Nonlinear thermoelectrics and Kondo effect in quantum dots

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The resistivity of a normal metal is a monotonically decreasing function with lowering temperature. However, when the metal contains magnetic impurities, the resistance reaches a minimum increases at lower temperatures. This anomalous behavior is called Kondo effect [1]. In this case the conductance has a logarithmic dependence on the temperature which takes place at temperatures higher than the Kondo temperature T_K. This complex phenomenon is caused by the highly correlations between the spin electron in the magnetic impurity with the spin density of the electrons in the metal. These interactions screen the magnetic moment of the impurity and creates a many-body singlet between the conducting and the localized electrons. Semiconductor quantum dots (QD) are able to mimic the magnetic impurity with the advantage of the easy tunability of the important parameters of the problem. In fact, QDs have spurred advances experimentally and theoretically. The typical setup in order to study transport consist of two reservoirs (left L and right R) connected to a quantum dot as we can observe in Fig. 1. Each reservoir is characterized by a electrochemical potential μ_α and temperature T_α ($\alpha = \{L, R\}$) and electrons travel from one reservoir to another with amplitude $\mathcal{V}_{\alpha k}$ with k the wavenumber of the electron.

Our aim in this work [2] is to study the Kondo effect in the presence of thermal gradients. In order to cover the whole range of temperature bias we consider three different approaches. First, we consider the perturbation analysis of the Kondo Hamiltonian using the procedure in Ref. [3]. This method allows us to obtain an analytical result of the relation of the Kondo temperature with the thermal bias θ,

$$T_K(\theta) = \sqrt{\left(\frac{\theta}{2}\right)^2 + T_{K0}} - \frac{\theta}{2} \qquad (1)$$

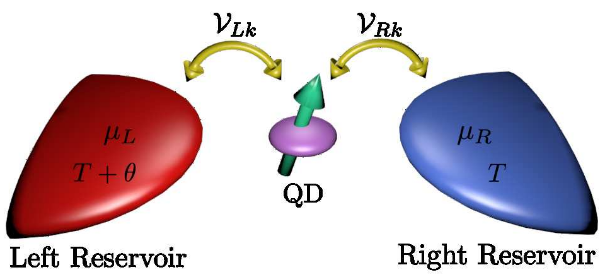

Figure 1: Sketch of the quantum dot system under the influence of a voltage ($\mu_L - \mu_R$) and temperature gradient (θ) applied between the reservoirs. The system consists of two reservoirs connected through tunnel barriers (with tunneling amplitudes $\mathcal{V}_{\alpha k}$) to an interacting quantum dot.

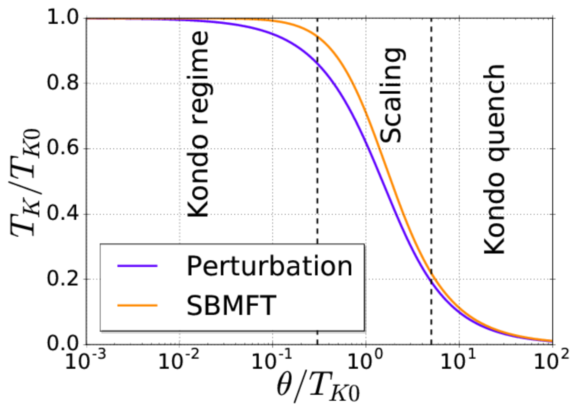

Figure 2: Normalized Kondo temperature T_K/T_{K0} as a function of the thermal gradient θ/T_{K0} applied to the quantum dot system. Blue line corresponds to the perturbative analysis result whereas orange line shows T_K derived from the SBMFT.

where $T_{K0} = T_K(\theta = 0)$. In this expression we identify three different regimes (Fig. 2): The Kondo regime where the Kondo temperature remains approximately constant, the scaling regime where it decreases quickly as the thermal bias increases and the Kondo quench where T_K slowly vanishes. In order to calculate the behavior of the Kondo temperature in the Fermi liquid case (low temperatures), we apply the slave boson mean field theory (SBMFT) to the Anderson Model at large charging energies finding the same qualitative results as in the previous model. In fact, the $T_K(\theta)$ curve shows the same shape even at temperature differences outside the regime of validity (Fig. 2).

Finally, we use the truncated equation-of-motion approach with the nonequilibrium Green's function formalism to analyze the local density of states of the system and to investigate their transport properties. In the voltage-driven case, we obtain the zero bias anomaly at $V = 0$ and different peaks around the electrochemical potentials of the leads. In the thermocurrent, we observe nonlinear transport with non trivial zeros at finite thermal bias θ. These nonlinear zeros are explained by the presence of different peaks in the densisty of states. Our results are relevant for the study of correlated systems driven out of equilibrium with strong thermal gradients.

[1] See, e. g., A. C. Hewson, *The Kondo problem to Heavy Fermions* (Cambridge University Press, Cambridge, 1993).

[2] M. A. Sierra, R. López and D. Sánchez, unpublished (2017)

[3] A. Kaminski, Y. V. Nazarov, and L. I. Glazman, Phys. Rev. B **62**, 8154 (2000).