Tunneling Measurement of a Single Quantum Spin

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Measurement of the tunneling current of spin-polarized electrons via a molecule with a localized spin provides information on the orientation of that spin. We show that a strong tunneling current due to the shot noise suppresses the spin dynamics, such as the spin precession in an external magnetic field, and the relaxation due to the environment (quantum Zeno effect). A weak tunneling current preserves the spin precession with the oscillatory component of the current of the same order as the noise. We propose an experiment to observe the Zeno effect in a tunneling system and describe how the tunneling current may be used to read a qubit represented by a single spin $1/2$.

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As the size of physical devices became smaller the quantum limit is reached. Then the laws of quantum mechanics absolutely manifest and the concept of *quantum measurement* [1–3] gets a practical meaning. Since quantum measurement is a dynamical process involving the apparatus, environment, and physical object being measured, one needs to carefully devise an experimental setup which extracts the relevant information of the quantum system with a large signal-to-noise ratio. This is not an easy task for a microscopic object because it is very strongly perturbed by the measurement. Typically, when the real object is a large number of quantum subsystems, we assume the notion of ensemble measurement and need not be concerned by such problems because disturbing some of the subsystems by measurement is not crucial. Meanwhile, measurement of a single spin turns out to be of relevance for quantum information processing since, for example, practical algorithms store the result of a long computation in a single *qubit* which may be represented by a single spin $1/2$.

An *indirect* measurement appears to be the natural candidate for the purposes of measuring a single spin. In this case, one does not measure the object but detects directly with a classical apparatus a property (observable) of a quantum probe that previously interacted with the object of interest. Since the interaction established a correlation between object and probe, the measurement contains information on the state of the object prior to the interaction. Moreover, a *consecutive* monitoring of the quantum probe's property should, in principle, give information on the time evolution, decoherence, and dissipation with the environment.

It was indicated that in the case of a strong coupling between a probe and a quantum object consecutive monitoring of the dynamics of the object is impossible because the measurement inhibits the change of its quantum state (quantum Zeno effect) [1–3]. This phenomenon was observed in optical experiments by Itano *et al.* [4]. Peres [2] also argued that in the opposite regime of very weak coupling the dynamics is affected insignificantly but measurements give inaccurate information on the dynamics of the quantum object.

In this Letter, we discuss probing of a single spin by a tunneling current (TC) as a particular example of indirect-consecutive measurement. We consider an experimental setup, where the quantum probe is represented by the electrons whose TC is consecutively monitored by an ampmeter. Tunneling devices for such measurements of a single spin are currently being developed [5]. In these setups a scanning tunneling microscope has been used, although one could use other measurement configurations such as a quantum dot between leads [6,7]. In this paper we describe such a general experimental setup and answer the fundamental questions: How do the spin dynamics and relaxation manifest in the TC; how does the TC affect the spin dynamics; and can measurement of a TC read a qubit?

We consider tunneling of electrons between similar electrodes A and B via a molecule with a spin $1/2$ placed between the electrodes. We assume that the electrons are fully polarized (with spin-up along the positive z axis) in the electrodes [8]. The voltage V applied to the electrodes induces a current between A and B. The energy level E_0 occupied by a single electron inside the molecule C is

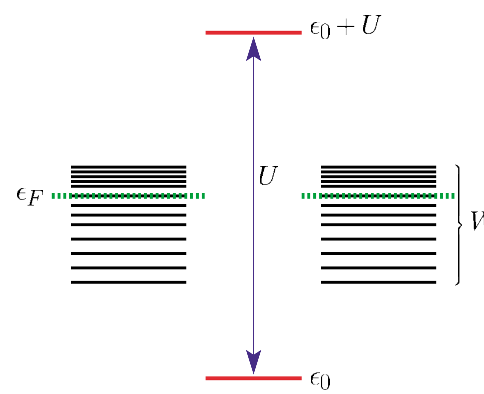

FIG. 1 (color online). Electron energy levels in electrodes and in the molecule.

well below the Fermi energy ϵ_F of the electrons inside the electrodes. When a second electron is placed in the level E_0, the energy increases by an amount U due to the Coulomb repulsion. The energy levels of the system are shown in Fig. 1. The tunneling matrix element between the electrode A (B) and the level E_0 with a single spin in the ground state we denote by t_{ac} (t_{bc}). We account only for virtual transitions of electrons via the molecule, i.e., for cotunneling current [6]. We express by t_{ab} the direct tunneling matrix element between electrodes and cotunneling contributions via the empty molecular levels. We assume also that a magnetic field $\mathbf{H}$ acts on the molecular spin. The Hamiltonian of the system is

$$\begin{aligned}
\mathcal{H} &= \mathcal{H}_a + \mathcal{H}_b + \mathcal{H}_T + \mathcal{H}_c, \\
\mathcal{H}_a &= \sum_n (\epsilon_n + eV) a^\dagger_{n\uparrow} a_{n\uparrow}, \\
\mathcal{H}_b &= \sum_m \epsilon_m b^\dagger_{m\uparrow} b_{m\uparrow}, \\
\mathcal{H}_T &= \sum_{nm} a^\dagger_{n\uparrow} t^{nm}_{ab} b_{m\uparrow} + a^\dagger_{n\uparrow} t^n_{ac} c_\uparrow + b^\dagger_{m\uparrow} t^m_{bc} c_\uparrow + \text{H.c.}, \\
\mathcal{H}_c &= E_0 \sum_{\sigma=\uparrow,\downarrow} c^\dagger_\sigma c_\sigma + U c^\dagger_\uparrow c_\uparrow c^\dagger_\downarrow c_\downarrow - \mu \mathbf{H}\cdot\mathbf{S},
\end{aligned} \tag{1}$$

where $a^\dagger_{n\sigma}$ and $b^\dagger_{m\sigma}$ are the creation operators of electrons in the electrodes A and B in the states characterized by the indexes n and m, respectively; ϵ_n are the energies of the electrons in the electrodes with bandwidth W. Further, $c^\dagger_\sigma$ is the creation operator of an electron at the level E_0 with spin σ in the molecule. We assume $\epsilon_F - W/2 > E_0$ and consider weak tunneling, $t_{ac}, t_{bc}, t_{ab} \ll (\epsilon_F - E_0), U$. In the molecular Hamiltonian $\mathcal{H}_c$, μ is the magnetic moment of the electron in the level E_0, and we introduce the spin operators $\mathbf{S} = (S_x, S_y, S_z)$ acting in the subspace of the wave functions with a single electron in the level E_0: $S_x = (c^\dagger_\uparrow c_\downarrow + c^\dagger_\downarrow c_\uparrow)/2$, $S_y = (c^\dagger_\uparrow c_\downarrow - c^\dagger_\downarrow c_\uparrow)/2i$, $S_z = (c^\dagger_\uparrow c_\uparrow - c^\dagger_\downarrow c_\downarrow)/2$.

Projecting the Hamiltonian onto the subspace of wave functions with a single electron in the level E_0, we write down the effective tunneling Hamiltonian between electrodes as

$$\begin{aligned}
\mathcal{H}_T &= \sum_{nm} a^\dagger_{n\uparrow}[t^{nm}_{ab} + T^s_{nm}(S_z)] b_{m\uparrow} + \text{H.c.}, \\
T^s_{nm}(S_z) &= t^n_{ac}(t^m_{bc})^* \left(\frac{1/2 - S_z}{U + \epsilon_n - E_0} - \frac{1/2 + S_z}{\epsilon_m - E_0} \right).
\end{aligned} \tag{2}$$

The term T^s_{nm} describes the spin-assisted cotunneling by virtual transitions. The first term in T^s_{nm} corresponds to the intermediate state when two electrons are positioned at the level E_0, while the second term corresponds to an empty level E_0 in the intermediate state. Both $U + \epsilon_n - E_0$ and $\epsilon_m - E_0$ are positive. Assuming that all matrix elements between states n and m are identical, we write the tunneling Hamiltonian as

$$\mathcal{H}_T = \sum_{nm} a^\dagger_{n\uparrow}(T_0 - T_s S_z) b_{m\uparrow} + \text{H.c.} \tag{3}$$

The TC operator between electrodes, $\hat{I}(t)$, at time t is given by the expression $\hat{I}(t) = e\dot{\mathcal{N}}_a = -ie[\mathcal{N}_a, \mathcal{H}_T]$, with $\mathcal{N}_a = \sum_n a^\dagger_{n\uparrow} a_{n\uparrow}$ and $[\hat{A}, \hat{B}] = \hat{A}\hat{B} - \hat{B}\hat{A}$. We obtain

$$\hat{I}(t) = -ie \sum_{nm} \{a^\dagger_{n\uparrow}(t)[T_0 - T_s S_z(t)] b_{m\uparrow}(t) - \text{H.c.}\}, \tag{4}$$

where the time dependence of an arbitrary observable $\hat{A}$ in the interaction representation with respect to $\mathcal{H}_T$ is determined by $\langle \hat{A}(t) \rangle = -i \int_{-\infty}^t dt' \langle [\hat{A}(t), \mathcal{H}_T(t')] \rangle_0$, and $\langle ... \rangle_0$ means average with respect to $\mathcal{H}_0 = \mathcal{H}_a + \mathcal{H}_b + \mathcal{H}_c$.

We approximate the electron density of states in the electrodes as $N(\omega) \approx 1/W$ in the frequency range of voltages which we consider in the following. Then the I-V characteristic is Ohmic. We assume that the dynamics of the electrons is much faster than that of the spin. Moreover, we assume that the characteristic time of the classical apparatus, τ, is smaller than any other relevant time scale. Thus, we obtain the following for the TC:

$$I(t) = I_0 - I_s m_z(t)/2, \qquad m_z(t) = 2\,\mathrm{Tr}[S_z \rho_s(t)], \tag{5}$$

where $I_0 = 2\pi e^2 V(T_0^2 + T_s^2) N^2(0)$, and $I_s = 4\pi e^2 V T_0 T_s N^2(0)$ is the amplitude of the spin-dependent part of the TC. Further, $1/\tilde{\tau}_s$ ($\tilde{\tau}_s \approx e/I_s$) is the rate of tunneling electrons' passings via the spin ($\approx 2 \times 10^{-10}$ s for $I = 1$ nA and $T_s/T_0 = 1/3$). $\rho_s(t)$ is the spin density matrix, i.e., the density matrix of the system traced over the electron variables. The TC explicitly depends upon the spin dynamics and thus its measurement provides information on the spin system.

An important point is that the TC exhibits noise [9] which masks the spin-dependent part of the current and, moreover, affects the spin dynamics. The current-current correlation function determines the noise power [9]

$$S_I(\omega) = \frac{1}{2} \int_{-\infty}^{\infty} dt \exp(i\omega t) \langle \hat{I}(t)\hat{I}(0) + \hat{I}(0)\hat{I}(t) \rangle_0. \tag{6}$$

According to the nonequilibrium fluctuation-dissipation theorem [9], the relation between the average current and the noise power is

$$S_I(\omega, eV) = \frac{e}{2} \sum_{\kappa=\pm} \coth\left(\frac{eV + \kappa\omega}{2T} \right) I(eV + \kappa\omega), \tag{7}$$

where T is the temperature. We consider low temperatures, $T \ll eV$, and the Ohmic regime, $eV \ll W$. Then $S_I(\omega) \approx eI$ when $\omega < eV$ (shot noise) and $S_I(\omega) \approx \omega/R$ if $\omega > eV$ (quantum noise regime), where $R \approx 1/[eT_0 N(0)]^2$ is the tunneling resistance.

The signal-to-noise ratio for spin dynamics detection is

$$\mathcal{R} = I_s \sqrt{2\overline{m_z^2}} / [S_I(\omega_s)\Delta\omega_s]^{1/2} \gtrsim 1, \tag{8}$$

where ω_s is the characteristic frequency, $\Delta\omega_s$ is the signal's bandwidth associated with the spin dynamics, and $(2\overline{m_z^2})^{1/2}$ is the amplitude of the m_z oscillations.

The effect of the random electron tunneling on the spin dynamics is described by the Hamiltonian $\mathcal{H}_T$, Eq. (3).

Such a backward effect is typical for quantum measurements. Generically, we have two interacting systems, electrons and spin. To simplify the description, we decouple them assuming weak spin-assisted tunneling, $T_s \ll T_0$. This allows us to neglect the effects of the spin dynamics on the electron tunneling when we consider the effect of this tunneling on the spin. The spin dynamics is described by the Hamiltonian

$$\mathcal{H}_s = -\mu[\mathbf{H} + \mathbf{h}_e(t) + \hat{h}_T(t)\hat{\mathbf{z}}] \cdot \mathbf{S}, \tag{9}$$

where $\mathbf{h}_e(t)$ is the fluctuating magnetic field caused by the environment with correlation functions $\langle h_{e,i}(t)h_{e,j}(0)\rangle = K_i(t)\delta_{ij}/\gamma^2$, and $\gamma = \mu/\hbar$. This field causes an intrinsic spin relaxation when the TC is absent. Further, $\hat{h}_T(t)$, according to Eq. (3), is the effective magnetic field acting on the spin due to the electron tunneling. It is described by the operator

$$\hat{h}_T(t) = \frac{T_s}{\mu}\sum_{nm} a^\dagger_{n\uparrow}(t)b_{m\uparrow}(t) + b^\dagger_{m\uparrow}(t)a_{n\uparrow}(t), \tag{10}$$

which does not commute with the Hamiltonian and therefore changes with time. When $T_s < T_0$, the effect of the spin on this effective field may be neglected. The Fourier transform of the correlation function for the random effective magnetic field, $S_h(t) = \langle \hat{h}_T(t)\hat{h}_T(0)\rangle_0$, is related to the Fourier transform of the current-current correlation function, Eq. (7), as $S_h(\omega) = (T_s/T_0 e\mu)^2 S_I(\omega)$ for tunneling between electrodes in the normal state [9]. In the following, we consider the effect of the TC on the localized spin classically. Fluctuations of the TC give rise to a random effective magnetic field $h_T(t) = h_0 + h_f(t)$ acting on the spin, where $h_0 = \langle \hat{h}_T(t)\rangle_0$ is of order $T_0 T_s N(0)/\mu$ [10].

We will show now that a fluctuating field induced by the electron tunneling *slows down* both the spin dynamics caused by the external dc magnetic field $\mathbf{H}$ as well as the spin relaxation due to the interaction with the environment (quantum Zeno effect). In the absence of backward effects of the electron tunneling on the spin, and in the case of negligible interaction with the environment, the spin would precess about the effective field $\mathbf{H}_{\text{eff}} = \mathbf{H} + h_0\hat{\mathbf{z}}$. In the following, we consider that $\mathbf{H} = H_x\hat{\mathbf{x}}$ is applied along the x axis. Consequently, the TC oscillates with the Larmor frequency $\Omega = \sqrt{\omega_x^2 + \omega_z^2}$, where $\omega_x = \gamma H_x$, and $\omega_z = \gamma h_0$. In the absence of an external magnetic field, relaxation to the state with $\langle S_z\rangle = 0$ at the rate $1/T_1 = \Gamma_0$ would take place. We show now that a strong TC, $\omega_x\tau_s \ll 1$, changes the spin precession to slow relaxation after averaging over TC realizations, while in the case of relaxation at $\Gamma_0\tau_s \ll 1$ the relaxation rate is diminished due to current fluctuations. Our consideration of quantum spin dynamics follows that presented by Zwanzig [11]. The equation of motion for the spin density matrix is $\dot{\rho}_s = -i[\mathcal{H}_s, \rho_s]$. Writing ρ_s as $\rho_s(t) = \frac{1}{2}\mathbb{1} + \mathbf{m}\cdot\mathbf{S}$, we see that $m_z(t) = 2\,\mathrm{Tr}[S_z\rho_s(t)]$ determines the time dependence of the TC in Eq. (5). The equation for $\mathbf{m} = (m_x, m_y, m_z)$ is

$$\dot{\mathbf{m}} = \gamma\{\mathbf{m} \wedge [\mathbf{H} + \mathbf{h}_e(t) + h_T(t)\hat{\mathbf{z}}]\}, \tag{11}$$

whose constant of motion is $|\mathbf{m}(t)|^2 = \text{const}$. We assume without loss of generality that at time $t = 0$ the spin is oriented along the z axis, $m_z(0) = 1$. For a single random magnetic field realization, solutions of Eq. (11) display different physical regimes depending upon the value of $\omega_x\tau_s$, all of them without relaxation. Relaxation appears as a result of an averaging procedure over noise realizations as shown below.

Using the local equilibrium approximation [11], we obtain

$$\dot{m}_z = -\int_0^t dt'[K_x(t-t') + K_y(t-t')]F(t-t')m_z(t'),$$
$$F(t) = g(t)\cos(\omega_z t),$$
$$g(t) = \left\langle \cos\left[\gamma\int_0^t dt' h_f(t')\right]\right\rangle_e, \tag{12}$$

where $\langle\cdots\rangle_e$ represents average over TC (noise) realizations. Using the Gaussian approximation for $\int_0^t dt' h_f(t')$, we get

$$-\ln g(t) = \frac{\gamma^2}{2}\int_0^t dt'\int_0^t dt''\langle h_f(t')h_f(t'')\rangle_e$$
$$= \int_0^W \frac{d\omega}{\omega^2} S_h(\omega)[1 - \cos(\omega t)]. \tag{13}$$

We obtain $\ln g(t) = -t/\tau_s - (e^2R)^{-1}\ln(W/eV)$ for $eVt \gg 1$. Here $1/\tau_s = T_s^2 I/(eT_0^2)$ differs from the rate of electron passings via the spin by the factor $(2T_s/T_0)$. The second (quantum noise) contribution to $\ln g(t)$ may be neglected because $1/(e^2R) \approx T_0^2/W^2 \ll 1$.

For the spin in the external field H_x, neglecting intrinsic relaxation, we have $K_x = \omega_x^2$ and $K_y = 0$, while for intrinsic relaxation due to the environment ($H_x = 0$), we have the correlation function $K(t) = K_{x,y}(t)$. We neglect a similar environment contribution $K_z(t)$ assuming that fluctuations of the TC (associated to $h_f(t)$] cause a stronger effect than the environment. The function $F(t)$ describes the effect of the TC fluctuations on the spin dynamics. Using the Markovian approximation [11], we see that m_z decays exponentially in both cases. For the spin in the external field, we get

$$m_z(t, I) = \exp[-\Gamma(I)t], \qquad \Gamma(I) = \frac{\omega_x^2\tau_s}{1 + \omega_z^2\tau_s^2}, \tag{14}$$

such that, if the TC increases, τ_s decreases, and $\Gamma(I) \to 0$. This is the Zeno regime. The intrinsic relaxation rate caused by the environment ($H_x = 0$) is renormalized by the TC as

$$\Gamma(I) = 2\int_0^\infty dt K(t)F(t, I). \tag{15}$$

The correlation function $K(t)$ depends on the strength of the environment noise and on the characteristic time τ_e. In the presence of a TC, the result $\Gamma = \Gamma_0$ is still valid if $\tau_e \ll \tau_s$, while in the opposite limit we obtain a renormalized relaxation rate $\Gamma \approx \Gamma_0 \tau_s/\tau_e$. Hence, measurements of $\Gamma(I)$ provide information on the intrinsic relaxation. Equation (15) allows one to compute the correlation function for the environment noise $K(t)$ if $\Gamma(I)$ is extracted from experimental data.

We conclude that, in the case of a strong TC, $\omega_x \tau_s \ll 1$, i.e., when the rate of electron passings via spin is bigger than the precession frequency, the spin precession is *completely* suppressed ($I = 1$ nA and $H_x = 0.01$ T give $\omega_x \tau_s = 0.32$).

Next, we consider the opposite limit of weak TC, $\omega_x \tau_s \gg 1$. In this limit, neglecting intrinsic relaxation, we obtain

$$m_z(t) = \frac{\omega_x^2}{\Omega^2} \exp(-\alpha_1 t) \cos(\Omega t) + \frac{\omega_z^2}{\Omega^2} \exp(-\alpha_2 t), \quad (16)$$

where $\alpha_1 = (1 - \omega_x^2/2\Omega^2)/\tau_s$ and $\alpha_2 = \omega_x^2/(\Omega^2 \tau_s)$. Thus, the spin is precessing with a renormalized frequency Ω and the oscillations of the average magnetization decay with the rate $\sim 1/\tau_s$. The average tunneling current, $I(t) = I_0 - I_s m_z(t)/2$, also shows damped oscillations, and the relaxation rate $1/\tau_s$ determines the bandwidth of the signal $\Delta\omega_s \sim 1/\tau_s$ in Eq. (8). When $\omega_x \tau_s \geq 1$, we get a signal-to-noise ratio $\mathcal{R}$ of order unity independently of I, in agreement with the results of Ref. [7]. The spin dynamics is modified insignificantly but the information on this dynamics, contained in the TC, is partly demolished [2]. In this weak measurement regime $\alpha_{1(2)} \to 0$ as $I \to 0$, while in the Zeno (or strong measurement) regime $\Gamma(I) \to 0$ as $I \to \infty$.

Hence, *the spin dynamics is either suppressed by the TC or the TC carries information on the spin dynamics with maximum signal-to-noise ratio of order unity.* In the optical experiments [4], the frequent short pulses used for measurements inhibit the rf transitions between quantum states; the same effect may be achieved by collisions. In our case the tunneling of electrons play the role of short pulses or collisions.

To observe the suppression of the spin precession in the external field by the TC (dynamic quantum Zeno effect), we propose the following experiment. At a first step, a magnetic field $H_z \gg T/\mu$ is applied to align the spin in the direction of the electron polarization in the electrodes. At a second step, the voltage is switched on to induce the current $I(0)$. At a third step, the magnetic field H_z is switched off and, in a fourth step, a field $H_x \ll I(0)T_s/(eT_0\gamma)$ is applied. In the absence of a TC it would cause a spin precession with frequency ω_x. Now, measurements should show an increase with time of the TC, $I(t) = I(0) + I_s\{1 - \exp[-\Gamma(I)t]\}/2$, with a rate $\Gamma(I) \propto 1/I(0)$ [Eq. (14)] vanishing in the limit of very strong TC. To observe a slowing down of the relaxation and compute $K(t)$, one needs to omit the fourth step, measure $I(t)$ at a different $I(0)$, and extract $\Gamma(I)$.

We discuss now how the probability to have a spin-up, $p_\uparrow = \rho_{\uparrow\uparrow} = (1 + m_z)/2$, may be determined from measurements of the TC. It can be extracted using the relation $m_z = 2(I_0 - I)/I_s$. If the spin before measurements was in the superposition $\alpha|\uparrow\rangle + \beta|\downarrow\rangle$, we obtain $|\alpha|^2 = p_\uparrow$. To determine the phase of α, we also need information on m_x, which can be obtained from measurements of the TC when the electrons' spins are polarized along the x axis.

In conclusion, a strong tunneling current via a localized spin *suppresses* the spin dynamics in processes such as precession in presence of an external field and relaxation due to the environment (quantum Zeno effect). This modification of the spin dynamics is due to backward effects of the tunneling current used for measurements. We proposed an experimental procedure to observe the Zeno effect. A weak tunneling current (weak measurement condition) introduces slow relaxation in the intrinsic spin dynamics in addition to that caused by the environment. In the case $T_s \ll T_0$, the current shows damped oscillations with a signal-to-noise ratio of order unity. We have also shown how the tunneling current may, in principle, be used to read a qubit. We note that in the quasiclassical approach presented here $\mathcal{R}$ is field and voltage independent. We have derived $\mathcal{R}$ using a full quantum mechanical treatment of the tunneling electrons and the localized spin in the steady state, which establishes after switching on V [8]. Then, $\mathcal{R}$ reaches its maximum, ≤ 4, at the resonance condition $eV = \hbar\Omega$.

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