Tunable Kondo Screening in a Qunatum Dot Device

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We consider electron transport along a quantum wire with a single-mode channel which is in contact, via tunnel junctions in its walls, with two quantum dots. Electron tunneling to and from the dots contributes to the electron backscattering, and thus modifies the channel conductance. If the dots carry spin, the channel conductance becomes temperature-dependent due to the Kondo effect. The two-dot device geometry (see Fig. 1) allows for a formation of $S = 1$ localized spin via RKKY interactions, and offers a possibility to study the crossover between fully screened and under-screened Kondo impurity. We show that the crossover may be achieved by tuning the magnetic field applied to the system, and detected in a measurement of the temperature dependence of the channel conductance (see Fig. 2).

We consider the Anderson Hamiltonian of two isolated dots of $s = 1/2$ states coupled to a 1D channel illustrated in Fig. 1. By doing the Schrieffer-Wolff transformation, we obtain the exchange Hamiltonian with the exchange constants $J_i(k, k')$ where $i = 1, 2$ is the dot index:

$$H_{ex} = \sum_{i=1,2} \sum_{\substack{k,k' \\ \sigma,\sigma'}} J_i(k,k') c^{+}_{k\sigma} c_{k'\sigma'} \vec{\sigma}_{\sigma\sigma'} \cdot \vec{S}_i + J_{\mathrm{RKKY}}(R) \left(\vec{S}_1 \cdot \vec{S}_2 \right) \tag{1}$$

$$J_i(k,k') = -\frac{U_i}{\varepsilon_{di}(\varepsilon_{di} + U_i)} V^{*}_{ik} V_{ik'} \tag{2}$$

where the first term represents the exchange interaction between dots (Kondo term) and the 1D channel and the second one represents the indirect exchange interaction between dots (RKKY term) of a distance $R = x_1 - x_2$. In the limit of strong ferromagnetic RKKY interaction, $S = 1$, and the effective exchange Hamiltonian is reduced to the two-channel Kondo Hamiltonian for spin 1 with two exchange constants J_a and J_b:

$$H_{\mathrm{2CKM}} = \sum_{\substack{k,\sigma \\ n=a,b}} \varepsilon_k \psi^{+}_{nk\sigma} \psi_{nk\sigma} + \sum_{\substack{k,k',\sigma,\sigma' \\ n=a,b}} J_n \psi^{+}_{nk\sigma} \psi_{nk'\sigma'} \vec{\sigma}_{\sigma\sigma'} \cdot \vec{S} \tag{3}$$

$$J_{a(b)} = \frac{J^{RR} + J^{LL} \pm 2J^{RL}}{4} \left(1 + \frac{\sin k_F R}{k_F R} \right) + \frac{J^{RR} + J^{LL} \mp 2J^{RL}}{4} \left(1 - \frac{\sin k_F R}{k_F R} \right) \tag{4}$$

where $J^{RR} = J_1(k_F, k_F) = J_2(-k_F, -k_F)$, $J^{LL} = J_1(-k_F, -k_F) = J_2(k_F, k_F)$, $J^{RL} = J_1(k_F, -k_F) = J_2(-k_F, k_F)$ and k_F is the Fermi wavenumber.

Symmetry of the exchange constants (in the absence of a magnetic field) requires the alignment of the positions of the dots but there is no need in a control over the electron wave functions in the dots. This is an advantage over the single-dot geometry considered in the previous works. The asymmetry can be introduced by means of a magnetic field (orbital effect), $J_{LL}J_{RR} - J_{LR}J_{RL} \propto B^2$. Backscattering correction to the ideal conductance is given by $G = G_0 - G_{\mathsf{back}}$ ($G_0 = 2e^2/h$).

In the symmetric state (or in the absence of magnetic fields), the localized spin $S = 1$ is under-screened below a characteristic temperature T_a,

$$G_{\mathsf{back}} = \frac{2e^2}{h}\frac{\pi^2}{2}\frac{1}{\ln^2(T/T_a)}, \quad T \gg T_a \tag{5}$$

$$G_{\mathsf{back}} = \frac{2e^2}{h}\left[1 - \frac{3\pi^2}{16}\frac{1}{\ln^2(T_a/T)}\right], \quad T \ll T_a. \tag{6}$$

The conductance G monotonically decreases with the T lowered. If a small asymmetry is introduced in the presence of magnetic fields, then another (small) energy scale T_b appears, $T_b \propto T_a^{1/\alpha B^2}$, where the parameter α depends on the channel width. If $T_b \ll T_a$, then at the lowest temperatures the spin is fully screened, and

$$G_{\mathsf{back}} = \frac{2e^2}{h}\left(\frac{\pi T}{T_b}\right)^2, \quad T \ll T_b. \tag{7}$$

In the intermediate temperature interval

$$G_{\mathsf{back}} = \frac{2e^2}{h}\frac{3\pi^2}{16}\left[\frac{1}{\ln(T_a/T)} - \frac{1}{\ln(T/T_b)}\right]^2, \quad T_b \ll T \ll T_a, \tag{8}$$

the conductance G reaches a minimum. At higher temperatures, $T \gg T_a$, the difference between the symmetric and non-symmetric models vanishes. Figure 2 schematically summarizes the temperature dependence of the conductance in Eqs. (5)-(8).

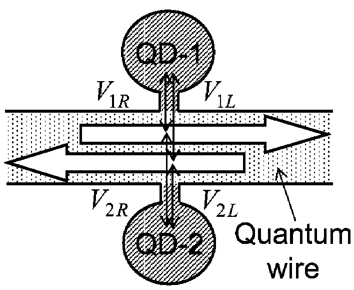

Fig. 1: Two quantum dots (QD-1 and -2) coupled to a quantum wire. $V_{i\alpha}$ is the coupling constants between dot $i = 1, 2$ and the left- or right-moving wave $\alpha = L, R$.

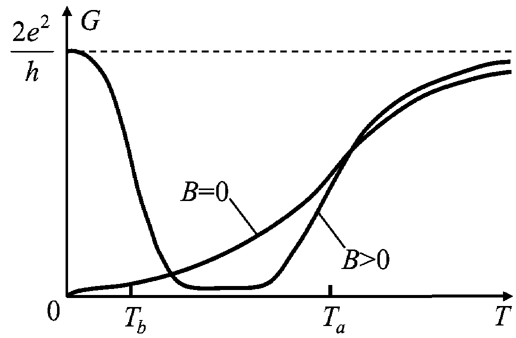

Fig. 2: Schematic dependence of the conductance as a function of temperatures T and magnetic fields B.