Electron transport through a quantum dot in the Kondo regime

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The Kondo effect in electronic transport through quantum dots manifests itself as an increased conductance below the Kondo temperature. Similarly as in alloys with magnetic impurities, the effect is due to formation of the Kondo peak in the density of states (DOS) at the Fermi energy. However, in the case of transport through a quantum dot, the presence of Kondo peak in DOS enhances transmission through the dot leading to almost perfect transmission at zero temperature.

The Kondo effect in a quantum dot strongly coupled to metallic leads has been analyzed theoretically within the non-equilibrium Green function formalism. The quantum dot with one energy level E_0 active in electronic transport is modeled by an Anderson impurity attached to two metallic leads. The system is described by the Hamiltonian $H = H_L + H_R + H_d + H_T$, where the terms H_β ($\beta = L, R$) describe left and right electrodes in non-interacting particle approximation, and H_d describes the dot. Electron interaction on the dot is taken into account via the Hubbard term with the correlation parameter U of arbitrary value. The term H_T describes tunneling processes between the dot and electrodes.

Electric current I flowing through the system (when a bias voltage is applied) is determined by retarded (advanced) $G^{r(a)}$ and lesser $G^{<}$ Green functions, which have been calculated by the equation of motion technique. The key point of the approach is consistency of the approximations used to calculate all the Green functions. In other words, self-energies corresponding to G^r and $G^<$ have been derived from the equation of motion within the same approximation scheme. The Green functions allowed us to derive some generalized formulae for electric current I and occupation numbers n. Electric current and charge accumulated on the dot have been calculated self-consistently. Moreover, the electrostatic potential of the dot has also been calculated self-consistently, which makes the approach gauge invariant [1].

The formalism described above was used to calculate DOS and differential conductance G_{diff} for nonmagnetic as well as ferromagnetic systems. Apart from this, the approach is applicable to systems with the electrodes coupled to the dot symmetrically or asymmetrically. The influence of external magnetic field can be taken into account, too. The calculated equilibrium DOS shows two broad maxima centered at E_0 and $E_0 + U$, and an additional narrow peak at the Fermi energy, which is typical of the Kondo effect [2]. When a bias voltage V is applied the Kondo peak becomes split, and the two peaks with lower intensities are formed at Fermi levels of both electrodes attached to the dot. Both components are separated in energy by eV.

The Kondo peak in DOS gives rise to a peak in G_{diff}. For nonmagnetic and symmetric systems the peak appears in the zero bias regime. Asymmetry in the couplings between the dot and the leads strongly influences the Kondo anomaly in G_{diff}. For highly asymmetric junctions with nonmagnetic electrodes the Kondo peak is shifted into the $V \neq 0$ regime, which is consistent with results obtained within other approaches [3]. When the electrodes are ferromagnetic or when an external magnetic field is applied to a nonmagnetic system, some splitting of the Kondo peak can occur. In such a case the renormalization of the dot level due to interaction of the dot with electrodes should be taken into account and calculated self-consistently [4]. Owing to this renormalization, the equilibrium Kondo peak in the DOS becomes spin-split. The appropriate splitting can be also observed in G_{diff} .

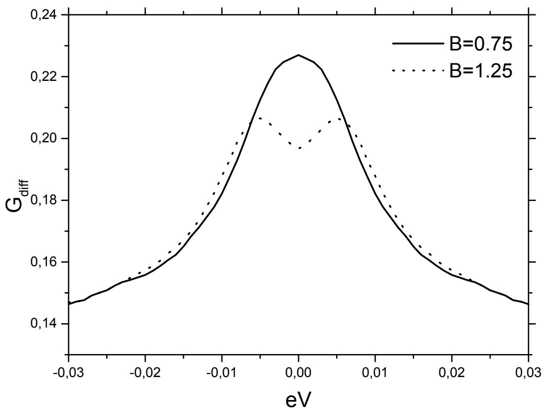

Fig. 1. Differential conductance as a function of bias voltage.

Calculations performed for a nonmagnetic system subject to an external magnetic field show that the splitting of the Kondo resonance can be obtained only for the field *B* higher than the threshold field B_0. Results obtained for two different values of magnetic field $B < B_0$ (solid line) and $B > B_0$ (dashed line) are presented in Fig. 1. The results are consistent with recent experimental data [5] and other theoretical approaches [6]. The magnitude of the Kondo peak splitting at high fields is of the order of $2g\mu_B B$. It is lager than that predicted by other theories [6], and is consistent with recent experimental data [5].

[1] B. Wang et al., J. Appl. Phys. 86, 5094 (1999).
[2] R. Swirkowicz, J. Barnaś, M. Wilczyński, Phys. Rev. B 68, 195318 (2003).
[3] M. Krawiec *et al.*, Phys. Rev. B 66, 165408 (2002).
[4] J. Martinek *et al*, Phys. Rev. Lett. 91, 127203 (2003).
[5] A. Kogan *et al*., cond-mat/0312186v1 (2003).
[6] J.E. Moore *et al*, Phys. Rev. Lett. 85, 172 (2000).

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