Hopping in a Multiple Ferromagnetic Terminal Configuration

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The Coulomb repulsion results in strong correlations between the contacts at tunneling transport through a trap or a small quantum dot. If the dot Fermi energy is below the Fermi energies in the source and the drain and if the Coulomb charging energy to add an electron at the dot is larger than the transport window, the regime of the Coulomb blockade is realized. In a three-terminal transistor-like configuration the potential and the energy of the dot can be modified by coupling it capacitively to the gate electrode. Then the current can flow, when the dot energy level with one extra electron is brought within the transport window, and a single-electron transistor is realized [1]. The transport blockade can also be due to another intrinsic electron property, the electron spin. The Pauli, or spin, blockade is due to the Pauli exclusion principle forbidding two electrons with the same spin projection to occupy the same quantum state. Spin correlations induced by the Pauli blockade result in a large magnetoresistance between the normal and the ferromagnetic terminals [2]. The value of non-zero spin at the trap is determined by the polarization of the drain electrode relative to the magnetic field. In the case when there are several ferromagnetic terminals e1, e2, e3 shown in Fig.1 the spin correlations and thus the currents through each junction are determined by the generalized equations (1) and (2).

$$\frac{d}{dt}n = \Gamma_S(1-n) - \Gamma_D n - \Gamma_D \mathbf{p_D s}\ , \Gamma_{S(D)} = \sum_i \Gamma_{S(D)i} \tag{1}$$

$$\frac{d}{dt}\mathbf{s} = \Gamma_S(1-n)\mathbf{p_S} - \Gamma_D \mathbf{s} - \mathbf{p_D}\Gamma_D n + [\mathbf{s}\times\boldsymbol{\omega}_L]\ , \mathbf{p}_{S(D)} = \frac{1}{\Gamma_{S(D)}}\sum_i \mathbf{p}_{S(D)i}\Gamma_{S(D)i} \tag{2}$$

Table 1 outlines the derivation of the equations starting with the equation for full density matrix including electrodes [3], and (1) and (2) are obtained by tracing irrelevant variables out [3]. For simplicity we assume all absolute values of electrode polarizations $|\mathbf{p}_i|=p$ and transition rates $|\Gamma_{S(D)i}| = \Gamma$ equal. The direction of $\mathbf{p}_1$ is fixed (Fig.1), $\mathbf{p}_2$ can be parallel or anti-parallel to $\mathbf{p}_1$, $\mathbf{p}_3$ forms an angle Θ with $\mathbf{p}_1$. The junction currents are positive if flowing from the trap to the corresponding electrode, so the condition $I_1+I_2+I_3=0$ is always satisfied. First, we consider the case, when the current flows from the electrodes e1 and e3 into e2. If $\mathbf{p}_1=\mathbf{p}_2$, a strong current I_2 modulation is observed with Θ (Fig.2). If $\Theta=0$, $\mathbf{p}_3=\mathbf{p}_1=\mathbf{p}_2$, only spins with one projection are injected and absorbed, and the current is maximal. For $\mathbf{p}_3=-\mathbf{p}_1=-\mathbf{p}_2$ ($\Theta=\pi$) the current is minimal due to the spin blockade because of a non-zero spin at the trap. As the spin value is determined by $\mathbf{p}_2$, the minimum current value depends on p. This also explains the current behavior, when the orientation of $\mathbf{p}_2$ is altered to $\mathbf{p}_2=-\mathbf{p}_1$ shown in Fig.3. Now the current is minimal at $\mathbf{p}_3=\mathbf{p}_1=-\mathbf{p}_2$. This is due to the spin injection orientation from e1 and e3 on the trap anti-parallel to $\mathbf{p}_2$. Due to the spin anti-parallel to the magnetization of e2, the electron cannot escape to e2 and dwells long at the trap.

As another electron cannot enter the occupied trap, the current is long blocked, which results in minimal average current (Fig.3). Now we consider the situation, when the current flows from e1 into e2 and e3, $\mathbf{p}_2$ is anti-parallel to $\mathbf{p}_1$: $\mathbf{p}_2 = -\mathbf{p}_1$. Fig.4 demonstrates that at Θ=0 ($\mathbf{p}_1 = \mathbf{p}_3$) the current I_3 is maximal, while I_2 is the smallest. This is expected as the spins injected from e1 go with no problem into e3, the magnetization of which is parallel to e1, while they go onto e2 rarely because of their anti-parallel orientation. If now one thinks of a current switch based on the spin blockade, it is desirable to have a configuration of fixed magnetization shown as in Fig.1. Then the current I_2 is small for polarization p close to one (Fig.3, Fig.4). The current I_3 is large when it flows into e3 in Fig.4, while it is suppressed in Fig.3, where it flows away from e3. Such a behavior is achieved, when the rate Γ_3 changes sign, for example, when it depends on voltages on e2 and e3. S*ingle spin* switch-like characteristics shown in Fig.5 are then realized.

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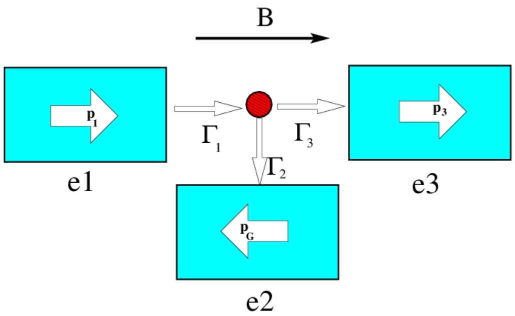

Fig.1 A three ferromagnetic terminal configuration. Electron transport is due to spin-dependent hopping.

$$i\frac{\partial}{\partial t}\Re = \frac{1}{\hbar}[\boldsymbol{\mathcal{H}},\Re] - 2\sum_i \Gamma_{Di}\{\wp_{Di},\Re\} + \sum_i \Gamma_{Si}\wp_{Si}(1-n),$$

$\Re$-full density matrix including terminals [3];

$\boldsymbol{\mathcal{H}}$-impurity Hamiltonian, n-trap occupation;

$\wp_{D,Si}$-projection on i-th drain-source magnetization

$[\boldsymbol{\mathcal{H}},\Re] = \boldsymbol{\mathcal{H}}\Re - \Re\,\boldsymbol{\mathcal{H}},\ \{\wp,\Re\} = \wp\Re + \Re\,\wp,$

Tr –partial trace over terminals' degrees

ρ =Tr $\Re$ describes only the trap (including spin):

$$i\frac{\partial}{\partial t}\rho = \frac{1}{2\hbar}[\boldsymbol{B\sigma},\rho] - \sum_i \Gamma_{Di}\left\{\frac{I}{2} + \boldsymbol{p}_{Di}\boldsymbol{\sigma},\rho\right\} + \sum_i \Gamma_{Si}\left(\frac{I}{2} + \boldsymbol{p}_{Si}\boldsymbol{\sigma}\right)\boldsymbol{\sigma}(1-n)$$

Table 1 Sketch of a derivation of the master equation for the density matrix on the trap generalized to multiple terminals.

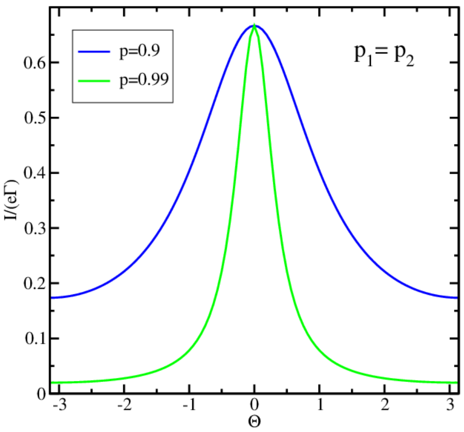

Fig.2 Current I_2, as a function of Θ, for $\mathbf{p}_1=\mathbf{p}_2$, when Γ_3 allows transport from e3 to the trap.

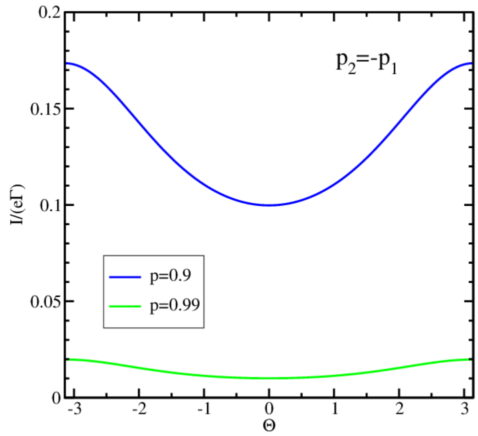

Fig.3 Current I_2 for $\mathbf{p}_1=-\mathbf{p}_2$, for other conditions similar to Fig.2. I_2 is reduced for $\mathbf{p}_3=\mathbf{p}_1=-\mathbf{p}_2$.

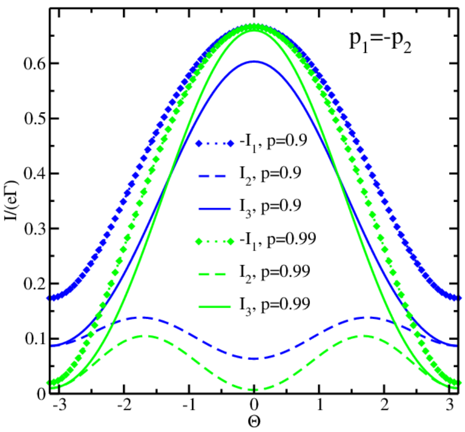

Fig.4 Current I, when Γ_3 allows transport from the trap to e3. I_3 is the highest and I_2 is the smallest, when $\mathbf{p}_3=\mathbf{p}_1=-\mathbf{p}_2$.

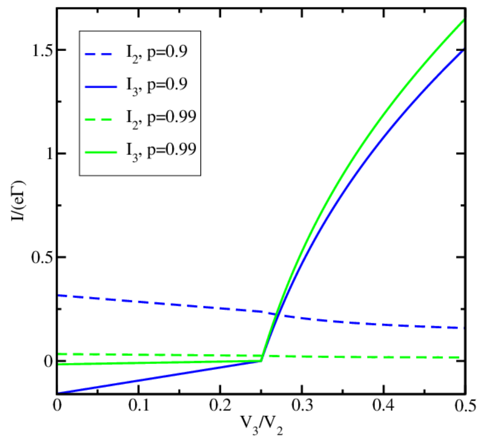

Fig.5 Switch-like characteristics are realized, if Γ_3 yields transport from e3 to the trap for $V_3 < 0.5\ V_2$ and from the trap to e3 for $V_3 < 0.5\ V_2$.

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