Kondo Effect in Quantum Dots Coupled to Ferromagnetic Electrodes

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Abstract

The Kondo effects in transport through a quantum dot (QD) coupled to ferromagnetic leads are shown to be modified by the spin polarization of the electrodes. For parallel alignment of the magnetization of the leads the zero-bias anomaly in the differential conductance is split even in the absence of an external magnetic field. For antiparallel alignment the peaks are split only in the presence of a magnetic filed, but show a characteristic asymmetry.

Key words: Kondo effect; spin-dependent transport; tunnel magneto-resistance

We study the Kondo effect [1] in a quantum dot (QD) coupled to ferromagnetic electrodes. The key questions which emerge are: (i) how does the spin-asymmetry affect the effect, (ii) how are the transport properties modified, and (iii) what is the ground state of the system? We analyze these and related questions using scaling arguments and the equation of motion (EOM) technique [2].

The Anderson model for QD coupled to leads can be written as

$$H = \sum_{k\sigma} \varepsilon_{k\sigma} c^\dagger_{k\sigma} c_{k\sigma} + \sum_{\sigma} \epsilon_{\mathrm{d}\sigma} d^\dagger_\sigma d_\sigma + U d^\dagger_\uparrow d_\uparrow d^\dagger_\downarrow d_\downarrow + \sum_{k\sigma} (V_{k\sigma} c^\dagger_{k\sigma} d_\sigma + V^*_{k\sigma} d^\dagger_\sigma c_{k\sigma}) + B S^{\mathrm{d}}_z \, . \quad (1)$$

If the leads are ferromagnetic the coupling parameters $V_{k\sigma}$ are spin dependent. In the following we will consider two magnetic configurations: the parallel (P) one with $\Gamma_{\mathrm{L}\sigma} = \Gamma_{\mathrm{R}\sigma}$, and the antiparallel (AP) one with $\Gamma_{\mathrm{L}\sigma} = \Gamma_{\mathrm{R}\overline{\sigma}}$, where $\Gamma_{\mathrm{L(R)}\sigma} = 2\pi \sum_{k\in \mathrm{L(R)}} |V_{k\sigma}|^2 \delta(\omega - \epsilon_{k,\sigma})$. In ferromagnetic materials the exchange interaction in general leads to a difference in the density of states (DOS) ρ_0 and the band width D for electrons with opposite spin orientations. For simplicity we ignore in the following the latter effects. We further restrict ourselves to the limit $U \to \infty$.

For the AP configuration, one can perform a canonical transformation [3], which shows that the Kondo temperature is the same as for nonmagnetic electrodes [1]. In order to investigate the P case we apply "poor man's" scaling techniques [4] which for $D \gg |\epsilon_{\mathrm{d}}|$ should be performed in two stages [5]. Using the Hubbard X-operator notation for the Anderson model [1] one can obtain scaling equations for the spin-dependent impurity level $\epsilon_{\mathrm{d}\sigma}$. From this one finds that apart from a renormalization of the level [5], the spin asymmetry leads to splitting of this level, $\Delta\widetilde{\epsilon}_{\mathrm{d}} = \widetilde{\epsilon}_{\mathrm{d}\uparrow} - \widetilde{\epsilon}_{\mathrm{d}\downarrow}$, which can be found from the scaling equation [6]:

$$\frac{d\Delta\widetilde{\epsilon}_{\mathrm{d}}}{d\ln(D/D_0)} = \frac{\Gamma_\uparrow - \Gamma_\downarrow}{2\pi}. \quad (2)$$

From this one finds: $\Delta\widetilde{\epsilon}_{\mathrm{d}} = (1/\pi) P\Gamma \ln(D/D_0) + \Delta\epsilon_{\mathrm{d}0}$, where $P \equiv (\Gamma_{\alpha\uparrow} - \Gamma_{\alpha\downarrow})/\Gamma$ is spin polarization, $\Gamma =$

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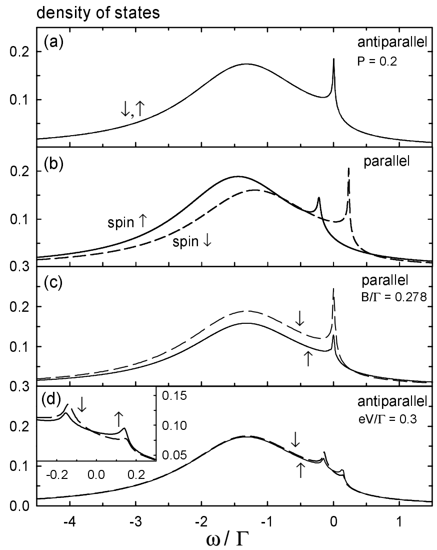

Fig. 1. Spin dependent density of states (solid and dashed lines for majority and minority electrons, respectively) for a QD connected to ferromagnetic leads with the spin polarization $P = 0.2$ for parallel and antiparallel alignments as indicated, and for applied magnetic field (c) and applied bias voltage (nonequilibrium situation) (d). The other parameters are $T/\Gamma = 0.005$ and $\epsilon_{\rm d}/\Gamma = -2$.

$\Gamma_{\alpha\uparrow} + \Gamma_{\alpha\downarrow}$, $\Gamma_\sigma \equiv \sum_\alpha \Gamma_{\alpha\sigma}$, D_0 is the initial value of D, and $\Delta\epsilon_0 = g\mu_B H$ is the Zeeman splitting. The scaling of Eq. (2) is terminated [5] when $\widetilde{D} \sim -\min(\widetilde{\epsilon}_{\rm d\sigma})$.

Then, in the second step, using the Schrieffer-Wolff transformation, one obtains the Kondo Hamiltonian

$$H_{\rm sd} = \sum_{k,k'} \{J_+ S^+ c^\dagger_{k,\downarrow} c_{k',\uparrow} + J_- S^- c^\dagger_{k,\uparrow} c_{k',\downarrow} + S_z (J_{z\uparrow} c^\dagger_{k,\uparrow} c_{k',\uparrow} - J_{z\downarrow} c^\dagger_{k,\downarrow} c_{k',\downarrow})\} + \Delta\widetilde{\epsilon}_{\rm d} S_z \, . \qquad (3)$$

Here $J_\pm$ and $J_{z\sigma}$ depend on the renormalized parameters $\widetilde{D}$ and $\widetilde{\epsilon}_{\rm d\sigma}$. The splitting $\Delta\widetilde{\epsilon}_{\rm d}$ acts like a magnetic field. It thus induces a splitting of the Kondo resonances, which in turn can be compensated by an applied external magnetic field. The resulting scaling equations for the Kondo model,

$$\frac{dJ_\pm}{dL} = \rho_0 J_\pm (J_{z\uparrow} + J_{z\downarrow}) \;\; , \;\; \text{and} \;\; \frac{dJ_{z\sigma}}{dL} = 2\rho_0 J_\pm^2 \qquad (4)$$

have the solution $4J_\pm^2 = (J_{z\uparrow} + J_{z\downarrow})^2 + \text{const.}$, with $L = \ln(D_0/D)$. The difference $J_{z\uparrow} - J_{z\downarrow}$ is constant and does not change in the scaling. It can be considered as small. From Eq. (4) one finds that the characteristic energy scale of the problem for P alignment is $T_K = D_0 \exp[-1/2\rho_0 J_0 \{P/\text{arctanh}(P)\}]$ [6].

The conductance in the unitary limit for P alignment in the compensated case is $G_{\rm P} = 2(e^2/h) 4\Gamma_{\rm L}\Gamma_{\rm R}/(\Gamma_{\rm L} + \Gamma_{\rm R})^2$, so it is the same as in the corresponding nonmagnetic case. For AP alignment, the conductance is reduced following the formula: $G_{\rm AP} = G_{\rm P}(1 - P^2)$.

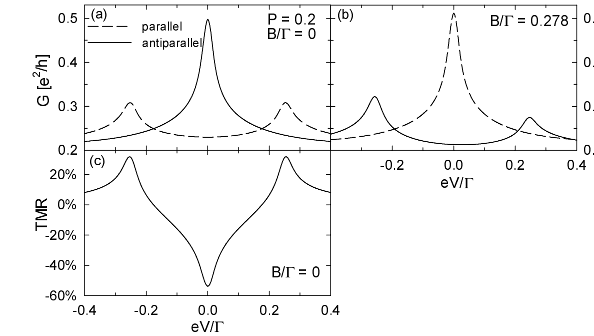

Fig. 2. Differential conductance vs. applied bias voltage at zero magnetic field (a) and at a finite magnetic field (b). Part (c) shows tunnel magneto-resistance ($\text{TMR} = (G_{\rm P} - G_{\rm AP})/G_{\rm AP}$) for the situation from (a).

Next we consider the DOS as well as nonequilibrium transport properties in the frame of a modified EOM approach [6] within which the the level splitting $\Delta\epsilon_{\rm d}$ is calculated self-consistently. In Fig. 1 we plot the density of states for both spin orientations in the AP and P configurations and for $P = 0.2$. We find a splitting of the Kondo resonance for P alignment without external magnetic field. This splitting can be compensated by applying a magnetic field [Fig. 1(c)]. In a nonequilibrium situation, some asymmetry in the Kondo peaks appears in the AP configuration [Fig. 1(d)].

The transport current can be calculated directly from the DOS. The splitting of the Kondo resonances induces a splitting of the zero-bias anomaly for the P configuration already without external magnetic field [Fig. 2(a)]. For the AP configuration in a magnetic field an asymmetry in the peaks is found [Fig. 2(b)]. It is possible to compensate the splitting in the P case. In addition, we find that at zero bias the tunneling magneto resistance significantly exceeds the conventional value ($\text{TMR}(P = 0.2) = P^2/(1 - P^2) = 4.17\%$) and has a negative sign [Fig. 2(c)].

In conclusion, we showed that the Kondo effect in QDs coupled to ferromagnetic leads has qualitatively new features as compared to the situation in a nonmagnetic case. In particular we find a splitting of the resonance for parallel alignment of the lead magnetization already in the absence of a magnetic field.

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