Quantum properties of hybrid and superconducting structures

In high critical temperature superconductors (HTS), and in general in complex oxides, electrons self-organize in ways qualitatively different from those of conventional metals and insulators, possibly generating unconventional phase transitions and novel forms of nanoscale ordering and quantum coherence. It is apparent that transport studies of nanoscale devices can be instrumental in clarifying the nature of the ground state, and to yield novel insights on dissipation and coherence in superconducting strongly correlated systems .
Here we report on robust macroscopic quantum behaviour in YBaCuO nanoscale junctions and rings, which also represent on a longer time scale the basic cell for novel superconducting/hybrid devices for solid state qubit architectures.

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An intense research activity has been focussed on the study of mesoscopic and macroscopic quantum properties in high critical temperature superconductor (HTS) junctions and nanostructures. The recent experiments on macroscopic quantum (MQ) effects in high critical temperature superconductor (HTS) junctions represent another significant step towards a Josephson platform, where important device functionalities are not anymore precluded to HTS junctions. The expected intrinsic limits due to dissipation and to still not completely identified low energy quasi-particles, have now to be reconsidered. Dissipation and coherence in unconventional d-wave systems with low energy quasi-particles on one hand, and nanoscale ordering on the other are the challenging objectives motivating these activities.
Nanoscale ordering and phase transition in complex oxides including HTS, where the electrons self-organize in ways qualitatively different from those of conventional metals and insulators, is one of the most outstanding problems in physics today. Strongly interacting electrons in the complex oxides have propensity to microscopically phase separate and to self-organize in patterns of lower dimension, and establish phase coherence between domains. This self assembly of electrons happens at a length scale of a few nanometers, with typical examples including the stripe ordering in HTS. It is apparent that transport studies of nanoscale devices can be instrumental in discerning the nature of the ground state. The physics of superconductivity in structures with reduced dimensions is very intriguing and still unsettled, touching interesting arguments as quantum suppression of superconductivity in nanowires, the phase diagram of the superconductor-insulator transition, the dissipative dynamics induced by phase slips mechanism and, in perspective, the possibility of controlling the state — superconducting or insulating — of a nanowire by changing its environment.
Studies on quantum properties of Josephson junctions respond to the wide-spread need of expanding quantum technologies and in particular of developing quantum computation. In solid state qubit architectures, superconducting junctions can be considered as "atoms with wires", which display energy-level quantization and strongly interact with electromagnetic environment. Hybrid systems encompassing superconductors, ultra-cold atoms degenerate gases,… seem to be the key for future quantum computer generations. HTS can offer specific qubit functionalities and unique read out protocols, and promote significant advances in the study of macroscopic quantum effects, coherence and dissipation in solid state systems.
We have realized various experiments on different systems, ranging from

high quality YBaCuO biepitaxial grain boundary junctions and nano-structures [1,2,3,4,5] to HTS superlattices [6,7] and low critical temperature superconductor hybrid structures [8] and we have benefited of international collaborations such as Chalmers University of Technology and IBM-Yorktown Heights/Stanford. Low-noise quantum measurements have been realized down to a few tenths of milliKelvin in the new low temperature facility developed at SUN/Napoli, being most of the samples designed and fabricated within CNR-INFM, SUN/Napoli and Pisa.

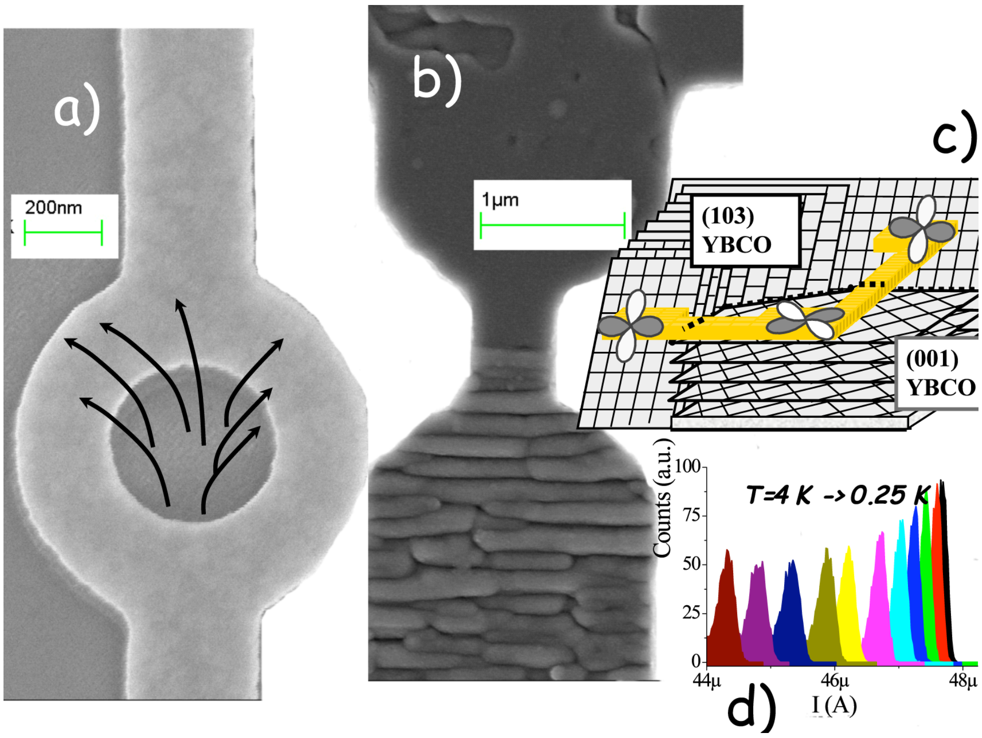

Fig. 1
a) Scanning Electron Microscopy (SEM) image of a c-axis YBaCuO nano-ring. b) SEM image of a YBaCuO grain boundary biepitaxial Josephson junction; the top electrode is oriented along the (001) direction and grows on a CeO_2 seed layer, while the bottom one is oriented along the (103) direction, respectively. The junction is schematized in c), along with the d-wave order parameter symmetry profile. By suitably patterning the seed layer, and as a consequence the interface grain boundary, junctions properties can be tailored and controlled by taking advantage of anisotropic d-wave superconductivity. d) Switching current probability distribution as a function of bias current at different temperatures for a YBaCuO grain boundary biepitaxial Josephson junction. These measurements are the basis for the study of macroscopic quantum properties in Josephson junctions.

YBaCuO grain boundary biepitaxial junctions, for instance, are among the best available junctions. They are characterized by atomically flat grain boundary barriers [1], which have already allowed challenging experiments such as those on macroscopic quantum effects [2,4,1], on mesoscopic coherence [3], and are driving novel efforts. We have proved phase-coherent electronic transport in HTS grain boundary junctions incorporating superconducting correlations and resulting in a combination of Universal Conductance Fluctuations and Andreev reflection. Results on the first sub-micron junctions indicate improved reproducibility and features, which point to more uniform and tunnel-like barriers. This is a significant step in view of the ultimate limit of grain boundary nanostructures, which is further supported by the realization of high quality YBCO nanowires of minimum width of 100 nm. They have shown excellent superconducting properties and intriguing collective behaviours [5].

We have realized one among the very first Little-Parks experiment on single HTS nano-rings, with evidence of non uniform vorticity [10]. This is the basic structure also for Aharonov-Bohm –like experiments in nano-structures in the underdoped regime, which are expected to shed light on the prominent categories of high-Tc models (preformed pairing, spin-charge separation, Bose condensation,…) by the direct measurement of the charge [11].

Hints on a fermionic scenario in Metal-Insulator Transition in HTS have been achieved through the direct measurement of sheet resistance in superlattices and ultra-thin films with thickness down to 1 nm [6]. These ultra-thin film offer ideal conditions to investigate vortex quantum tunnelling phenomena and quantum phase transitions because of the extremely long extension of Pearl vortices [7,6].

In conclusion HTS nano-devices are the key for junctions with superior performances and reproducibility, for one dimensional YBaCuO wires, single electron transistors, nano-SQUIDs, relevant targets in view of a broader vision of integrated quantum electronics, and for future experiments based on the d-wave symmetry at the nanoscale.

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