

KONDO RESONANCE IN A NANOTUBE QUANTUM DOT COUPLED TO A NORMAL AND A SUPERCONDUCTING LEAD

M.R. GRÄBER, T. NUSSBAUMER, W. BELZIG, T. KONTOS and C. SCHÖNENBERGER
Institut für Physik, Universität Basel, Klingelbergstrasse 82, 4056 Basel, Switzerland

We report on electrical transport measurements through a carbon nanotube quantum dot coupled to a normal and a superconducting lead. The ratio of Kondo temperature and superconducting gap T_K/Δ is identified to govern the transport properties of the system. In the case of $T_K < \Delta$ the conductance resonance splits into two resonances at $\pm\Delta$. For the opposite scenario $T_K > \Delta$ the conductance resonance persists, however the conductance is not enhanced compared to the normal state due to a relative asymmetry of the lead-dot couplings. Within this limit the data is in agreement with a simple model of a resonant SN-interface.

Over the last years there has been growing interest in studying electronic correlations and their interplay in mesoscopic systems. Prime examples for such correlations are magnetism and superconductivity. From an experimental point of view carbon nanotubes offer a well-suited platform to investigate such phenomena and test theoretical predictions. Recent advances in nano-fabrication allow the preparation of intermediate-transparent superconducting contacts on carbon nanotube quantum dots allowing the observation of both superconducting and (magnetic) Kondo correlations. The scenario of a quantum dot (QD) in between two superconducting leads was investigated experimentally by Buitelaar *et al.* identifying the ratio of Kondo temperature T_K and superconducting order parameter Δ to govern the interplay of both correlations^{1,2} in agreement with theoretical works^{3,4}. In this article we consider a slightly different setup with a nanotube quantum dot coupled to one superconducting and one normal lead (S-QD-N). This geometry has been studied extensively on a theoretical basis and various predictions such as Δ -sidepeaks, excess Kondo resonances, enhancement or suppression of the conductance have been made^{5,6,7,8}. However, in the normal state the many-particle-phenomenon Kondo effect reduces effectively to a non-interacting resonance for temperatures well below T_K . This gives rise to the question whether this picture is still valid in an S-QD-N geometry. We will thus in the following compare our experimental data with the model of a non-interacting resonance in between a normal and a superconductor as given by Beenakker for the linear response regime and by Khlus *et al.* for a finite bias voltage^{9,10}.

We report on electrical transport measurements through a multi-walled carbon nanotube (MWNT) contacted by short-spaced (300 nm) metal electrodes, thus acting as a quantum dot at low temperatures. The superconducting contact is formed by a 45 nm Au/ 160 nm Al proximity bilayer, the normal one by a 45 nm Au layer. Further experimental details are described elsewhere¹¹. By applying a magnetic field of 25 mT being bigger than the Aluminum critical field but small in terms of the Zeeman shift of the nanotube levels the superconducting electrode is driven into the normal state and the system can be characterized in an N-QD-N configuration. Figure 1(a) shows a greyscale representation of the differential conductance through our device in the normal state at 90 mK. Clear traces of Coulomb blockade diamonds for an even number of electrons on the dot and high-conductive Kondo ridges around zero source-drain voltage in between the diamonds are evident. The Kondo effect occurs when the number of electrons on the dot is odd thus acting as a localized magnetic moment with spin $S=1/2$. Below T_K the spins in the leads try to screen this localized moment by co-tunnelling processes allowed only on a short timescale within the Heisenberg uncertainty principle. This results in a resonance of the linear differential conductance around zero source-drain voltage. The Kondo temperature T_K can be determined from the temperature dependence of the linear differential conductance given by $G(T) = G_0/(1 + (2^{1/s} - 1)(T/T_K)^2)^s$ where $s=0.22$ for a spin 1/2 system¹². A best fit to the data yields 0.3 K and 1.3 K for the ridges labelled “A” and “B”, respectively.

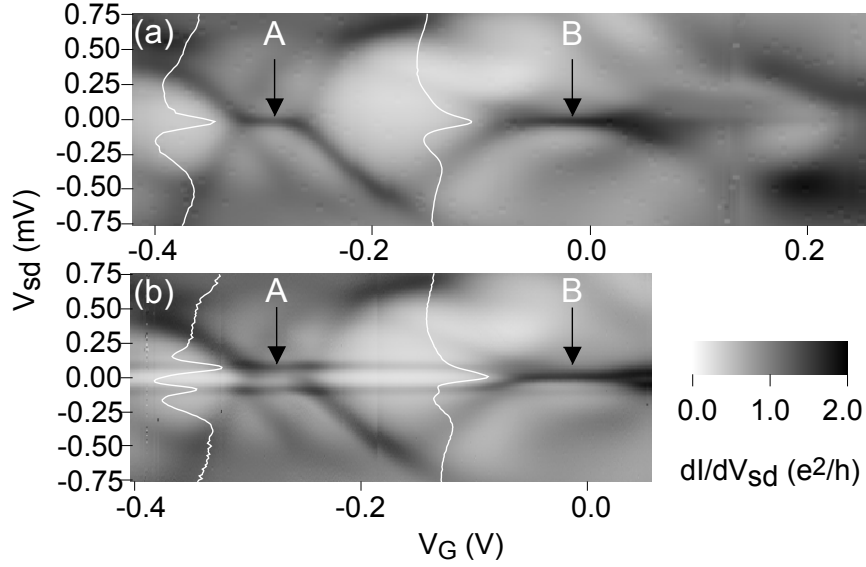


Figure 1: (a) Greyscale representation of the normal state conductance at 90 mK and B=25 mT (dark = more conductive). The white curve on the left (right) shows the differential conductance versus the applied source-drain voltage at the position of the left (right) arrow. The two Kondo ridges are labelled “A” and “B”. (b) Greyscale representation of the conductance in the superconducting state at 90 mK and B=0 mT.

The maximum conductances in the unitary limit $T \ll T_K$ turn out to be $G_{0,A} = 1.54 e^2/h$ and $G_{0,B} = 1.57 e^2/h$.

When one of the two electrodes enters the superconducting state the Kondo effect becomes modified. It was shown for a S-QD-S geometry that the Kondo effect is suppressed by superconductivity when $\Delta > T_K$. In the present setup of an S-QD-N geometry one faces an asymmetric situation with the Kondo processes between normal lead and dot remaining unaffected by the onset of superconductivity. However, this is not the case for the processes between the superconducting electrode and the dot. In figure 2(c) the electronic spectrum of the QD and the leads is depicted. Depending on the ratio Δ/T_K there are two possible scenarios for the superconductor-dot coupling. For $T_K > \Delta$ the Kondo effect is expected to persist since quasiparticle states in the superconducting lead can participate in the Kondo spin flip processes. A natural question to ask now is whether the presence of the superconducting electrode results in an enhancement of the conductance through the quantum dot. Like for any high transmission SN contact one would expect an enhanced conductance of up to $4 e^2/h$ being the maximum conductance of a perfectly-transmitting channel. If, however, $T_K < \Delta$ states around the superconductor chemical potential are missing and the Kondo coupling between the dot and the superconducting lead will be strongly suppressed. Yet a resonance with renormalized $T_K < T_K^*$ persists in the dot local density of states which is pinned to the normal lead chemical potential. Due to the effective lowering of the dot-superconductor coupling in this scenario Andreev reflections become less probable and the conductance resonance at zero source-drain voltage vanishes. On the other hand one expects additional features at $V_{sd} = \pm\Delta/e$, i.e. when the remaining Kondo resonance and the BCS singularities in the density of states are lined up.

Figure 1(b) shows the differential conductance through our device in the superconducting state at T=90 mK and B=0 mT. The magnitude of the superconducting gap can be deduced from the horizontal feature at $eV_{sd} = \Delta \approx 0.09$ meV. The Kondo ridges “A” and “B” thus represent the two cases described above with $T_{K,A}/\Delta \approx 0.3$ and $T_{K,B}/\Delta \approx 1.3$. As expected

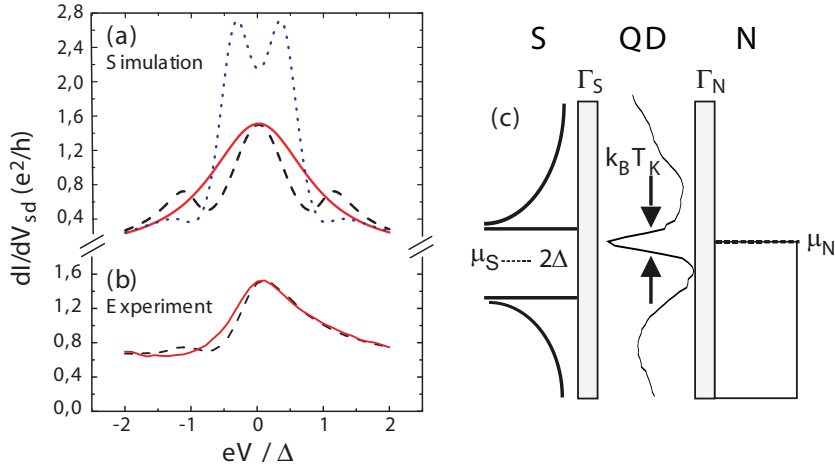


Figure 2: (a) Calculated differential conductance versus source-drain voltage at $T=0.1 \Delta$. The solid curve represents the normal state with $\Gamma_{L/R} = 0.60$ and $\Gamma_{R/L} = 0.37 \cdot 0.6 = 0.22$. The dashed (dotted) curve corresponds to the superconducting state and $\Gamma_{S(N)} = 0.22$ and $\Gamma_{N(S)} = 0.6$. (b) Measured differential conductance at $T=90$ mK in the normal (solid line) and superconducting (dashed line) state at the center of Kondo ridge “B”. (c) Simplified schematics of a quantum dot coupled to a normal and a superconducting lead in the Kondo regime.

for ridge “A” the resonance in the linear differential conductance does not persist but highly conductive features at the position of the superconducting gap are apparent. In contrast to the latter case the conductance resonance at zero bias persists in the superconducting state for ridge “B”. However, besides a small feature at $V_{sd} = -\Delta/e$ the shape and the absolute value remain almost unchanged. When fitting the temperature dependence as described above one obtains a maximum conductance of $G_{0,B} = 1.55 e^2/h$. For the temperature dependence of the measured Kondo conductance resonances we ask the reader to refer to reference¹¹.

The resonance of ridge “B” remains in the superconducting state, but its conductance is not increased. At first sight this behavior seems surprising, since resonances indicate a high effective transmission for which a doubling in conductance is expected in the unitary limit. This, however, only holds for a symmetrically coupled junction. Using the zero temperature expression for the normal state conductance on resonance of a single level $G_0 = (2e^2/h) 4\Gamma_L\Gamma_R/(\Gamma_L + \Gamma_R)^2$, which should hold in the unitary limit, we obtain a relative asymmetry of the lead coupling of $\Gamma_L/\Gamma_R = 0.37$ (or the inverse). Between a normal and a superconducting lead the linear (Andreev) conductance at zero temperature has the form $G_0 = (4e^2/h) [2\Gamma_S\Gamma_N/(\Gamma_S^2 + \Gamma_N^2)]^2$ ⁹. Using the Γ -ratio determined before one obtains for the resonance conductance in the superconducting state $G_0 = 1.69 e^2/h$. This value is only slightly higher than the one in the normal state and the relative asymmetry of the dot-lead coupling therefore explains our experimental observation.

Quite remarkably, extending the picture of a non-interacting resonance in between a normal and a superconductor to finite bias allows us to determine not only the asymmetry of the two couplings Γ_S and Γ_N but also which one of the two dominates. In order to do so we follow the BTK-like approach to NS resonant tunnelling as given by Khlus *et al.*¹⁰. Figure 2(a) shows the results of our simulation where we took finite temperature into account by setting $T=0.1 \Delta$. The solid line represents the normal state conductance resonance for $\Gamma_{L/R} = 0.60$ and $\Gamma_{R/L} = 0.37 \times 0.60 = 0.22$ as obtained from the asymmetry and a rough match of the peak width. The dotted curve represents the resonance in the superconducting state with a stronger coupling to the superconductor, i.e. $\Gamma_S = 0.60$ and $\Gamma_N = 0.22$. In this case the

simulation data show two pronounced conductance resonances at $V \approx \pm\Delta/2e$ with a maximum conductance of approximately $2.7 e^2/h$. The features are smeared out by finite temperature, hence resulting in a linear conductance bigger than the zero-temperature limit $G = 1.69 e^2/h$. The dashed line shows the second possible scenario in which the normal lead has a stronger coupling to the quantum dot, thus $\Gamma_N = 0.60$ and $\Gamma_S = 0.22$. Here the maximum conductance of order $1.6 e^2/h$ is reached in the linear-response regime, while additional structures occur at the position of the gap. Let us now compare the simulation to the experimental data. Figure 2(b) shows the measured differential conductance of ridge “B” at 90 mK plotted versus the applied source-drain voltage for the normal (solid line) and superconducting (dashed line) case. Indeed the calculated conductance assuming a bigger coupling to the normal conductor and the measured conductance agree quite well. Both peak height and the feature at $V = -\Delta/e$ can be reproduced. The corresponding feature for positive source-drain voltages, though, is washed out by the asymmetric shape of the measured Kondo resonance. Yet we are able to conclude that for our sample the normal lead exhibits a better coupling to the dot than the superconducting lead with an asymmetry of $\Gamma_N \approx \Gamma_S/0.37$.

In this article we studied a carbon nanotube quantum dot in the Kondo regime coupled to a normal and a superconductor. In the case of $T_K < \Delta$ the Kondo ridge at zero bias disappears and peaks at the position of the gap occur. In the case $T_K > \Delta$ the Kondo resonance persists but does not show an enhancement of the conductance compared to the normal state which we attribute to an asymmetric coupling of the electrodes. Agreement was found when comparing the data to a simple model of a resonant NS-interface. Future experiments will have to (a) clarify whether the Kondo resonance can actually be enhanced in presence of the superconducting electrode by tuning the coupling asymmetry Γ_S/Γ_N and (b) explore the possibility of generating pairs of entangled electrons by making use of nanotubes coupled to normal and superconducting leads¹³.

Acknowledgments

We thank M. Buitelaar, B. Choi, L. Grueter and S. Sahoo for experimental help and A. Clerk, J. Cuevas, A. Levy Yeyati and P. Recher for discussions. We thank L. Forró for the MWNT material and J. Gobrecht for the oxidized Si substrates. This work has been supported by the Swiss NFS and the NCCR on Nanoscience.

References

1. MR Buitelaar, T Nussbaumer and C Schönenberger *Phys. Rev. Lett.* **89** 256801 (2002)
2. MR Buitelaar *et al.* *Phys. Rev. Lett.* **91** 057005 (2003)
3. MS Choi, M Lee, K Kang, and W Belzig *submitted to Phys. Rev. Lett.*
4. Y Avishai, A Golub and AD Zaikin *Phys. Rev. B* **67** 041301 (2002)
5. JC Cuevas, A Levy Yeyati and A Martín-Rodero *Phys. Rev. B* **63** 094515 (2001)
6. A Clerk, V Ambegaokar and S Hershfield *Phys. Rev. B* **61** 3555 (2000)
7. Q Sun, H Guo and T Lin *Phys. Rev. Lett.* **87** 176601 (2001)
8. R Fazio and R Raimondi *Phys. Rev. Lett.* **80** 2913 (1998)
9. CWJ Beenakker *Phys. Rev. B* **46** 12841 (1992)
10. VA Khlus, AV Dyomin and AL Zazunov *Physica C* **214** 413 (1993)
11. MR Gräber, T Nussbaumer, W Belzig and C Schönenberger *cond-mat/0403431*
12. D Goldhaber-Gordon *et al.* *Phys. Rev. Lett.* **81** 5225 (1998)
13. P Recher and D Loss, *Phys. Rev. B* **65** 165327 (2002); C Bena, S Vishveshwara, L Balents and MPA Fisher *Phys. Rev. Lett.* **89** 037901 (2002); V Bouchiat, N Chtchelkatchev, D Feinberg, GB Lesovik, T Martin and J Torres *Nanotechnology* **14** 77 (2003)