Summary of the project

Superconductors continue to be the most versatile and technologically relevant macroscopic quantum coherent systems. Any local perturbation of the superconducting state, such as a Josephson weak link, a vortex or a magnetic impurity, leads to the creation of bound quasiparticle states that are linked to the condensate through Andreev reflection. Andreev bound states have been observed in many systems through tunneling spectroscopy at length scales of order of the superconducting coherence length [1,2,3]. These are mesoscopic quantum states whose energy can be, in principle, modified by means of gate electrodes or by an external magnetic field[1]. Using Andreev states located in different places one could also generate non-local quantum entangled states. For instance, the much discussed topologically protected Majorana fermions proposed for quantum computation [4,5] are nothing but zero energy excitations in topological superconductors which have a similar origin as Andreev bound states. Understanding and controlling Andreev states at a microscopic level is therefore of crucial importance for the progress of this potential technology.

The first direct observation and manipulation of the energy levels of Andreev bound states was made recently in a Josephson junction formed by a carbon nanotube between Al leads [1]. However, the measurement was invasive and there is still no way to study the interaction among spatially separated Andreev states. Here we propose to attack this problem using a non-invasive technique, millikelvin scanning tunneling microscopy and address the interaction between Andreev levels and their surrounding by obtaining vivid images of the quasiparticle states at length scales from the superconducting coherence length down to the Fermi wavelength.

The challenge will be to make atomic scale spectroscopy in systems that include the knob required to manipulate Andreev levels. To this end, we will study Andreev levels around a normal region in a superconductor in two systems, a carbon nanotube Josephson junction across a superconducting thin film and a π-junction in a pnictide superconducting material. We will modify the energy levels by changing the phase across the junction using the magnetic field, and a gate voltage for the carbon nanotube, as knobs. In parallel, we will make a realistic model of these experiments. We will include details of their microscopic electronic structure which were so far left out from the mostly phenomenological approaches used to interpret experimental data.

IFIMAC will benefit from the integration of theory with the available infrastructure for millikelvin tunneling microscopy, establishing the sought internal dialogue among theory and experiment.