

# Kondo effect in quantum dots coupled to ferromagnetic leads

Jan Martinek

*Institut für Theoretische Festkörperphysik, Universität Karlsruhe, 76128 Karlsruhe, Germany*

*Institute for Materials Research, Tohoku University, Sendai 980-8577, Japan*

*Institute of Molecular Physics, Polish Academy of Sciences, 60-179 Poznań, Poland*

*martinek@ifmpan.poznan.pl*

We study the Kondo effect in a quantum dot (QD), which is coupled to ferromagnetic leads, and analyze its properties. The main goal of our work is to investigate how ferromagnetic leads influence the Kondo effect. In the extreme case of half-metallic leads, minority-spin electrons are completely absent, i.e., the screening of the dot spin is not possible, and no Kondo-correlated state can form. What happens, however, for the generic case of partially spin polarized leads (typical situation of most magnetic materials)? How does the spin-asymmetry affect the Kondo effect? Is there still a strong coupling limit, and how are transport properties modified?

Based on a poor man's scaling analysis we first show that a splitting of the Kondo resonance similar to the usual magnetic-field-induced splitting will appear. The most important result is that this splitting can be fully compensated by an appropriately tuned external magnetic field and the strong coupling limit of the Kondo effect can be restored. We found the analytical formulas describing the spin-splitting and the Kondo temperature dependence on the spin polarization for the compensate case. It occurs that the spin-splitting depends linearly on spin polarization, what means that it can be easy compensate. However, the value of the Kondo temperature decreases with increase of the spin polarization and is suppressed to zero for the full spin-polarized system (half-metallic leads).

Moreover, we adapt the NRG method to the case of a QD coupled to ferromagnetic leads. We show that the Kondo effect in the presence of ferromagnetic leads has unique properties such as a strong spin polarization of the density of states (DOS) at the Fermi level, similarly as for ferromagnetic and/or spin-polarized materials. In addition, we find, surprisingly, that even in the presence of strong spin asymmetry in the QD spectral function at the Fermi level, the ground state of the system has a fully compensated local spin and displays Fermi liquid behavior. We also verify that the Friedel sum rule is fulfilled for this system and gives predictions consistent with the ones obtained by NRG. Electronic transport is investigated in the unitary limit at  $T = 0$ , and we find that the system has the same conductance  $G_{\uparrow} = G_{\downarrow} \leq e^2/h$  for each spin channel, despite of the strong spin asymmetry in the spectral density at the Fermi level.

We also analyze within an EOM approach the nonlinear transport through the QD. We find that for parallel alignment of the lead magnetizations the zero-bias anomaly is split. This splitting can be removed by appropriately tuning of a magnetic field. In the antiparallel configuration of the lead magnetizations and symmetric coupling no splitting occurs.

A conceivable realization of proposed system might be carbon nanotubes or other molecular systems in contact to ferromagnetic leads, or magnetic tunnel junctions with magnetic impurities in the barrier.

[1] J. Martinek, Y. Utsumi, H. Imamura, J. Barnas, S. Maekawa, J. König, and G. Schön, cond-mat/0210006.

[2] J. Martinek, M. Sindel, L. Borda, J. Barnas, J. König, G. Schön, and J. von Delft, cond-mat/0304385.