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Coherent electronic transport through magnetic junction

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A quantum dot with a single energy level coupled to ferromagnetic electrodes is considered within the slave boson approach. Magnetic polarisation of the leads induces the spin accumulation at the dot. Its maximum occurs in the mixed valence range and decreases to zero in the Kondo regime. We have calculated the conductance for parallel and antiparallel orientations of polarisation of electrodes. Magnetoresistance takes the largest values in the empty state regime, considerably decreases in mixed valence range and reaches the smallest values in the Kondo regime, where in some cases even negative magnetoresistance can occur.

1. Introduction Recent progress in nanofabrication made it possible to study the electron transport in quantum dots (QDs). At low temperatures the dissipation in these devices is negligible and therefore QD is an excellent system for studying the phenomena associated with quantum coherence. Observation of the Kondo effect in QDs [1, 2] opened a new path for the investigation of strongly correlated electrons and a hope for many applications. QD offers the possibility of continuos tuning of the relevant parameters governing the Kondo effect. The number of electrons and the level position of the quantum dot as well as the coupling strength of the leads are made controllable by the change of gate voltages. The most recent research in nanosystems focuses on the spin-dependent tunneling. Spin-based devices hold promises for future applications in field sensors [3], conventional computer hardware (e.g. magnetic random access memories (MRAMs) [3] and in quantum computers [4]. In the present paper we study Kondo correlation effects on the magnetoresistance (MR) of the QD weakly coupled to ferromagnetic leads.

2. Slave boson mean field approach Transport through a QD connected to the leads can be described by the single level Anderson model. In the following we discuss the limit of infinite Coulomb interaction, where double occupancy of the dot is forbidden. A very useful tool to describe strong correlations in this case is the Colenman's slave boson (SB) representation [5]. The electron annihilation operator at the dot c_σ is decomposed in this approach into auxiliary boson b^+ which creates an empty state at the dot and pseudofermion f_σ which annihilates the single occupied state with spin σ: $c_\sigma \to b^+ f_\sigma$. The Hamiltonian of QD coupled to ferromagnetic leads in the SB representation reads

$$H = \sum_{k,\sigma,\alpha} \epsilon_{k\alpha} c^+_{k\alpha\sigma} c_{k\alpha\sigma} + \sum_{k,\sigma,\alpha} t_\alpha (c^+_{k\alpha\sigma} b^+ f_\sigma + \mathrm{h.c.}) + \sum_\sigma \epsilon_0 f^+_\sigma f_\sigma + \lambda \Big(\sum_\sigma f^+_\sigma f_\sigma + b^+ b - 1 \Big) . \qquad (1)$$

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The first term describes electrons in the left ($\alpha = \mathrm{L}$) and the right ($\alpha = \mathrm{R}$) ferromagnetic electrode, the second the tunnelling between the leads and the dot, the third term gives the site energy, and the last with the Lagrange multiplier λ is the constraint, which assures the single occupancy at the dot. In the following we use the mean field approximation (MFA), which neglects the fluctuations of the boson field ($b \to \langle b \rangle \equiv r$). Fluctuations do not play an important role in the Kondo limit and at low temperatures. A crucial advantage of Coleman's formulation is that already at the MFA level it reproduces, in accordance with exact results, the singlet ground state. The minimisation or the free energy with respect to λ and r yields the self-consistent equations which determine these parameters. The current (J) may be expressed in terms of time evolution of either the occupation operator of the left electrode $N_\mathrm{L} = \sum_{k,\sigma} c^+_{kL\sigma} c_{kL\sigma}$ or the right electrode N_R. Evaluating the correlation function with the use of non-equilibrium Keldysh Green functions one gets [6]

$$J \equiv -e\left\langle \frac{\mathrm{d}N_\mathrm{L}}{\mathrm{d}t} \right\rangle = \frac{ie}{\hbar} \sum_{k,\sigma} t_\mathrm{L} r \langle c^+_{kL\sigma} f_\sigma \rangle - \text{c.c.}) = \frac{2e}{\hbar} \sum_{k,\sigma} \frac{\mathrm{d}\omega}{2\pi} \,\mathrm{Re}\,[t_\mathrm{L} r G^<_{\sigma,kL\sigma}(\omega)]\,, \tag{2}$$

where $G^<_{\sigma,kL\sigma}(\omega)$ is the Fourier transform of $G^<_{\sigma,kL\sigma}(t) \equiv i\langle f^+_\sigma(0)\, c_{kL\sigma}\rangle$. Next we use the Dyson equation to express the non-equilibrium Green functions by only the bare Green functions of the leads and the dressed Green functions of the dot. Assuming a quasi-elastic transport through the dot, for which the current conservation rule is fulfilled for any ω and taking constant densities of states for electrons in the leads ($\rho_{\alpha\sigma} = 1/2D_{\alpha\sigma}$ for $|\epsilon| < D_{\alpha\sigma}$) one gets

$$J = \frac{2e}{\hbar} \sum_\sigma \frac{\Gamma_{\mathrm{L}\sigma}\Gamma_{\mathrm{R}\sigma}}{\Gamma_{\mathrm{L}\sigma} + \Gamma_{\mathrm{R}\sigma}} \,(n_{\mathrm{R}\sigma} - n_{\mathrm{L}\sigma})\,, \tag{3}$$

where the coupling to the leads $\Gamma_{\alpha\sigma}$ is given by $\pi\rho_{\alpha\sigma} t^2_\alpha$,

$$n_{\alpha\sigma} = \int\limits_{-D_{\alpha\sigma}}^{D_{\alpha\sigma}} \frac{\mathrm{d}\omega}{\pi} f_\alpha(\omega)\,\mathrm{Im}\,[G^a_{\sigma,\sigma}(\omega)]\,, \tag{4}$$

f_α denotes the Fermi distribution function for electrons in the lead α and the advanced Green's function for the dot reads

$$G^a_{\sigma,\sigma}(\omega) = \frac{1}{\omega - \tilde{\epsilon}_0 - i\Delta_\sigma}\,, \tag{5}$$

where $\tilde{\epsilon}_0 = \epsilon_0 + \lambda$ and $\Delta_\sigma = r^2(\Gamma_{\mathrm{L}\sigma} + \Gamma_{\mathrm{R}\sigma})$.

The charge and spin accumulation at QD are expressed as $n \equiv \sum_\sigma n_\sigma = \sum_{\alpha,\sigma} \gamma_{\alpha\sigma} n_{\alpha\sigma}$ and $s \equiv \sum_\sigma \sigma n_\sigma = \sum_\sigma \sigma\gamma_{\alpha\sigma} n_{\alpha\sigma}$ respectively, with $\gamma_{\alpha\sigma} = \Gamma_{\alpha\sigma}/(\Gamma_{\mathrm{L}\sigma} + \Gamma_{\mathrm{R}\sigma})$.

For $T = 0$ Eq. (4) simplifies

$$n_{\alpha\sigma} = \frac{1}{\pi} \arctan\left(\frac{\mu_\alpha - \tilde{\epsilon}_0}{\Delta_\alpha}\right) + \frac{1}{2}\,, \tag{6}$$

μ_α is the chemical potential (in equilibrium $\mu_\mathrm{L} = \mu_\mathrm{R} = \mu$). In the limit of zero bias voltage $V \to 0$ and $T = 0$ the conductance can be expressed as

$$g = \frac{\mathrm{d}J}{\mathrm{d}V}\bigg|_{V=0} = \frac{e^2}{h} \sum_\sigma \frac{4\Gamma_{\mathrm{L}\sigma}\Gamma_{\mathrm{R}\sigma}}{(\Gamma_{\mathrm{L}\sigma} + \Gamma_{\mathrm{R}\sigma})^2} \sin^2(\pi n_\sigma)\,. \tag{7}$$

3. Results We consider the case of weak coupling of the leads to the dot $\Gamma_{\alpha\sigma} \ll D_{\alpha\sigma}$. The polarisation of the leads is controlled in our calculations by the change of the ratio of the densities of states for different spin orientation $\xi \equiv \rho_{\alpha-}/\rho_{\alpha+} = D_{\alpha-}/D_{\alpha+}$. Magnetic polarisation of the leads causes the spin-dependent tunnelling of electrons. For parallel orientation of spin polarisation of the leads the

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Kondo resonance centred at $\tilde{\epsilon}_0$ consists of two Lorentzian lines with renormalised spin dependent widths Δ_σ, $(\Delta_+/\Delta_- = \xi)$. Polarisation of the leads induces the spin accumulation at the dot (Fig. 1c). Maximum of the dot magnetisation occurs in the mixed valence (MV) range and it tends to zero for the Kondo regime $(\epsilon_0 \ll \mu, n \to 1)$ and in the empty state range $(\epsilon_0 \gg \mu, n \to 0)$. For symmetric coupling $(t_L = t_R)$ the conductance in the Kondo regime reaches the value $2e^2/h$ (Fig. 1a). For both spin directions the unitary limit of transmission is reached in this case. For $t_L \neq t_R$ the full transparency is not achieved and a reduction of conductance in Kondo range is observed. For antiparallel orientation of magnetisation of the leads the asymmetry of the leads for a given spin orientation is introduced even for the case $t_L = t_R$ and the open-channel conductance is not achieved in the Kondo regime. The effect of changing the relative orientations of magnetisation of the leads is most clearly visible in magnetoresistance $\mathrm{MR} = (g(\uparrow\uparrow) - g(\uparrow\downarrow))/g(\uparrow\uparrow)$, the arrows denote the orientations of magnetisation of the leads. Magnetoresistance increases with the increase of polarisation of the electrodes. MR takes the largest values in the empty state range, considerably decreases in the MV range and takes the smallest values in the Kondo regime, where for sufficiently strong asymmetry of coupling to the leads even a negative magnetoresistance can occur (Fig. 1b). The presented results for the MV range require a caution, since important in this range charge fluctuations are neglected in SBMFA. In the empty state regime the correlation effects are of minor importance and the many body renormalisation of the width and position of the resonance is negligible. The low temperature SB predictions in this range agree with the results for the tunnelling of noninteracting electrons, but the formalism breaks down for higher temperatures. Figure 2 presents the conductance for different temperatures. In the Kondo range

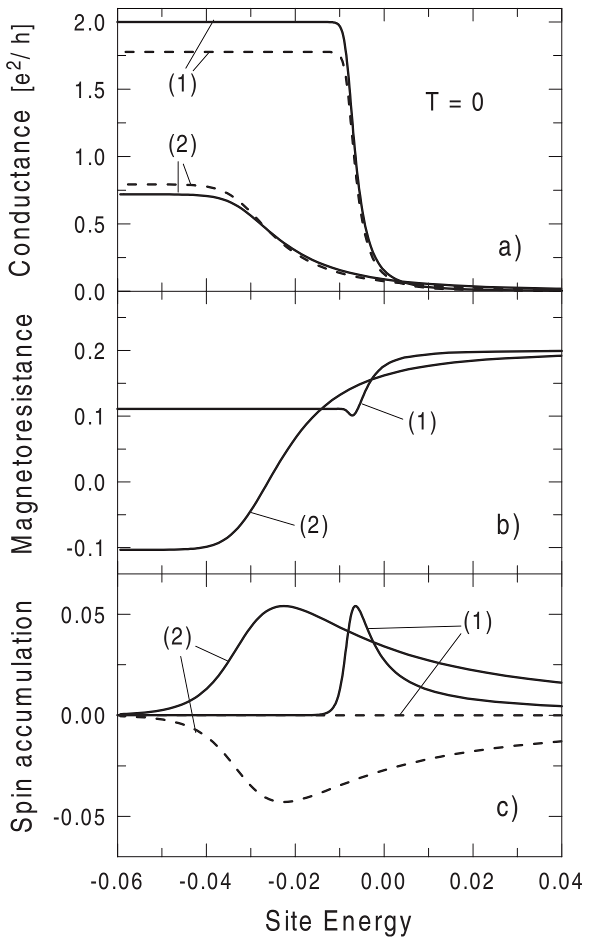

Fig. 1 a) Conductance, b) magnetoresistance, and c) spin accumulation of a QD for $T = 0$. Solid and broken curves correspond to the parallel and antiparallel orientation of polarisation of the leads $\xi = 0.5$. (1) mark the curves for symmetric junction $t_L = t_R = 0.02$ and (2) for asymmetric $t_L = 0.02$: $t_R = 0.06$. Energy is measured in the band half-widths $D_{L+} = 1$.

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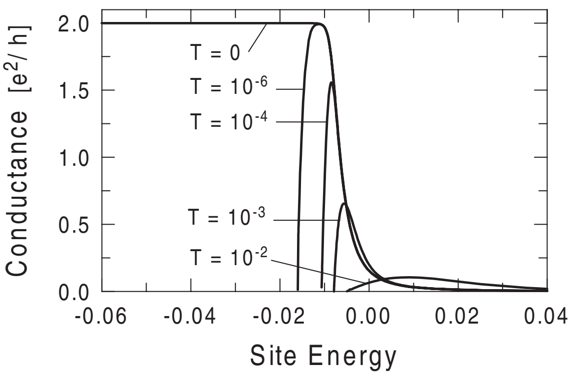

Fig. 2 Conductance of the QD coupled to the ferromagnetic leads $\xi = 0.5$, $t_L = t_R = 0.02$ for different temperatures expressed in the energy units.

it drops rapidly to zero at some value of site energy. For deeper positions of the dot level $k_B T$ exceeds the widths of Kondo resonance. The rapidity of the drop is exaggerated in MFA. The Kondo temperature decreases with lowering the site energy. This explains why, even for the lowest temperatures ($T = 10^{-6}$), the character of the conductance curve is different from the case $T = 0$. An open question is an influence of magnetic field at the dot induced by the electrode polarization. Strong fields destroy the Kondo resonance, weak fields split it. In the latter case, the effects similar to the described above are expected, but for finite bias voltage.

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References

[1] D. Goldhaber-Gordon et al., Nature **391**, 1569 (1998).
[2] S. M. Cronenwett, T. H. Oostekamp, and L. P. Kouwenhoven, Science **281**, 540 (1998).
[3] J. L. Simonds, Phys. Today **4**, 27 (1995).
[4] D. Loss and D. P. Di Vincenzo, Phys. Rev. A **57**, 120 (1998).
[5] P. Colemann, Phys. Rev. B **29**, 3035 (1984).
[6] H. Haug and A. P. Jauho, Quantum Kinetics in Transport and Optics of Semiconductors (Springer-Verlag, Berlin/Heidelberg/New York, 1998).