ELECTRONIC CORRELATIONS IN TRANSPORT THROUGH MAGNETIC NANOSTRUCTURES*

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The coherent electronic transport through a quantum dot coupled to ferromagnetic electrodes is calculated for the parallel and antiparallel orientations of polarizations. The influence on transport of both the charge fluctuations and the Kondo resonance are considered by using the equation of motion method for the non-equilibrium Green functions. The largest spin accumulation is observed in mixed valence range. In Kondo regime the state of a particle is a singlet for any polarization of the leads.

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1. Introduction

The transport of spin-polarized electrons through the point contacts and tunnel junctions has recently attracted a lot of interest. This is stimulated by expected application in magnetic random access memories (MRAMs) and in magnetic sensors. In the present paper we discuss the coherent transport through a quantum dot (QD) coupled to ferromagnetic leads as a function of position of particle energy level and temperature. With the increase of temperature or by a shift of particle level close to the Fermi level decreases the role of the Kondo resonance and the resonance transport through the charge fluctuation peak becomes more important. In the following we discuss how the evolution of this behavior is influenced by polarization of the leads. One expects the increasing role of polarization of conduction electrons on the conductivity for regions outside the Kondo range due to the weakening of correlations of electrons with opposite spins.

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2. Model and calculations of the current

The Hamiltonian for the QD coupled to ferromagentic leads is

$$\begin{aligned} H &= \sum_{k,\alpha,\sigma} \epsilon_{k\alpha\sigma}\, c^{\dagger}_{k\alpha,\sigma} c_{k\alpha,\sigma} + \sum_{\sigma} \epsilon_0\, c^{\dagger}_{0\sigma} c_{0\sigma} + U \hat{n}_{0+}\hat{n}_{0-} \\ &\quad + \sum_{k,\alpha,\sigma} t_{\alpha}\, (c^{\dagger}_{k\alpha,\sigma} c_{0\sigma} + \mathrm{h.c.})\,. \end{aligned} \tag{1}$$

The first term describes electrons in the left ($\alpha = L$) and the right ($\alpha = R$) ferromagnetic electrode, the second and the third one correspond to electrons at the QD with the single energy level ϵ_0 and the onsite Coulomb interaction U of two electrons with the opposite spins $\sigma = +$ and $\sigma = -$, the fourth term describes tunneling between the electrodes and the QD.

The current is determined by means of the non-equilibrium Green function method [1] as

$$J = \frac{e}{\hbar} \sum_{\sigma} \frac{2\Gamma_{\mathrm{L}\sigma}\Gamma_{\mathrm{R}\sigma}}{\Delta_{\sigma}} \left(n_{\mathrm{R}\sigma} - n_{\mathrm{L}\sigma}\right)\,, \tag{2}$$

where

$$n_{\alpha\sigma} = -\frac{1}{\pi} \int_{-D_{\alpha\sigma}}^{D_{\alpha\sigma}} d\omega f_{\alpha}(\omega) \mathrm{Im}[G^{r}_{0\sigma,0\sigma}(\omega)]\,, \tag{3}$$

$\Delta_{\sigma} = \Gamma_{\mathrm{L}\sigma} + \Gamma_{\mathrm{R}\sigma}$, $\Gamma_{\alpha\sigma} = \pi\rho_{\alpha\sigma}t^2_{\alpha}$ and $\gamma_{\alpha\sigma} = \Gamma_{\alpha\sigma}/\Delta_{\sigma}$. The formula (2) was derived under the assumption of the elastic transport and the lesser, retarded and advanced bare Green functions in the electrodes are taken as $g^{<}_{\alpha\sigma} = 2i\pi\rho_{\alpha\sigma} f_{\alpha}$ and $g^{r,a}_{\alpha} = \mp i\pi\rho_{\alpha\sigma}$. Here, f_{α} denotes the Fermi distribution function for electrons in the α-electrode and $\rho_{\alpha\sigma} = 1/(2D_{\alpha\sigma})$ is the constant density of states for $|\omega| < D_{\alpha\sigma}$. The charge and the spin accumulation at the QD are expressed as $n_0 \equiv \sum_{\sigma} n_{0\sigma} = \sum_{\alpha,\sigma} \gamma_{\alpha\sigma} n_{\alpha\sigma}$ and $m_0 \equiv \sum_{\sigma} \sigma n_{0\sigma} = \sum_{\alpha,\sigma} \sigma\gamma_{\alpha\sigma} n_{\alpha\sigma}$, respectively.

In order to determine the Green function $G^{r}_{0\sigma,0\sigma}$ we choose, among a few known approaches [2], the equation of motion (EOM) method [3] adapted for the nonequilibrium situation [4]. The equation for the single-particle Green function generates higher-order Green's functions. In order to truncated the series of equations we use the self-consistent decoupling procedure proposed by Lacroix [3]. The method allows for the description of the system in the whole parameter range. In the limit $U \to \infty$ one gets

$$G^{r}_{0\sigma,0\sigma}(\omega) = \frac{1 - n_{0\bar{\sigma}} + H_{\bar{\sigma}}(\omega)}{\omega - \epsilon_0 + i\Delta_{\sigma} + i2\Delta_0 H_{\bar{\sigma}}(\omega) + F_{\bar{\sigma}}(\omega)}\,, \tag{4}$$

where $2\mathit{\Delta}_0 = \mathit{\Delta}_+ + \mathit{\Delta}_-$ and

$$H_{\bar{\sigma}}(\omega) = \sum_{\alpha} \Gamma_{\alpha\bar{\sigma}} \int \frac{d\omega'}{\pi} \frac{f_\alpha(\omega') G^a_{0\bar{\sigma},0\bar{\sigma}}(\omega')}{\omega' - \omega - i0^+}, \tag{5}$$

$$F_{\bar{\sigma}}(\omega) = \sum_{\alpha} \Gamma_{\alpha\bar{\sigma}} \int \frac{d\omega'}{\pi} \frac{f_\alpha(\omega')}{\omega' - \omega - i0^+}. \tag{6}$$

These equations and the condition $n_0 = \sum_{\alpha,\sigma} \gamma_{\alpha\sigma} n_{\alpha\sigma}$ form a set of self-consistent integral equations, which have to be solved.

3. Results and conclusions

We solved numerically the set of the integral equations for a small voltage $V \to 0$. Integration around the singularity point ϵ_{F} was performed according to a logarithmic discretization procedure [2]. In the calculations the density of states has been taken $\rho_{\mathrm{L}+} = \rho_{\mathrm{R}+} = 1$ and $\rho_{\mathrm{L}-} = \rho_{\mathrm{R}-} = 1/2$ for the parallel configuration. Following the Julliere approach [5] one can express the polarization as $P_\alpha = (\rho_{\alpha+} - \rho_{\alpha-})/(\rho_{\alpha+} + \rho_{\alpha-})$, which in our case is $P_{\mathrm{L}} = P_{\mathrm{R}} = 1/3$. Fig. 1 presents the conductance ($\mathcal{G}_{\mathrm{P}}$) for the parallel orientation of magnetization in the electrodes, the magnetoresistance MR $= (\mathcal{G}_{\mathrm{P}} - \mathcal{G}_{\mathrm{AP}})/\mathcal{G}_{\mathrm{P}}$ and the spin accumulation at the QD as a function of the position of the QD level ϵ_0. It is seen that the conductance peak increases and is shifted towards the Kondo regime with lowering the temperature T. For the assumed asymmetric junctions ($t_{\mathrm{L}} = 0.02$, $t_{\mathrm{R}} = 0.06$), the maximal value of $\mathcal{G}_{\mathrm{P}} = (e^2/h) \sum_\sigma 4\gamma_{\mathrm{L}\sigma}\gamma_{\mathrm{R}\sigma}$ for our case is $0.72 \times (e^2/h)$. A change of the magnetoresistance MR, when the systems goes from the empty state regime to the Kondo regime, is shown in Fig. 1(b). For the uncorrelated transport we recover the Julliere formula [5] MR $= 2P_{\mathrm{L}}P_{\mathrm{R}}/(1 + P_{\mathrm{L}}P_{\mathrm{R}})$. In the Kondo regime MR is reduced and can be negative for the asymmetric junctions. If both the electrodes have the same polarization $P_{\mathrm{L}} = P_{\mathrm{R}} = P$ one can find

$$\mathrm{MR} = \frac{P^2(1 - 3\alpha^2 + \alpha^2 P^2 + \alpha^4 P^2)}{(1 - \alpha^2 P^2)^2}, \tag{7}$$

where $\alpha = (t_{\mathrm{L}}^2 - t_{\mathrm{R}}^2)/(t_{\mathrm{L}}^2 + t_{\mathrm{R}}^2)$ describes asymmetry between the left and the right junction. MR is weakly temperature dependent in the empty state regime, whereas in the Kondo regime MR increase with T. This results from a strong temperature dependence of the Kondo peaks for different spin orientations. A spin accumulation at the QD (shown in Fig. 1(c)) has an interesting behavior, namely, it increases in the mixed valence regime and decreases to zero in the Kondo regime. It means that the conductance achieves the unitary limit and electrons with the opposite spin orientations are transmitted with the same transition rates through the QD.

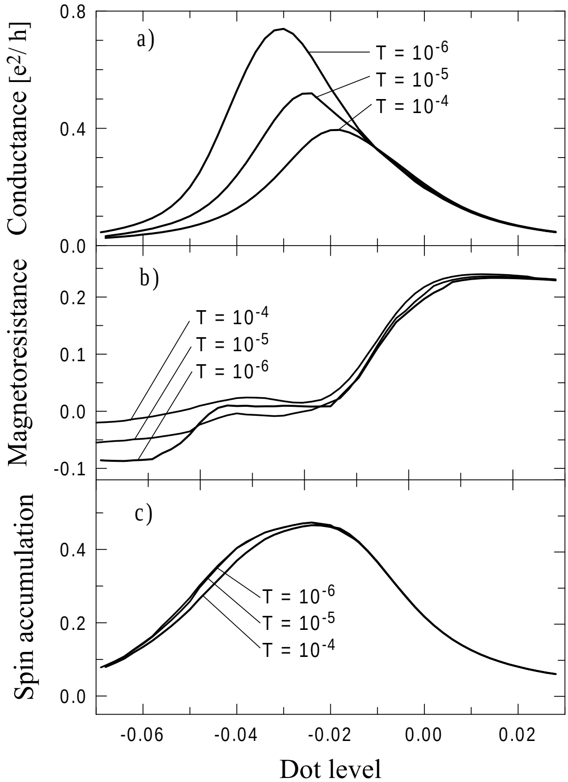

Fig. 1. The conductance (a), the magnetoresistance (b) and the spin accumulation (c) as a function of the position of the dot level for different temperatures $T = 1 \times 10^{-6}$, 1×10^{-5} and 1×10^{-4}. The conductance and the spin accumulation are determined for the parallel configuration of magnetization.

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REFERENCES

[1] See for example: H. Haug, A.-P. Jauho, *Quantum Kinetics in Tranport and Optics of Semiconductors*, Springer Verlag, Berlin, Heildelberg, New York 1998.

[2] A.C. Hewson, *The Kondo Problem to Heavy Fermions*, Cambridge University Press, Cambridge 1993.

[3] C. Lacroix, *J. Phys. F: Metal Phys.* **11**, 2389 (1981).

[4] B.R. Bułka, P. Stefański, *Phys. Rev. Lett.* **86**, 5128 (2001).

[5] M. Julliere, *Phys. Lett.* **54A**, 225 (1975).