KONDO EFFECT IN A SINGLE QUANTUM DOT ASYMMETRICALLY COUPLED TO MAGNETIC ELECTRODES

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ABSTRACT

The Kondo effect is studied theoretically in the framework of the non-equilibrium Green function formalism as well as 'Poor man's scaling' technique. The system under consideration consists of a single quantum dot asymmetrically coupled to ferromagnetic electrodes, whose magnetic moments are non-collinear. The spin-dependent density of states and transport characteristics like differential conductance and tunneling magnetoresistance through the system are obtained using the equation of motion method. Numerical illustration of the mentioned quantities is presented. Moreover, within the scaling approach the spin splitting of the dot level is discussed and numerical illustration of the Kondo temperature for asymmetrical coupling to the leads is presented.

MODEL

The system under consideration is a single level quantum dot attached to ferromagnetic leads, whose magnetic moments are in general non-collinear.
The system is described by the Hamiltonian of the general form

$$H = \sum_{\alpha} H_\alpha + H_D + H_T. \tag{1}$$

- H_α ($\alpha = L, R$), describes electrons, within non-interacting approximation, in the left and the right electrode, respectively.

$$H_\alpha = \sum_{\mathbf{k}} \sum_{\beta=\pm} \epsilon_{\alpha\,\mathbf{k}\,\beta}\, a^\dagger_{\alpha\,\mathbf{k}\,\beta}\, a_{\alpha\,\mathbf{k}\,\beta}, \tag{2}$$

- H_D, describes the dot, where ϵ^d_σ is the single-particle energy of the dot level, and U stands for the Coulomb correlation parameter, which is assumed to by finite.

$$H_D = \sum_{\sigma=\uparrow\downarrow} \epsilon^\sigma_d d^\dagger_\sigma d_\sigma + U n_\uparrow n_\downarrow, \tag{3}$$

where $n_\sigma = d^\dagger_\sigma d_\sigma$.

- H_T is the tunneling term, which describes electron hopping between the dot and electrodes
$$H_T = \sum_{\alpha\,\mathbf{k}} \sum_{\beta\,\sigma} T_{\alpha\,\mathbf{k}\,\beta} a^\dagger_{\alpha\,\mathbf{k}\,\beta} R_{\alpha\,\beta\,\sigma} d_\sigma + \text{h.c.}, \tag{4}$$
with $T_{\alpha\,\mathbf{k}\,\beta}$ as a tunneling matrix elements, and $\mathbf{R}_\alpha$ being the relevant spin rotation matrix $\mathbf{R}_\alpha$, where ϕ_α is the angle between the global quantization axis on the dot and the local quantization axis in the α-th electrode
$$\mathbf{R}_\alpha = \begin{pmatrix} \cos(\phi_\alpha/2) & -\sin(\phi_\alpha/2) \\ \sin(\phi_\alpha/2) & \cos(\phi_\alpha/2) \end{pmatrix}.$$
- the coupling strength is described by $\Gamma_{\alpha\,\beta}(\epsilon) = 2\pi \sum_{\mathbf{k}} |T_{\alpha\,\mathbf{k}\,\beta}|^2 \delta(\epsilon - \epsilon_{\alpha\,\mathbf{k}\,\beta})$ and is assumed to be energy independent within the bandwidth extending from $-D$ to D,
- within the bandwidth $\Gamma_{\alpha\,\beta}(\epsilon) = \Gamma_{\alpha\,\beta} = \Gamma^0_\alpha(1 \pm p_\alpha)$, where p_α denotes spin polarization in the α-th electrode.
- the coupling asymmetry parameter γ has been introduced *via* $\Gamma^0_R = \gamma\,\Gamma^0_L$, for $1 \geq \gamma \geq 0$, which means that system is coupled symmetrically for $\gamma = 1$.

EQUATION OF MOTION METHOD

- the equation of motion for the Green function of the dot $G_{\sigma\sigma'}(\epsilon) = \langle\langle d_\sigma | d^\dagger_{\sigma'} \rangle\rangle$

$$\langle\langle d_\sigma | d^\dagger_\sigma \rangle\rangle = \langle \{ d_\sigma, d^\dagger_\sigma \} \rangle + \langle\langle [d_\sigma, H], d^\dagger_{\sigma'} \rangle\rangle, \tag{5}$$

- obtaining the retarded, advanced and lesser Green functions $G^{r(a)}_{\sigma\sigma'}(\epsilon) = G_{\sigma\sigma'}(\epsilon \pm i\eta)$, $\mathbf{G}^<(\epsilon)$
- the self-consistent numerical calculation of $n_{\sigma\sigma}$, $n_{\sigma-\sigma}$ and $\mathbf{G}^<(\epsilon)$

$$\langle n_{\sigma\sigma} \rangle = \langle d^\dagger_\sigma d_\sigma \rangle = \mathrm{Im} \int_{-\infty}^{+\infty} \frac{d\epsilon}{2\pi} G^<_{\sigma\sigma}, \tag{6}$$

$$\langle n_{\sigma-\sigma} \rangle = \langle d^\dagger_\sigma d_{-\sigma} \rangle = -i \int_{-\infty}^{+\infty} \frac{d\epsilon}{2\pi} G^<_{-\sigma\sigma}, \tag{7}$$

- current flowing from the α-th electrode to the dot

$$J_\alpha = \frac{ie}{\hbar} \int_{-\infty}^{+\infty} \frac{d\epsilon}{2\pi} \mathrm{Tr}[\mathbf{\Gamma}_\alpha(\mathbf{G}^<(\epsilon) + f_\alpha(\epsilon)[\mathbf{G}^r(\epsilon) - \mathbf{G}^a(\epsilon)])], \tag{8}$$

NUMERICAL RESULTS-NGF METHOD

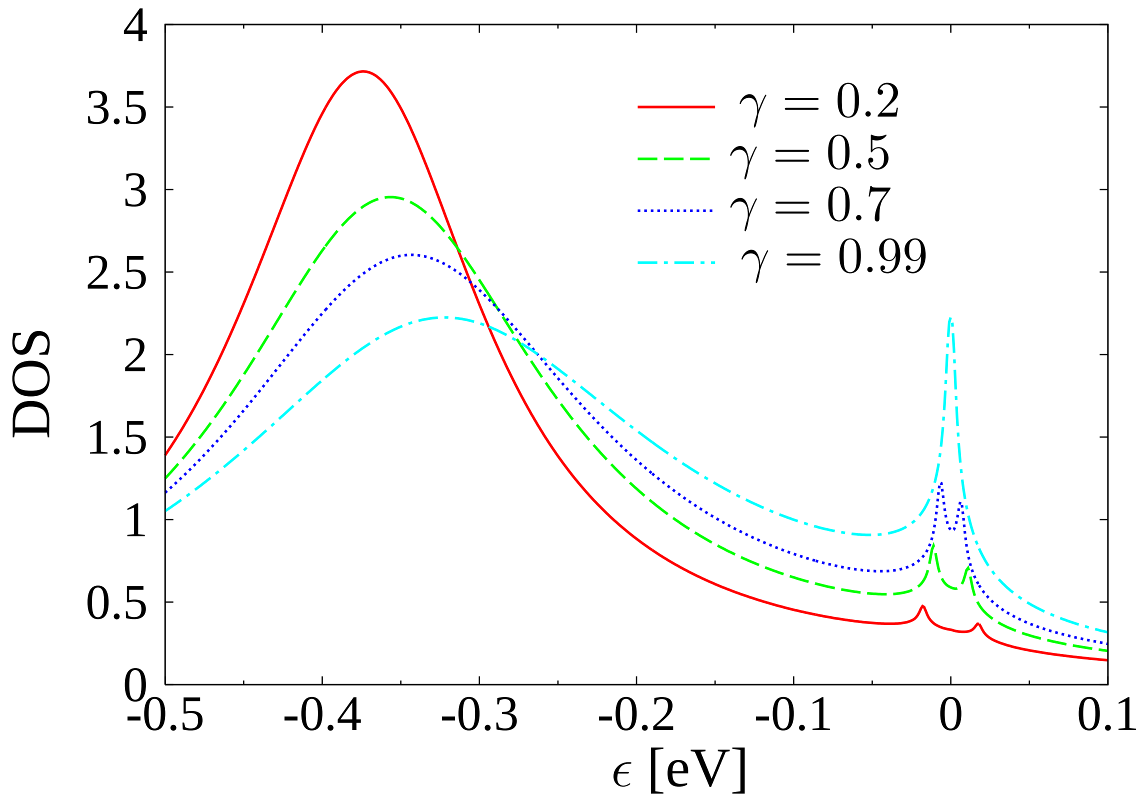

Figure 1: Density of states of the quantum dot attached to magnetic leads in antiparallel configuration, calculated for several asymmetry parameters γ as indicated in figure. The other parameters are: $\epsilon_d = -0.45$ eV, $U = 5$ eV, $\Gamma_0 = 0.15$ eV, $k_B T = 0.002$ eV, $p_L = p_R = 0.2$ and electron band width extending from -25 eV to 25 eV.

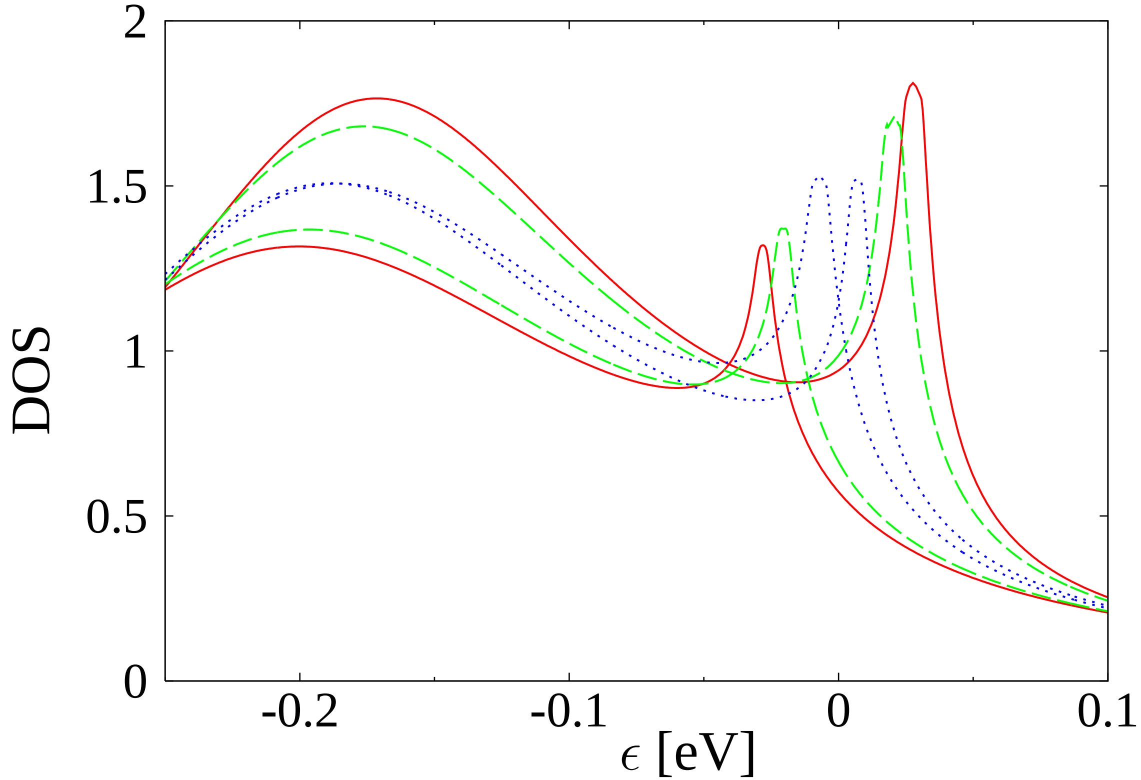

Figure 2: Density of states calculated for different magnetic configurations: $\phi = 0$ (solid line), $\phi = \pi/2$ (dashed line) and $\phi = \pi$ (dotted line) and parameters: $\gamma = 0.1$, $\epsilon_d = -0.3$ eV, $U = 5$ eV, $\Gamma_0 = 0.2$ eV, $k_B T = 0.001$ eV, $p_L = 0.1$, $p_R = 0.6$, electron band width extending from -25 eV to 25 eV.

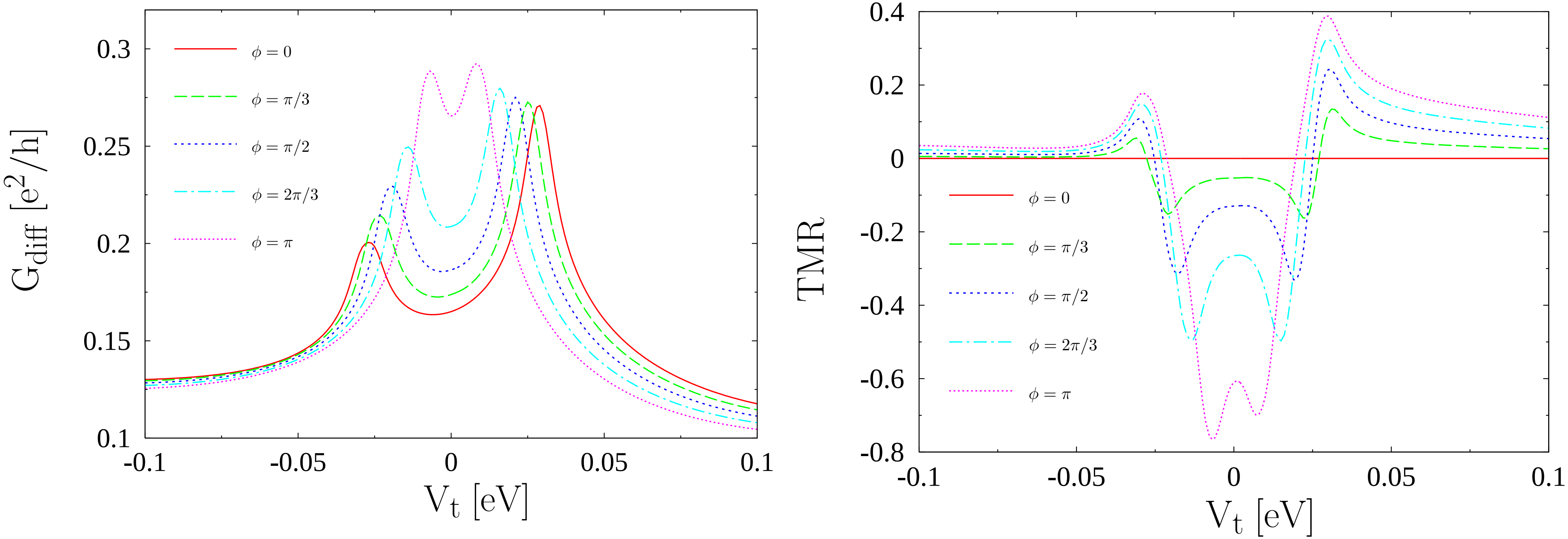

Figure 3: Differential conductance (left panel) and tunnel magnetoresistance $\mathrm{TMR} = [G_{\mathrm{diff}}(\phi_L = 0, \phi_R = 0) - G_{\mathrm{diff}}(\phi_L, \phi_R)]\,/\,[G_{\mathrm{diff}}(\phi_L = 0, \phi_R = 0)]$ (right panel) calculated for parameters as in Fig.2 and for magnetic configurations as indicated in the figure.

POOR MAN'S SCALING METHOD

- scaling for the Anderson-like Hamiltonian (1), for the symmetrical case ($-\phi_L = \phi_R = \phi = \theta/2$), leads to effective spin splitting of the dot level

$$\delta\epsilon = \epsilon^d_\uparrow - \epsilon^d_\downarrow = p\Delta\cos(\theta/2)\log(D/\tilde{D}) - g\mu_B B^z_{ext}, \tag{9}$$

  where B^z_{ext} stands for external magnetic field applied along global quantization axis

- asymmetrical coupling introduced *via* asymmetry parameter $\Gamma^0_R = \gamma\ \Gamma^0_L,\ \ 1 \geq \gamma \geq 0$, ($\gamma = 1$ symmetrical case)

- scaling for the Anderson-like Hamiltonian (1), for the asymmetrical case ($-\phi_L = \phi_R = \phi = \theta/2$), leads to effective spin splitting of the dot level

$$\delta\epsilon = \frac{\Delta}{\pi} p \sqrt{\cos^2\theta/2 + \left(\frac{\gamma-1}{\gamma+1}\right)^2 \sin^2\theta/2} \times \ln(D/\tilde{D}) - g\mu_B B^z_{ext}, \tag{10}$$

  where $p = p_L = p_R = \frac{\rho_\uparrow - \rho_\downarrow}{\rho_\uparrow + \rho_\downarrow}$ stands for the polarization of the lead, $\Delta = \sum_\alpha \Gamma^\alpha_0$.

- The Kondo temperature for symmetrical case is given by formulae

$$T_{\rm K} = \tilde{D} \exp\left(- \frac{\mathrm{arctanh}(p \cos(\theta/2))}{2p(\rho_\uparrow + \rho_\downarrow) J_0 \cos(\theta/2)} \right), \tag{11}$$

where $J_0 = (\Delta/\pi)(U/(|\epsilon^d|(U + \epsilon^d)))$.

- The Kondo temperature for asymmetrical case is given by formulae

$$T_K = \tilde{D} \exp\left(- \frac{\mathrm{arctanh}(p\sqrt{\cos^2\theta/2 + a^2 \sin^2\theta/2}}{2(\rho_\uparrow + \rho_\downarrow) J_0 p \sqrt{\cos^2\theta/2 + a^2 \sin^2\theta/2}} \right), \tag{12}$$

with J_0 defined as for symmetrical case.

NUMERICAL RESULTS-SCALING METHOD

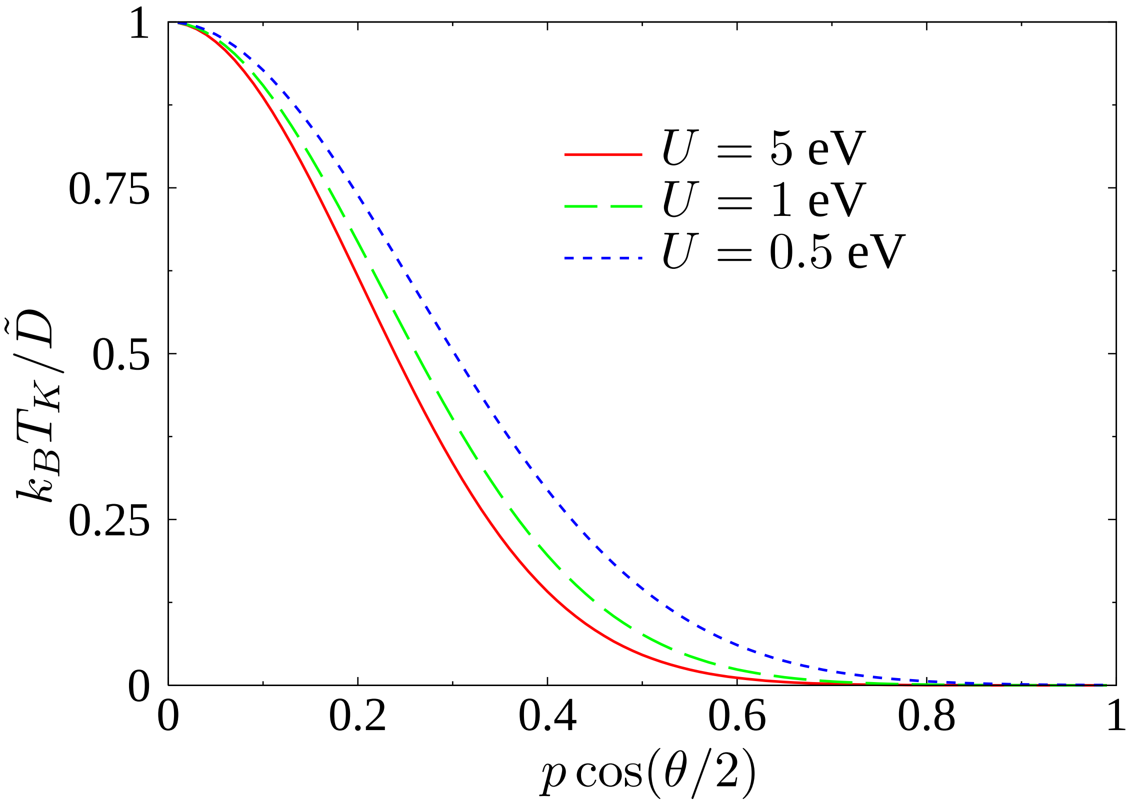

Figure 4: The Kondo temperature for QD symmetrically coupled to leads vs. $p\cos(\theta/2)$, for $\gamma = 1$, $p = 0.5$, $\epsilon^d = -0.2$ eV, $D = 25$ eV, $\Delta = 0.1$ eV.

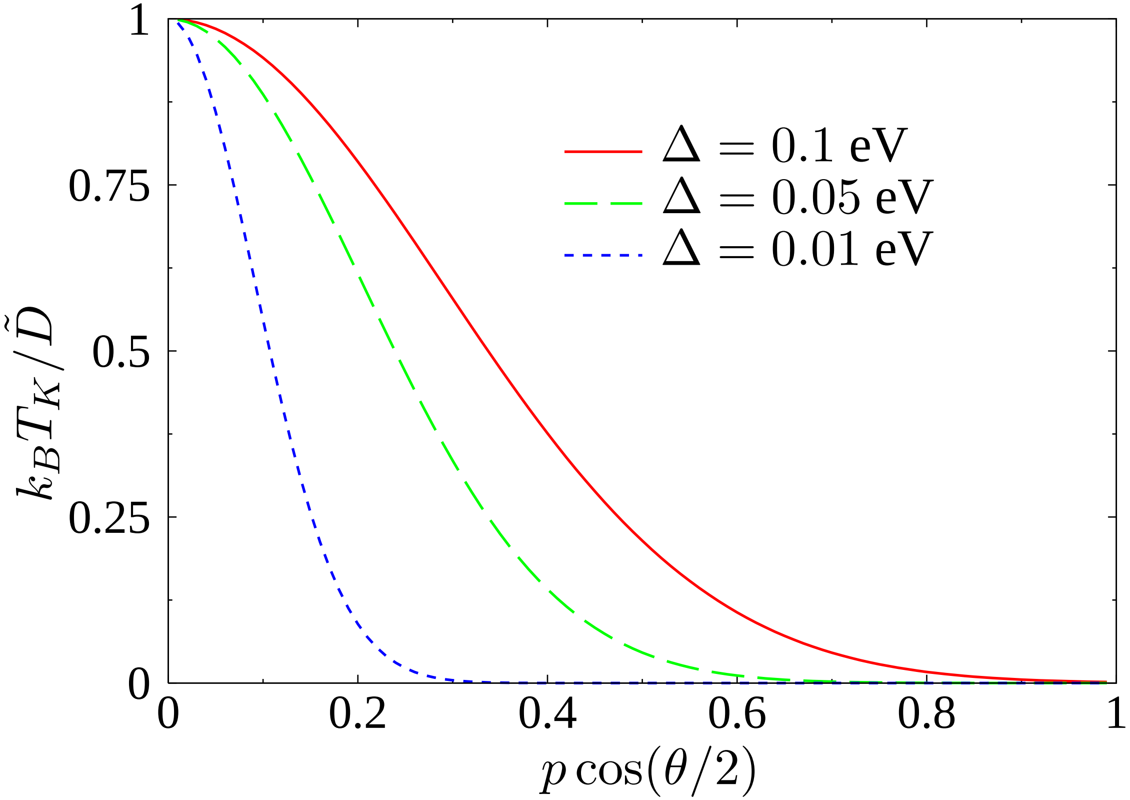

Figure 5: The Kondo temperature for QD symmetrically coupled to leads vs. $p\cos(\theta/2)$, for $\gamma = 1$, $p = 0.5$, $\epsilon^d = -0.2$ eV, $U = 5$ eV, $D = 25$ eV.

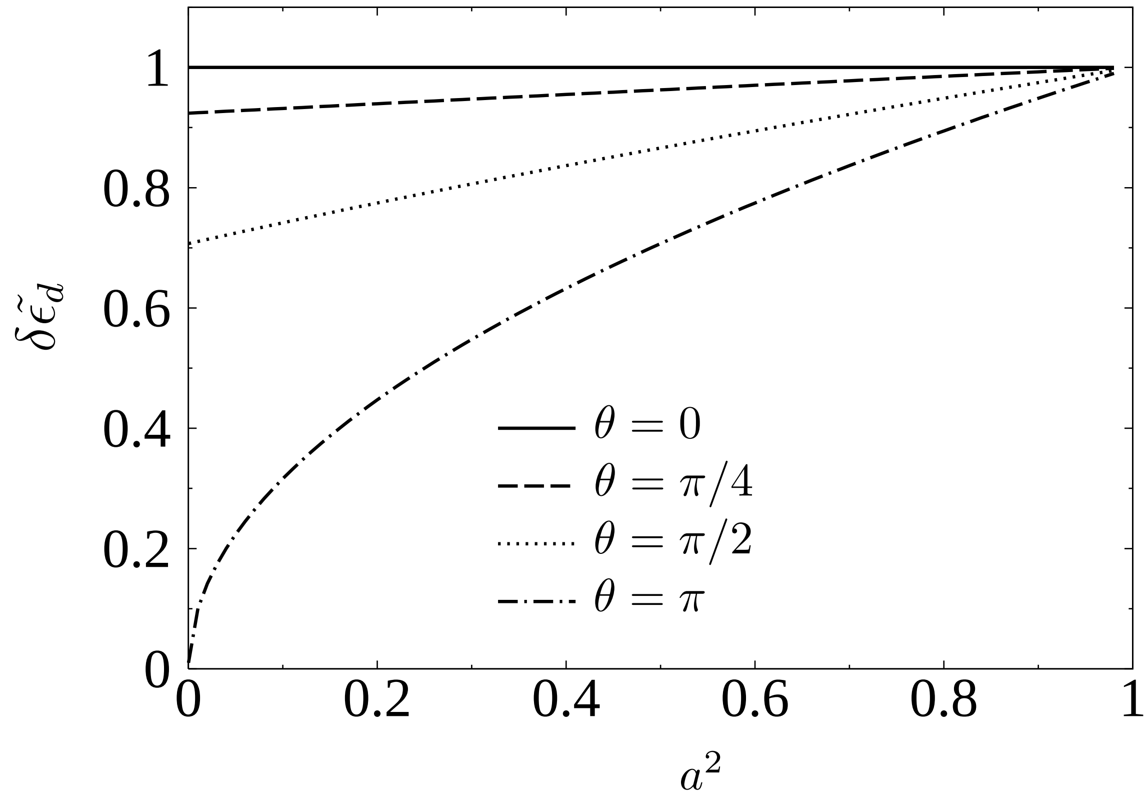

Figure 6: The spin splitting for QD asymmetrically coupled to leads vs. $a^2 = (\gamma - 1)/(\gamma + 1)$ for several indicated magnetic configurations, the other parameters are $p = 0.5$, $\epsilon^d = -0.2$ eV, $U = 5$ eV, $D = 25$ eV.

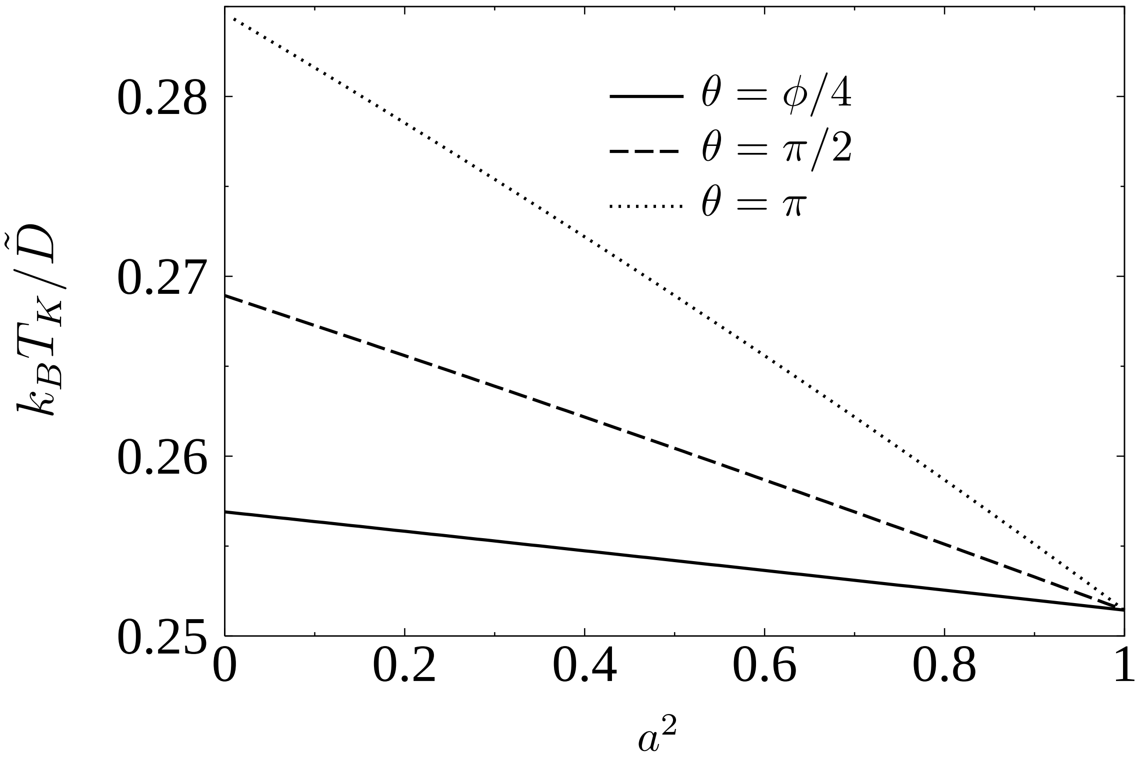

Figure 7: The Kondo temperature for QD asymmetrically coupled to leads vs. $a^2 = (\gamma - 1)/(\gamma + 1)$ for several indicated magnetic configurations, the other parameters are $p = 0.5$, $\epsilon^d = -0.2$ eV, $U = 5$ eV, $D = 25$ eV.

CONCLUSIONS-NGF METHOD

- smearing and suppression of the Kondo peak in spin-dependent density of states for the antiparallel magnetic configuration may be achieved introducing coupling asymmetry.
- suppression of the Kondo resonance increases with increasing asymmetry (decreasing γ parameter).
- spin-splitting of the Kondo resonance for asymmetrical coupling is clearly visible for all magnetic configurations and tends to decrease with changing configuration from parallel to antiparallel one.
- this splitting is a result of non-zero exchange field occurring on the dot.
- such spin-splitting exists also for the situation of the symmetrically coupled quantum dot when polarization of the left and right electrodes differs ($p_L \neq p_R$), due to $\Gamma_{\alpha\,\beta}(\epsilon) = \Gamma_{\alpha\,\beta} = \Gamma^0_\alpha(1 \pm p_\alpha)$
- the Kondo peaks in differential conductance are asymmetrical with respect to the bias reversal, this asymmetry is also visible in TMR

CONCLUSIONS-SCALING METHOD

- the Kondo temperature goes to zero when $p \to 1$ and magnetic configurations tends to parallel alignment
- for parallel magnetic configuration ($\theta = 0$) spin splitting is maximal and does not depend on asymmetry parameter
- for antiparallel magnetic configuration ($\theta = \pi$) the spin splitting is minimal for whole range of asymmetry parameter, but does not vanish for the case of asymmetrical coupling
- for all non-collinear magnetic configurations as well as for antiparallel magnetic configuration the spin splitting increases with increasing coupling asymmetry
- the coupling asymmetry reduces the Kondo temperature and moreover Kondo temperature increases with increasing θ angle, and reaches maximal values for the antiparallel magnetic configuration

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