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Tunnel Magnetoresistance in Carbon Nanotube Quantum Dot

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The out-of-equilibrium transport properties of carbon nanotube quantum dot in the Kondo regime are studied by means of the non-equilibrium Green function. The equation of motion method is used. The influence of the polarization of electrodes and orbital level splitting, as well as left-right asymmetry, on the spin polarizations of differential conductance are discussed. For zero bias voltage and orbitally degenerate states the SU(4) symmetry of Kondo state is preserved for antiparallel configuration of polarizations of electrodes, whereas it is broken for parallel. In the former case a suppression of linear conductance with increasing polarization is observed. In the latter the behaviour is nonmonotonic due to splitting of the Kondo peak and bringing closer one of the peaks to the Fermi level with increasing polarization. This gives rise to giant tunnel linear magnetoresistance for large polarization.

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1. Introduction

Spin-depenendent tunnelling through nanostructures has become a very active area of research due to its possible applications in field sensors and disc-drive read heads [1]. In commonly used magnetoresistive devices the ferromagnetic electrodes are used. To control the transport its dependence on the relative orientation of magnetic moments of the leads is exploited. It is already possible to attach ferromagnetic leads to carbon nanotube [2] and a carbon nanotube quantum dot (CNTQD) has been shown to display Kondo physics below an unusually high temperature [3, 4], which offers the prospects for using this effect in practical applications.

The aim of the present paper is to discuss the spin-valve properties of CNTQDs attached to ferromagnetic leads in the Kondo regime. Most drastic changes of magnetoresistance are expected for small values of bias voltage, since differential conductance in this region reflects changes of the Kondo resonance induced by polarization induced symmetry breaking.

It is expected that breaking of spin-orbital SU(4) symmetry of Kondo ground state by polarization of electrodes reflects most spectacularly in small bias tunnel magnetoresistance.

2. Model and formalism

Carbon nanotube quantum dots exhibit fourfold shell structure in the low energy spectrum [5, 6]. In the present considerations we restrict to the single shell and the dot is modelled by an extended double orbital Anderson Hamiltonian with intraorbital U and interorbital Coulomb interaction parameter U_1:

$$\begin{aligned} H = {} & \sum_{k\alpha m\sigma} E_{k\alpha m\sigma} c^{+}_{k\alpha m\sigma} c_{k\alpha m\sigma} + \sum t_{k\alpha m\sigma} (c^{+}_{k\alpha m\sigma} d_{m\sigma} + \text{c.c.}) \\ & + \sum E_{m\sigma} d^{+}_{m\sigma} d_{m\sigma} + \sum_{m} U n_{m+} n_{m-} + \sum_{\sigma\sigma'} U_1 n_{1\sigma} n_{-1\sigma'} . \end{aligned} \tag{1}$$

The energies of orbital states ($m = \pm 1$), corresponding to clockwise and counterclockwise wrapping modes of CNTQD [5, 7] are given by $E_{m\sigma} = E + m\Delta E - \sigma\mu_{\mathrm{B}} h_{\mathrm{SDIPS}}$ ($g = \mu_{\mathrm{B}} = e = 1$), where ΔE is orbital level mismatch, h_{SDIPS} is an effective magnetic field which accounts for the spin dependence of interfacial phase shifts (for the details see [7]) and $\alpha = \mathrm{L}, \mathrm{R}$ labels left and right electrode respectively.

Current flowing through CNTQD can be expressed in terms of the Green functions

$$I_\alpha = \frac{\mathrm{i}e}{\hbar} \int_{-\infty}^{+\infty} \frac{\mathrm{d}\omega}{2\pi} \sum_{m\sigma} \Gamma_{\alpha m\sigma}(\omega) \cdot \{ G^{<}_{m\sigma}(\omega) + f_\alpha(\omega) [G^{\mathrm{R}}_{m\sigma}(\omega) - G^{\mathrm{A}}_{m\sigma}(\omega)] \} \tag{2}$$

where $G^{<}$, G^{R}, G^{A} are lesser, retarded, and advanced Green functions, respectively, f_α is the Fermi function of α lead and $\Gamma_{\alpha m\sigma} = 2\pi |t_{\alpha m\sigma}|^{\rho}_{\alpha m\sigma}$ ($\rho_{\alpha m\sigma}$ is density of states, DOS of the lead). The lesser Green function $G^{<}$ is found using Ng ansatz [8], according to which the lesser self-energy $\Sigma^{<}$ is proportional to the self-energy of the corresponding noninteracting system $\Sigma^{<}(\omega) = A\Sigma^{<}_{0}(\omega)$, and A can be found by the Keldysh requirement $\Sigma^{<} - \Sigma^{>} = \Sigma^{\mathrm{R}} - \Sigma^{\mathrm{A}}$.

Tunnel magnetoresistance is defined as the relative difference of differential conductances ($\mathrm{DC} = \mathrm{d}I/\mathrm{d}V$) for parallel (P) and antiparallel (AP) configurations of polarizations of the leads

$$\mathrm{TMR} = \frac{\mathrm{DC}_{[\mathrm{P}]} - \mathrm{DC}_{[\mathrm{AP}]}}{\mathrm{DC}_{[\mathrm{AP}]}} . \tag{3}$$

3. Results and discussion

We present numerical results for $E = -4$ and the Coulomb parameters $U = 15$ and $U_1 = 12$ ($\Gamma = \sum_{\alpha m\sigma} \Gamma_{\alpha m\sigma}$ is taken as the energy unit). Figure 1 presents the polarization dependence of magnetoresistance for orbitally degenerate states (a) and illustrates an effect of orbital level mismatch (b). Generally, TMR increases with the increase in spin-polarization of the leads. In parallel configuration and strong enough polarization of electrodes the Kondo peak splits due to the broken spin degeneracy, which destroys a local minimum in DC for this configuration. For AP configuration the equilibrium Kondo state preserves spin-orbital symmetry SU(4), but the introduced asymmetry of the leads suppresses Kondo effect. The resulting zero bias peak of DC conductance for P orientation and zero bias dip for AP orientation give rise to the observed giant zero-bias TMR. This effect is observed up to the Kondo temperature ($T_{\mathrm{K}} \approx 0.04$). For a typical value of $\Gamma = 0.5$ meV [6] this gives $T_{\mathrm{K}} = 230$ mK. For orbitally nondegenerate case a dramatic suppression of tunnel magnetoresistance is seen (inset of Fig. 1b). For $\Delta E \neq 0$ a dip of TMR is observed for small bias because due to the broken orbital degeneracy the Kondo peak splits. As a consequence the DC curve for AP configuration has a peak for small bias instead of a dip for $\Delta E = 0$. For large enough level mismatch a rapid change of TMR is observed also for bias voltage VSD $2\Delta E$ due to the interorbital transitions. The oscillations observed in this region reflect transitions between different spin channels.

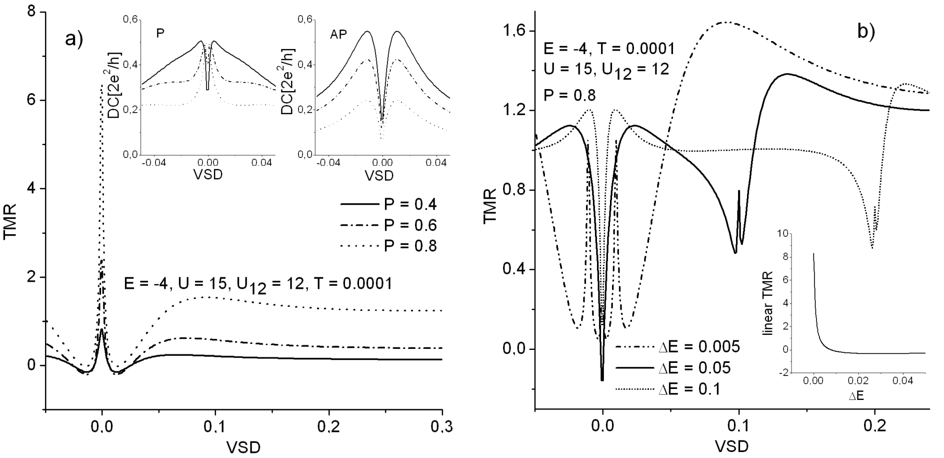

Fig. 1. TMR vs. bias voltage: (a) for different values of polarization of the leads, insets show differential conductance for parallel (P) and antiparallel (AP) configurations, (b) for different orbital level mismatch ΔE, inset shows linear TMR vs. level splitting.

Figure 2 presents the effect of left-right asymmetry. Asymmetric coupling reflects in asymmetric TMR evolution vs. bias voltage. A slight increase in negative TMR is observed with the increase in asymmetry in the region of Kondo induced maximum of DC for AP configuration. Inset of Fig. 2 illustrates the expected effect on TMR of the spin dependent interfacial scattering. Further increase in zero-bias TMR is seen and for VSD $\sim 2h_{\mathrm{SDPIS}}$ the field induced wide satellite peaks emerge.

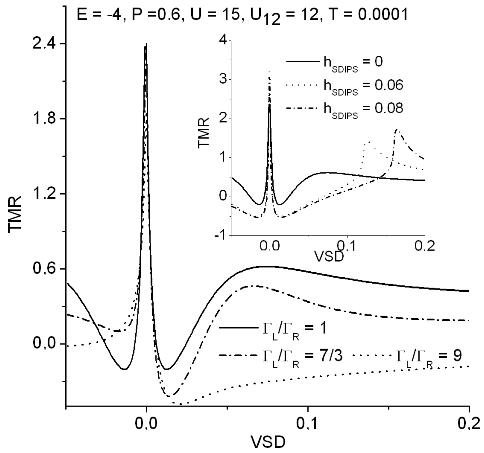

Fig. 2. TMR for asymmetric leads ratios compared with the symmetric case. Inset presents influence of spin dependent interfacial phase shifts represented by effective field (h_{SDPIS}).

To summarize, our calculations point out on the possibility of achieving giant values of tunnel magnetoresistance in carbon nanotube dots in the Kondo range. The effect is very sensitive to the orbital level mismatch.

Acknowledgments

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