Controlling the magnetic state of a carbon nanotube Josephson junction with the superconducting phase. [1]

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Even though a carbon nanotube is not an intrinsic superconductor, it can sustain a supercurrent provided that it is contacted by superconducting leads. This supercurrent is a periodic function of the superconducting phase $\Delta\varphi$ across the junction. Among all the systems in which such a superconducting proximity effect is possible, carbon nanotubes have the characteristic of being quantum dots, in which it is possible to control the number of electrons with a gate voltage.

This electronic occupancy strongly affects the current-phase relation of a Josephson junction. Indeed, a Cooper pair can easily pass through a dot containing an even number of electrons. But an odd occupancy implies the reversal of the pair and thus a change of the sign of the supercurrent: this is called a π-junction, while 0-junction refers to the situation of an even occupancy. This gate dependent 0- π transition has been extensively studied theoretically and experimentally.

In addition to that, if the dot is oddly occupied, the Kondo effect has to be considered as well. This effect originates from the interaction between a magnetic moment localized (here on the dot) with the delocalized electrons of the contacts and leads to the screening of the ½ spin of the dot. When the contacts are superconducting, provided that the Kondo energy $k_B T_K$ is large enough compared to the superconducting gap Δ, the supercurrent is enhanced thanks to the formation of the Kondo singlet: the 0-junction is recovered while the dot's occupancy is still odd. On the other side, if $\Delta \gg T_K$, the superconducting correlations destroy the Kondo screening, leading to a π-junction behavior [2].

In this work, we are interested in the case of strongest competition between the Kondo and superconducting proximity effects, $k_B T_K \approx \Delta$. Then, it is predicted that the current-phase relation is neither 0 nor π but π around $\Delta\varphi = \pi$ and 0 around $\Delta\varphi = 0$ [3,4].

Until now, this phase dependence of the Kondo screening, and thus of the magnetic moment of the dot, had not been observed experimentally. We report here the measurement of the current-phase relation of a carbon nanotube based Josephson junction all over the 0- π transition, highlighting that the Kondo screening can be controlled by the superconducting phase difference across the junction $\Delta\varphi$ (figure 1). This has been achieved inserting the carbon nanotube in an asymmetric SQUID, where $\Delta\varphi$ is controlled by a magnetic field perpendicular to the sample [5].

An important part of our analyses relies on the comparison between the measured current-phase relations and the one predicted from an Anderson model with superconducting leads and a numerically exact Quantum Monte Carlo method (QMC).

The agreement is excellent, confirming that we measured indeed a transition induced by strong electronic correlations. We extract from these data the critical phase at which the system switches from spin doublet to singlet. Despite the finite temperature of the experiment, we show that we can plot a zero-temperature phase diagram of the system versus $\Delta\varphi$ (figure 2).

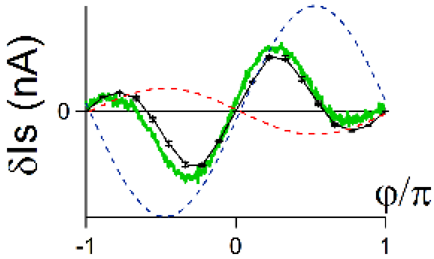

Figure 1: current-phase relation close to the transition (green continuous line), compared to the QMC calculations (black line). The dashed lines are guide to the eyes representing singlet contribution (0-junction, in blue) and doublet contribution (π -junction, in red).

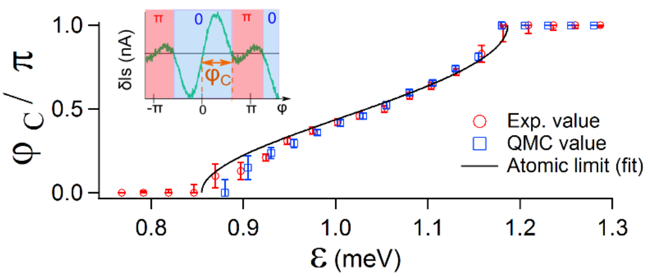

Figure 2: Critical phase (see inset for the definition) versus ε, the energy level of the QD. In red, the experimental values are compared to the one extracted from the QMC calculations (in blue). The black line represents a two parameters fit using the analytical expression obtained in the atomic limit [4], showing the robustness of this phase diagram.

[1] R. Delagrange, D. J. Luitz, R. Weil, A. Kasumov, V. Meden, H. Bouchiat & R. Deblock. Accepted in *Phys. Rev. B*

[2] R. Maurand, T. Meng, E. Bonet, S. Florens, L. Marty and W. Wernsdorfer. *Phys. Rev. X*, **2**, 019901 (2012).

[3] E. Vecino, A. Martin-Rodero, and A. Levy Yeyati. *Phys.Rev*. **B** 68, 035105 (2003).

[4] C. Karrasch, A. Oguri, and V. Meden. *Phys. Rev. B* **77**, 024517 (2008).

[5] J. Basset, R. Delagrange, R. Weil, A. Kasumov, H. Bouchiat, and R. Deblock. *Journal of Applied Physics*, **116**, 024311 (2014).