Final Report: 291845 DiraCooper

The DiraCooper project's goal was to discover how Dirac electrons in graphene interact with Cooper pairs and quasiparticles in superconductors. It was to be implemented by fabricating and measuring electrical transport in hybrid devices incorporating superconductors and high-quality graphene. Over the course of the Marie Curie fellowship, the project evolved to a much larger scope: performing spectroscopy of quasiparticles and collective excitations in general mesoscopic devices using superconducting circuits. We developed a powerful spectroscopy technique exploiting the microwave emission properties and sensitive detection capabilities of Josephson junctions. Not only can this technique be used to study Dirac electrons in graphene and Cooper pairs in superconductors, but it could also be used to probe other exotic excitations such as Majorana modes.

The initial phase of the project was design, fabrication, and testing of the spectrometer. Afterwards, it was used to measure excitations of Andreev pairs in superconducting atomic contacts. This work was published in *Nature* [1]. During this experiment on atomic contacts, we also realized an alternative spectroscopy technique which gave information on complementary quasiparticle transitions. These results were published in *Physical Review X* [2]. Finally, a theoretical understanding of the various transition rates and decay mechanisms culminated in two publications in *Physical Review B* [3, 4]. A summary of the experimental results are shown in Figure 1a.

More recently, exciting results have been obtained both in development of a second-generation Josephson junction spectrometer (Figure 1b) as well as in the coherent manipulation of Andreev pairs (Figure 1d).

Progress has also been made toward obtaining the high-quality graphene samples for spectroscopy of quasiparticles in graphene at the Dirac point. As a result of the collaboration with Jean-Damien Pillet, postdoctoral researcher in the group of Cory Dean at Columbia University, a sample is ready to be coupled to a Josephson junction spectrometer (Figure 1c).

Finally, the Marie Curie researcher working under my supervision, Ç. Girit, has launched a promising career as an independent researcher. He has been appointed to a permanent position by the French national research agency (CNRS). He has also been selected by an international committee to lead a research group at the Young Team Incubator in the Physics Institute of Collège de France, Paris. This position comes with a startup package including lab space, personnel, and funding. He has also received a French national research grant for young researchers and may soon obtain an ERC Starting Grant. As an independent researcher, he will build a research program centered on Josephson junction spectroscopy of mesoscopic systems.

The Marie Curie fellowship has played a crucial role in the discoveries we have made and in securing a permanent position for Ç. Girit.

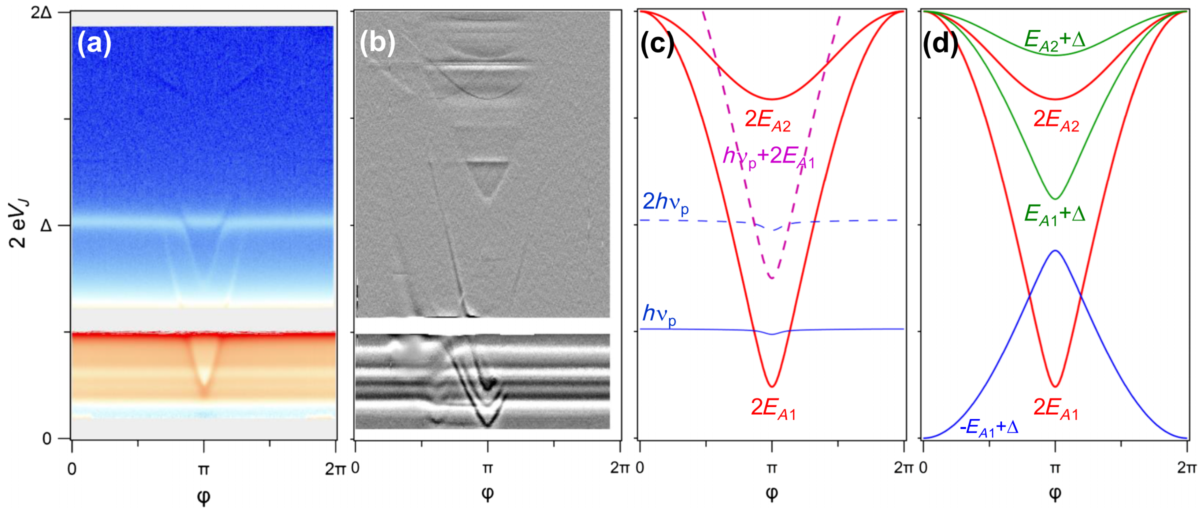
[1] L. Bretheau, C. O. Girit, *et al.* *Nature* 499 (2013), pp. 312–315. DOI: 10.1038/nature12315.

[2] L. Bretheau, Ç. Ö. Girit, *et al.* *Phys. Rev. X* 3 (2013), p. 041034. DOI: 10.1103/PhysRevX.3.041034.

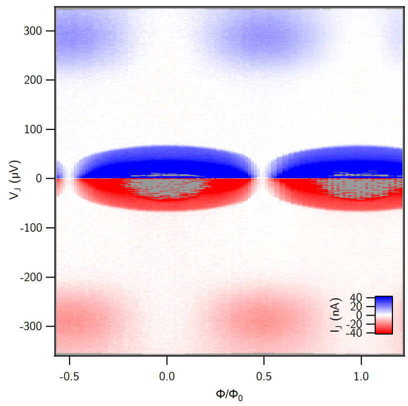
[3] D. G. Olivares, A. Levy Yeyati, *et al.* *Phys. Rev. B* 89 (2014), p. 104504. DOI: 10.1103/PhysRevB.89.104504.

[4] L. Bretheau, Ç. Ö. Girit, *et al.* *Phys. Rev. B* 90 (2014), p. 134506. DOI: 10.1103/PhysRevB.90.134506.

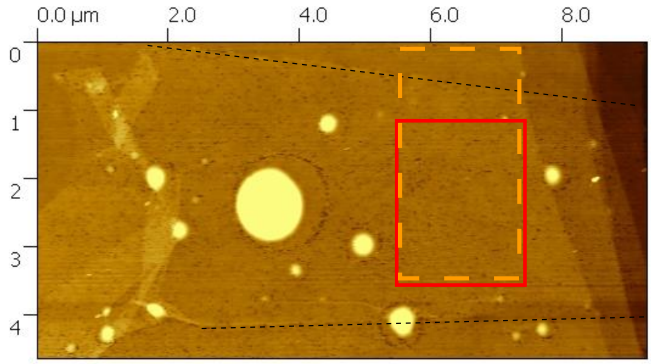
[5] C. Janvier, L. Tosi, *et al.* *ArXiv e-prints* (2014). arXiv:1409.8065 [cond-mat.supr-con].



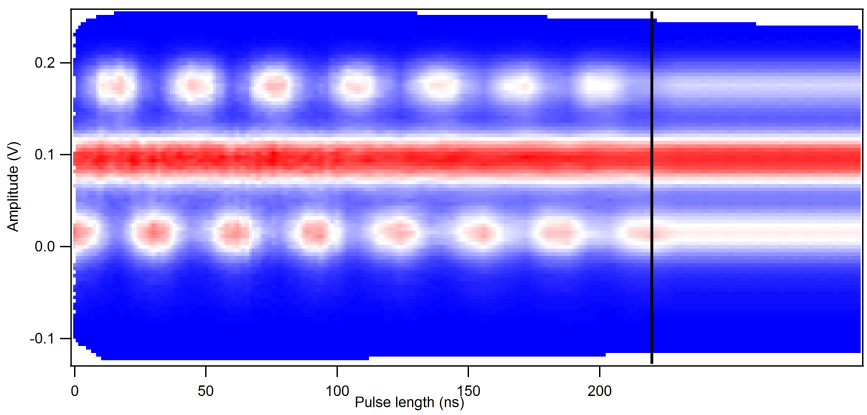
(a) Spectroscopy of Andreev states: experimental data (panels a and b); identification of transitions (panels c and d). Details in [2].



(b) Image plot of background signal of second generation spectrometer. Current, proportional to the photon absorption rate, is plotted as a function of bias voltage, proportional to photon energy, and applied flux, which tunes the output power. The supercurrent response is near zero voltage. The faint red and blue blobs at ±300 µV correspond to a designed electromagnetic resonance in the spectrometer's environment.



(c) Atomic force microscopy image of exfoliated graphene sample transferred onto boron nitride substrate and then covered with boron nitride: a BN/graphene/BN stack. Dimensions of the graphene flake are indicated by black dashed line. Bright white spots are bubbles produced during transfer. Red rectangle corresponds to clean region to be used for capacitive coupling to spectrometer.



(d) Coherent manipulation of Andreev states for a single conduction channel in a superconducting atomic contact. An external microwave field drives Rabi oscillations between ground (lower blobs) and excited (upper blobs) Andreev bound state.