Quantum transport in hybrid normal-superconductor nanostructures

The quantum mechanical character of electronic transport can be accessed in nanoscale systems at low temperatures, typically below 1 K. Quantum behavior is of particular relevance in hybrid nanostructures, which are realized by putting into contact materials whose transport properties are different in nature, such as superconductors and normal metals (or semiconductors). While in the latter transport is due to essentially independent electrons, in superconductors electrons find themselves in a collective quantum state which yields transport without dissipation (supercurrent). In normal-superconductor hybrid nanostructures some superconducting properties are induced in the normal material giving rise to a large variety of phenomena, the most celebrated one being the Josephson effect. Our efforts in this field are directed both to experimental and theoretical aspects and comprise different issues such as spin-dependent effects, Josephson nanodevices and the characterization of entanglement.*

Fabio Taddei

f.taddei@sns.it

Collaborators
F. Beltram
P. D'Amico
F. Dolcini
R. Fazio
C. P. García
F. Giazotto
S. Pugnetti
J. Splettstoesser
S. Tirelli

Spin-dependent properties, which are at the basis of spintronics devices, can be observed in hybrid systems. In this context we have analyzed the spin-dependent transport properties in systems composed of a normal region tunnel coupled to two superconductors with exchange fields induced by the proximity to thin ferromagnetic layers [1]. We have demonstrated that the quasiparticle distribution functions in the normal region depend on spin and are strongly sensitive to the relative angle between exchange fields in the two superconductors. As a result, the electric current flowing through the system is found to be strongly dependent on the relative angle between exchange fields, giving rise to a huge value of magnetoresistance. By tunnel coupling the normal region to an additional superconducting electrode, we have shown that it is possible to implement a spin-polarized current source of both spin species, depending on the bias voltages applied. Extraordinary large tunnel magnetoresistance, as large as 10^6%, could be also obtained in a superconducting double spin valve device which takes advantage of the interplay between the spin-filtering effect of ferromagnetic insulators and superconductivity-induced out-of-equilibrium transport [2]. Importantly, magnetoresistance can be tuned over several orders of magnitude under voltage biasing. Furthermore we have investigated the spin-polarized transport in normal metal–superconductor (NS) junctions as a function of interface transmissivity as well as temperature when the density of states of a superconductor is Zeeman-split in response to an exchange field [3]. Similarly to the "absolute spin-valve effect" predicted in Ref. [4], we have shown that NS junctions can be used to generate highly spin-polarized currents, in alternative to half-metallic ferromagnets. In particular, the spin-polarized current obtained is largely tunable in magnitude and sign by acting on bias voltage (Fig. 1). The effect can be enhanced by electron "cooling" provided by the superconducting gap.

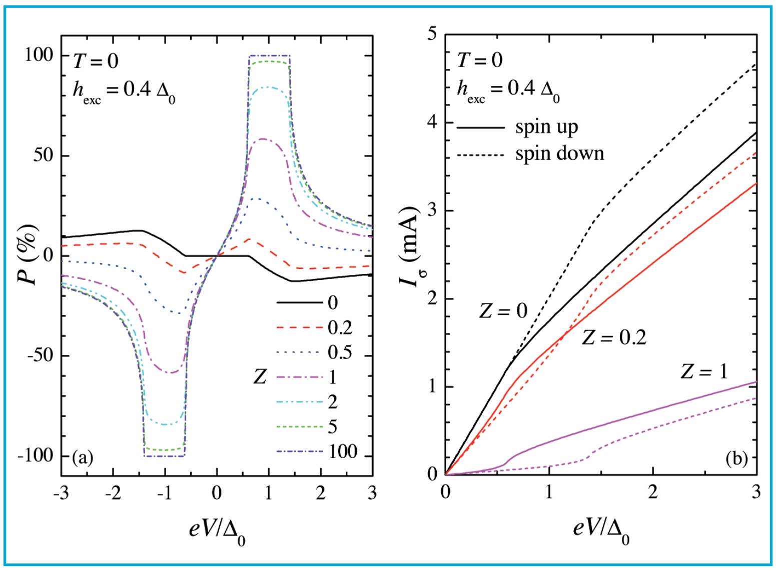


Fig. 1.
(a) Current polarization P vs bias voltage V for several values of interface transmissivity Z at T=0. (b) Spin-dependent electric current I_s vs V calculated for some Z values at T=0.

Another topic attracting a growing interest in the field of hybrid systems is the one concerning Josephson devices in which of interest is the supercurrent flowing between two superconducting regions separated by a weak link. On the theoretical side, we have demonstrated that when the weak link consists of a normal ballistic Aharonov-Bohm ring one can realize a fully controllable Josephson π-junction [5]: both the magnitude and the sign of the supercurrent can be tuned by the combined use of the magnetic flux threading the ring and the electrostatic gate located in one of the ring arms (Fig. 2). Estimates of the supercurrent for realistic implementations using InGaAs rings coupled to Nb electrodes lead to values of hundreds of nanoamperes, allowing to envisage this system as a promising realization of Josephson transistors. When the weak link is a single-walled metallic carbon nanotube we have analyzed the effects of the electron–electron interactions on the supercurrent within the Luttinger liquid theory [6]. We have found that in the long junction limit the strong electronic correlations of the nanotube, together with its peculiar band structure, induce oscillations in the critical current as a function of the junction length and/or the nanotube electron filling. These oscillations represent a signature of the Luttinger liquid physics of the nanotube, for they are absent if the interaction is vanishing. This effect can be exploited to reverse the sign of the supercurrent, realizing a tunable π-junction. Out-of-equilibrium current has been investigated in the case where the weak link consists of a quantum dot. In particular, we have analyzed the effects of both Rashba and Dresselhaus spin-orbit couplings of the dot on the current-voltage characteristics, in the regime of strong dot-lead coupling [7]. The multiple Andreev reflection (MAR) subgap peaks are found to be modified, but not suppressed, by the spin-orbit interaction in a way that it strongly depends on the shape of the dot confining potential. In an isotropic dot

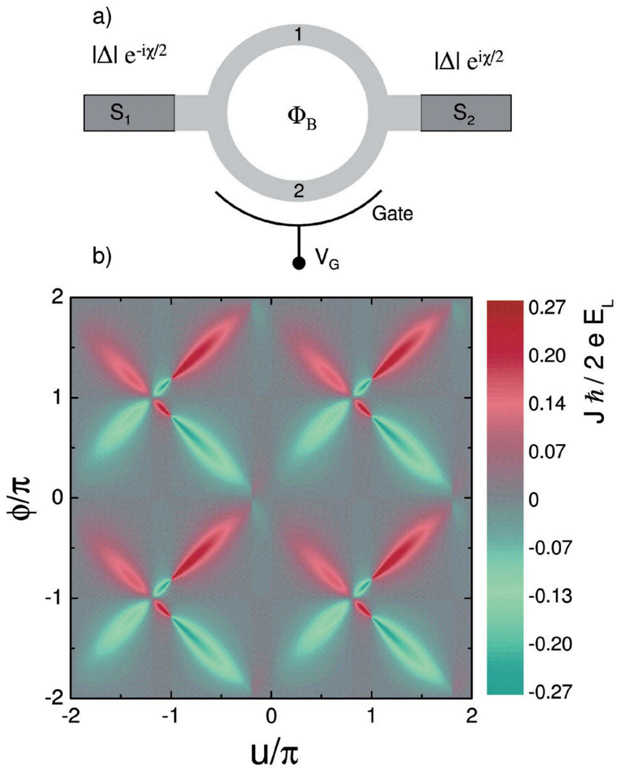


Fig. 2.
(a) Scheme of the Aharonov-Bohm Josephson junction. The light gray region indicates the normal metal ring, whereas dark green regions denote the superconducting leads. (b) Josephson current (in arbitrary units) as a function of gate voltage $u=eV_G/E_L$ and normalized magnetic flux f, for a ring of 600nm long arms (E_L is the Thouless energy). Both magnitude and sign of the Josephson current can be tuned.

the MAR peaks are enhanced when the strength of Rashba and Dresselhaus terms are equal. In contrast, when the anisotropy of the dot confining potential increases, the dependence of the subgap structure on the Rashba-to-Dresselhaus spin-orbit angle decreases. Remarkably we have found that, when an in-plane magnetic field is applied to a strongly anisotropic dot, the peaks of the nonlinear conductance *G* oscillate as a function of the magnetic-field angle. This allows for a straightforward read-out of the spin-orbit angle through the location of maxima and minima of *G*. Regarding Josephson devices, we have conducted experimental investigation on two different nanosystems. The first one is a radiation detector based on a long superconductor-normal metal-superconductor Josephson junction [8]. The operation of this proximity Josephson sensor relies on large kinetic inductance variations under irradiation due to the exponential temperature dependence of the critical current. Coupled with a dc superconducting quantum interference device readout, the device is able to provide a signal to noise ratio up to 1000 in the terahertz regime if operated as calorimeter, while very low electrical noise equivalent power at 200 mK can be achieved in the bolometer operation. The high performance together with the ease of fabrication make this structure attractive as an ultrasensitive cryogenic detector of terahertz electromagnetic radiation. The second system [9] consists of a planar V/Cu/V nanoscopic Josephson weak link (see Fig. 3). We have analyzed the low-temperature behavior of junctions of different length. The shorter junctions exhibit critical currents of several tens of microamperes at 350 mK, while Josephson coupling persists up to ~2.7 K. Good agreement is obtained by comparing the measured switching currents to a model which holds in the diffusive regime. Our results demonstrate that V is an excellent candidate for the implementation of superconducting nanodevices operating at a few kelvins.

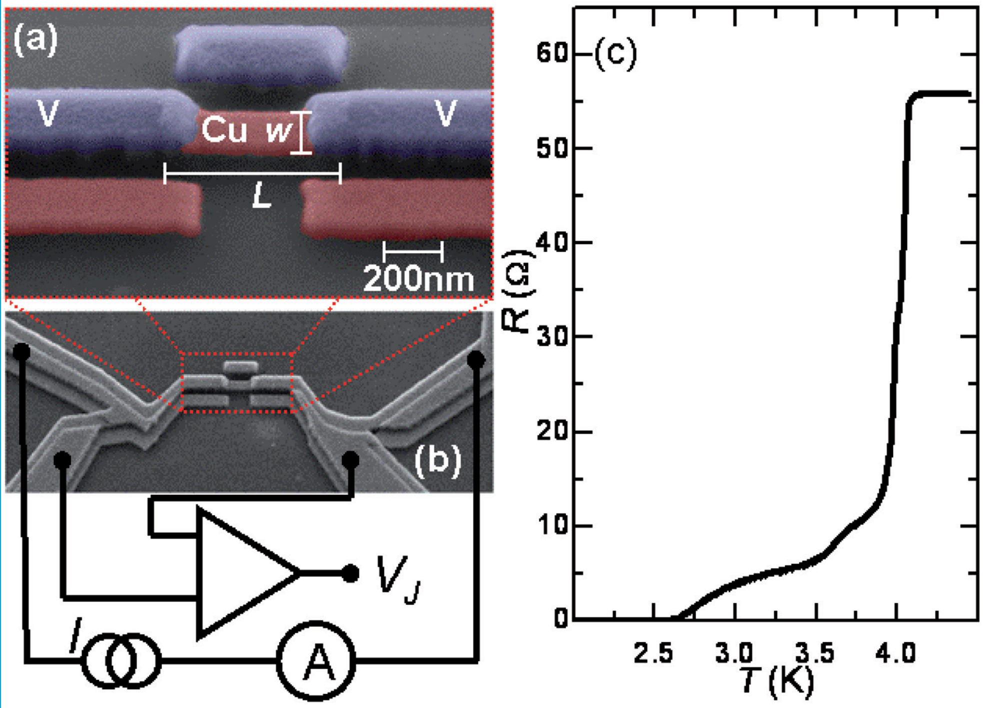
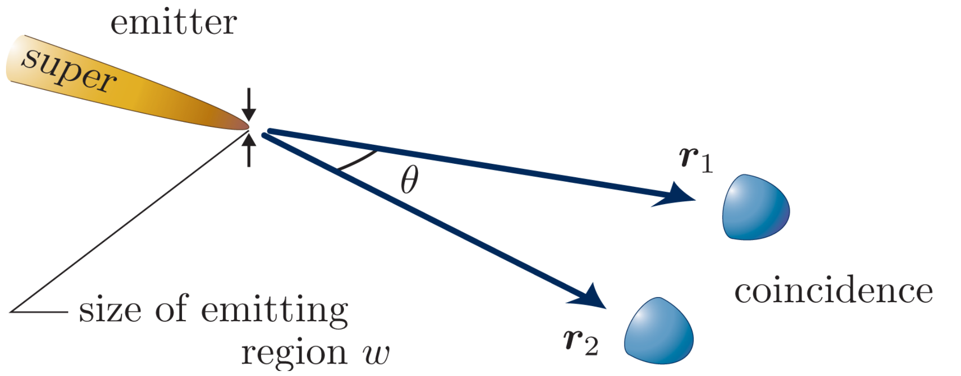


Fig. 3.
(a) Scanning electron micrograph showing the blowup of a V/Cu/V weak link in a typical device. (b) Sketch of the measurement setup. (c) Zero-bias resistance vs temperature for one of the samples.

Finally, we have investigated the entanglement of electrons field-emitted from a superconducting tip into vacuum [10]. We have analyzed the nonlocal correlations by studying the coincidences of the field-emitted electrons (see Fig. 4) taking into account the interplay between the bosonic nature of Cooper pairs and the fermionic nature of electrons. By orienting the detectors in opposite directions, we have shown that one can optimize the fraction of entangled electrons in order to perform a test of Bell's inequality.

Fig. 4.
(a) Field emission of electrons and coincident detections. The size of the emitting region at the tip is w, and two of the emitted electrons are detected at r_1 and r_2.



References

[1] F. Giazotto, F. Taddei, P. D'Amico, R. Fazio, F. Beltram, Phys. Rev. B 76, 184518 (2007).
[2] F. Giazotto, Appl. Phys. Lett. 95, 042503 (2009)
[3] F. Giazotto, F. Taddei, Phys. Rev. B 77, 132501 (2008).
[4] D. Huertas-Hernando, Yu. V. Nazarov, W. Belzig, Phys. Rev. Lett. 88, 047003 (2002).
[5] F. Dolcini, F. Giazotto, Phys. Rev. B 75, 140511(R) (2007).
[6] S. Pugnetti, F. Dolcini, R. Fazio, Solid State Commun. 144, 551 (2007).
[7] F. Dolcini, L. Dell'Anna, Phys. Rev. B 78, 024518 (2008).
[8] F. Giazotto, T. T. Heikkilä, G. P. Pepe, P. Helistö, A. Luukanen, J. P. Pekola, Appl. Phys. Lett. 92, 162507 (2008).
[9] C. Pascual Garcia, F. Giazotto, Appl. Phys. Lett. 94, 132508 (2009).
[10] K. Yuasa, P. Facchi, R. Fazio, H. Nakazato, I. Ohba, S. Pascazio, S. Tasaki, Phys. Rev. B 79, 180503 (2009).