform a projective measurement on the nuclear spin via the entanglement with the electron spin. Besides, once one generates such an entanglement, the nuclear spin is observed.
by the environment via the dephasing of the electron spin. The non-diagonal terms disappares and the state becomes \( \rho = |\alpha|^2 |1\rangle_n (1/2 \alpha^2 - 1/2 \beta^2 |1\rangle_n - 1/2 \alpha | -1\rangle_n - 1/2 \beta | -1\rangle_n | -1\rangle_e | -1\rangle_e \). In order to separate the electron spin from the nuclear spin, one can perform another controlled-not gate, and therefore one obtains the target nuclear spin state \( \rho = |\alpha|^2 |1\rangle_n + |\beta|^2 - 1/2 \alpha | -1\rangle_n - 1/2 \beta | -1\rangle_n | -1\rangle_e | -1\rangle_e \) as described in Fig. 3. This is another feasible implementation of the non-selective measurement on the nuclear spin.

Although the implementation of the non-selective measurement mentioned above is for \( \sigma_z \), one can easily construct a non-selective measurement about \( \sigma_x \) via a sequence of RF pulses. Firstly, one performs a \( \frac{\pi}{2} \) rotation \( U_y \) around y axis. Secondly, the non-selective measurement about \( \sigma_x \) is performed. Finally, one performs a rotation \( U_y^\dagger \) around y axis. Note that such a single qubit rotation can be performed in tens of micro seconds, much shorter than the life time of the nuclear spins, and therefore the effect of decay during these process is negligible. As a result, the combination of the three operations results in \( \hat{E}_{\text{NSM}}(\rho) = U_y^\dagger |1\rangle_n \langle 1| U_y \rho U_y^\dagger |1\rangle_n \langle 1| U_y + U_y^\dagger | -1\rangle_n \langle -1| U_y \rho U_y^\dagger | -1\rangle_n \langle -1| U_y - |+\rangle_1 (|+\rangle_1 |+\rangle_1 + | -\rangle_1 (-| -\rangle_1 ) | -\rangle_1, which is equivalent to the non-selective measurement of \( \sigma_x \) (FIG. 4). Here, \( \hat{E}_{\text{NSM}} \) denotes a superoperator for a density matrix represented by an operator sum form [40].

We estimate how much QZE can suppress the dephasing with NMR compared with the case of the FID. We can obtain an analytical form of a density matrix when we perform \( N \) times of non-selective measurements for a total time \( T \) under

FIG. 3: A pulse sequence to construct a non-selective measurement on the nuclear spin via a coupling with an electron spin. The nuclear spin state initially has a superposition between an excited state and a ground state, and this state acquires small unknown phase \( \theta \) due to low frequency noise. A controlled-not gate is performed so that the nuclear spin is entangled with an electron spin, and the composed state decoheres as quickly as the electron spin state. In order to separate the electron spin from the nuclear spins, another controlled-not gate should be performed. These processes eliminate the non-diagonal term of the density matrix of the nuclear spin, and therefore can be considered as the non-selective measurement to z axis for the nuclear spins. If one needs to construct a non-selective measurement to x axis, \( \pm \frac{\pi}{2} \) pulses on the nuclear should be performed before and after the procedure for the z direction measurement.

FIG. 4: A schematic of a quantum state in a Bloch sphere to verify QZE for a decay process. An initial state \(|+\rangle\) is freezeed by frequent measurements for \( \sigma_z \). In order to construct a measurement about \( \sigma_z \), \( \pm \frac{\pi}{2} \) pulses are performed before and after a measurement about \( \sigma_z \), which are the same as illustrated in Fig. 3. Note that a measurement here refers to an interaction with another classical system to remove the non-diagonal term of the quantum state, which we call a non-selective measurement.

FIG. 5: Fidelity of quantum states with NMR is against the total time under

where the unit of time is a second. The first plot from the left denotes a fidelity without measurement. The other five plots are fidelities when one performs \( N = 1, 2, 3, 4, 5 \) measurements in a total time \( T \), respectively. The figure clearly shows that the decay is suppressed via frequent measurements. The noise parameter is the same as in FIG 2.
Moreover, a key component for QZE, namely a measurement on the nuclear spin, can be constructed with existing technology of NMR by using non-selective architecture. Our proposal is feasible in the current technology.

[FIG 6: Difference between a fidelity with measurements and a fidelity without measurement plotted against the total time where the unit of time is a second. The lowest plot denotes a subtraction of a fidelity without measurement from a fidelity with a single measurement during the total time \( T \). The other four plots are subtractions of a fidelity without measurement from fidelities when one performs \( N = 2, 3, 4, 5 \) measurement during the total time \( T \), respectively. The parameter of the noise is the same as in FIG 2.]

the effect of low frequency noise described by (5) as follows.

\[
\rho_N = \frac{\hat{\rho}^{N \times N} \cdots \hat{\rho}^{N \times N} \hat{\rho}^{N \times N} \hat{\rho}^{N \times N} |+\rangle \langle +|}{2} + \frac{1 - e^{-\Gamma(N \times N) \cdot \tau}}{2} |+\rangle \langle +| + \frac{1 - e^{-\Gamma(N \times N) \cdot \tau}}{2} |-\rangle \langle -|
\]

Here, \( \hat{\rho}^{N \times N} \) denotes a superoperator to induce the dephasing of \( 1/f^{1.5} \) for a period \( \frac{\tau}{N+1} \) and \( \Gamma(t) \) denotes a time dependent decoherence rate defined in (2). So the fidelity is calculated as \( F_{\text{QZE}}(T, N) = \langle +| \rho_N |+ \rangle = \frac{1 + e^{-\Gamma(N \times N) \cdot \tau}}{2} \). We plot the fidelity in FIG 5 and this clearly shows the suppression of the dephasing via frequent measurements. Also, in FIG 6 we compare this fidelity with the fidelity \( F_{\text{FID}}(T) \) for the FID. This shows that even performing a single measurement increases the fidelity up to 11% and performing 5 measurements can increase the fidelity up to 25%, compared with the fidelity for the free induction decay. These result show the feasibility of our proposal even in the current technology.

In conclusion, we suggest a scheme to verify QZE of a decay process with NMR. We show that the decay behavior of quantum states with NMR is non-exponential, and therefore the decoherence dynamics with NMR is easily affected by measurements. Moreover, a key component for QZE, namely

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