Kondo phase shift in quantum point-contacts

A quantum point-contact is a very small constriction in a plane of electrons, defined by gate electrodes. At temperatures near absolute zero, in addition to the well-known quantization of its conductance, this device exhibits anomalous features attributed to strong Coulomb interactions between electrons in the constriction. The nature of this correlated electronic state is not yet understood and novel experiments are needed to get new information, in particular to determine the phase of the electron waves exiting from the constriction. This can be done by using the ultra-sharp tip of a Scanning Gate Microscope to create interference effects in these waves.

In quantum mechanics, electron transport through nanometre-scale devices is characterized by transmission and reflection coefficients which are complex numbers, with real and imaginary parts, meaning that not only the modulus contains information, but also the phase. Though the phase is rarely probed in usual electrical transport experiments, it can sometimes be the unique signature of a physical phenomenon. However, measuring the phase of the transmitted electron waves is not trivial. It requires the realization of an interferometer to convert the scattering phase into a change of the conductance magnitude through an interference effect.

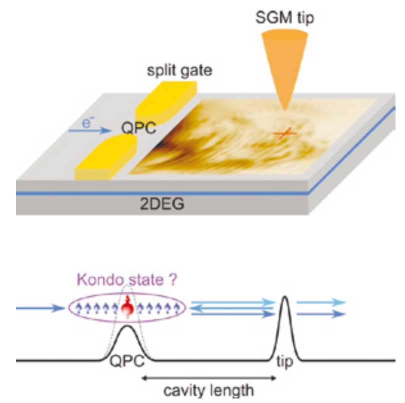

***Fig. 1 (a)**: A metal gate (yellow) with a 300 nm wide split defines a Quantum Point Contact (QPC) between two large reservoirs in a 2-Dimensional Electron Gas (the blue plane) in a GaAs semiconductor device. When a polarized tip (orange) is scanned across the surface, interference fringes appear in a map of the point contact's conductance.*

***(b)**: The tip and the QPC repulsive potentials together form a variable-length, one-dimensional "cavity". The interferences in the cavity are sensitive to the formation of a Kondo cloud of spins around a localized spin situated in the QPC.*

Our quantum point-contact is a 300 nm width x 270 nm length constriction defined in a two-dimensional electron gas by a negatively polarized split-gate electrode (see Fig. 1). This constriction connecting two large electron reservoirs is so narrow that electron waves propagate through it in discrete transverse modes. Each mode can carry current with a quantized conductance of $2e^2/h$. However, this ideal single-particle picture breaks down when the conductance becomes lower than one quantum. An anomalous increase in the non-linear curve of conductance versus the device's source-to-drain bias, the "zero-bias anomaly", appears at very low voltage, see Fig. 2a. In this regime, Coulomb interactions between the very few electrons present in the constriction trigger the formation of a complex many-body state. Its nature is not yet fully understood, but the repulsive interactions are expected to induce localization of one or several electrons within the point contact.

This is propitious for the occurrence of a screening effect first described by Jun Kondo to explain a conductivity anomaly seen in metals containing some magnetic impurity atoms. In our case, electrons of the 2DEG could form a screening "Kondo cloud" of spins around the point-contact, due to their exchange coupling with a localized, unpaired electron spin in the constriction (Fig. 1b). But a clear experimental demonstration of a Kondo effect in quantum point contacts has been missing.

To answer this long-standing question, we did interferometric measurements on a quantum point contact, searching for a particular signature of the Kondo effect, namely its very peculiar phase shift: In the Kondo regime, an electron wave is scattered with a $\pi/2$ phase shift.

We used the ultra-sharp metallic tip of a scanning probe microscope as a local gate to remove all the electrons in a small region of the 2D electron gas at a distance from the constriction (Fig. 1). The electron waves exiting from the quantum point-contact are partly scattered backwards by this depleted region and they interfere with themselves. The resultant change in the device's conductance contains information about the point contact's scattering phase.

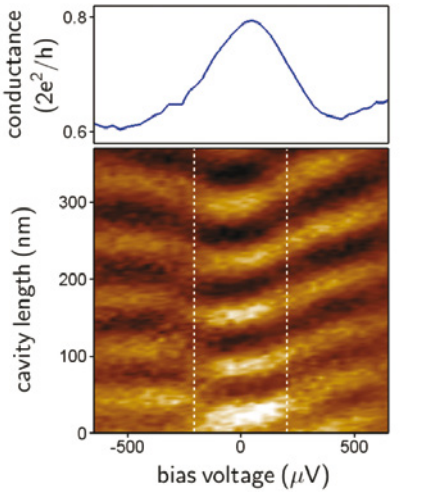

***Fig. 2 (a)**: The zero-bias anomaly at T= 25 mK (an increase in the conductance of the point-contact device as the source-to-drain bias approaches zero).*

***(b)**: The interference fringes, recorded by changing the scanning-tip distance, present a shift in the voltage range (the dotted lines) of the zero-bias anomaly. This shift corresponds to a $\pi/2$ phase shift, consistent with a Kondo effect.*

When we did this experiment at milliKelvin temperature in collaboration with Benoit Hackens at the University Louvain-la-Neuve (Belgium), we observed a clear shift of the interference pattern around zero bias voltage *i.e.* when the ultra-cold electrons travel through the point contact with very small excitation energies (see Fig. 2b). The observed shift corresponds precisely to a $\pi/2$ transmission phase shift, signature of the existence of a Kondo effect for a quantum point contact.

This result confirms the Kondo origin of the QPC zero-bias anomaly, and it illustrates the utility of Scanning Gate Microscopy when other measurements fail to uncover the microscopic origin of quantum phenomena in nanoscale electronic devices.

CONTACT

Hermann SELLIER
hermann.sellier@neel.cnrs.fr

PhD student:
Boris BRUN

FURTHER READING...

"Electron phase shift at the zero-bias anomaly of quantum point contacts"
B. Brun, et al.
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"Viewpoint: Kondo physics in a quantum channel"
R. Aguado
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