Thermal properties at the nanoscale: cooling and nonequilibrium

The understanding and the control of thermal properties is an interesting issue in nanoscale systems [1]. Due to their reduced sizes, out-of-equilibrium conditions can be reached and exploited once the energy relaxation mechanisms are under control. In this context electron cooling realized through electrostatic means is probably one of the most relevant aspects. The prototype refrigeration scheme, operating around or below 1K, is based on superconductors, which are characterized by a poor thermal conductivity in a well-defined energy widow. This yielded substantial electron temperature reduction in metallic nanostructures. Our research interests in this field comprise both experimental and theoretical activities and focussed on different aspects: novel refrigeration schemes, manipulation of out-of-equilibrium conditions, study of relaxation mechanisms, and study of thermal transport properties in the presence of superconducting correlations.

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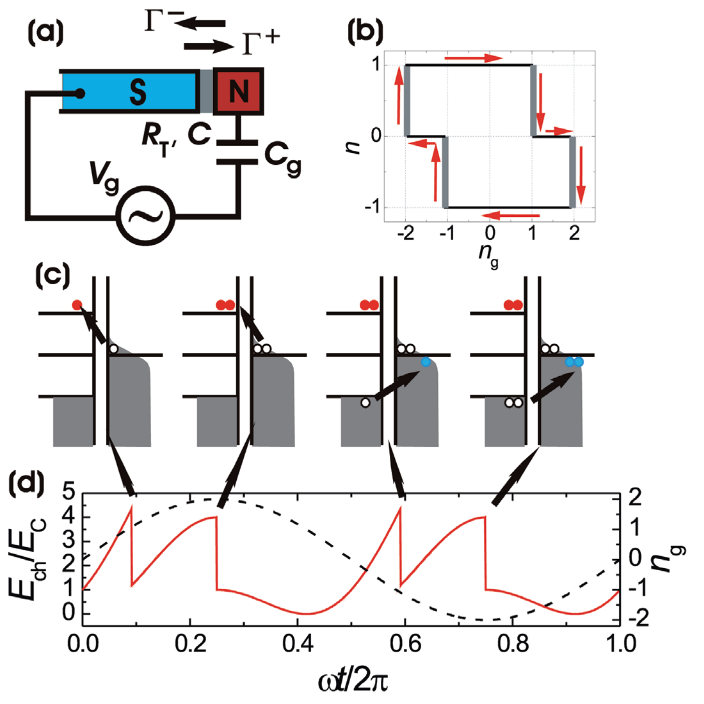
Several important open questions concerning the cooling scheme based on superconductors have been addressed. On the experimental side, in the first instance we have proposed a cyclic refrigeration principle [2] which uses the sequential tunneling of electrons in a Coulomb-blockaded normal metal-superconductor single electron box (see Fig. 1). This results in a cooling power of about $k_B T \times f$ at temperature T over a wide range of cycle frequencies f. Electrostatic work, done by the gate voltage source, removes heat from the Coulomb island with an efficiency of about $k_B T/\Delta$, where Δ is the superconducting gap parameter. The performance is not affected significantly by nonidealities, for instance by offset charges. Secondly, we have conducted experiments [3] on a superconductor–normal-metal electron refrigerator in a regime where single-electron charging effects are significant. The system functions as a heat transistor; i.e., the heat flux out from the normal-metal island can be controlled with a gate voltage. A theoretical model developed within the framework of single-electron tunneling provides a full quantitative agreement with the experiment. This work serves as the first experimental observation of Coulombic control of heat transfer and, in particular, of refrigeration in a mesoscopic system.

On the theoretical side, we have analyzed the influence of an ac drive on heat transport in a hybrid normal metal-superconductor tunnel junction in the photon-assisted tunneling regime [4]. We have found that the useful heat flux out of the normal metal is always reduced as compared to its magnitude under static and quasi-static drive conditions. Our results are useful to predict the operative conditions for ac-driven superconducting electron refrigerators. Furthermore, we have proposed two novel refrigeration schemes. The first one starts from the consideration that when the cooling mechanism is based on a superconductor,

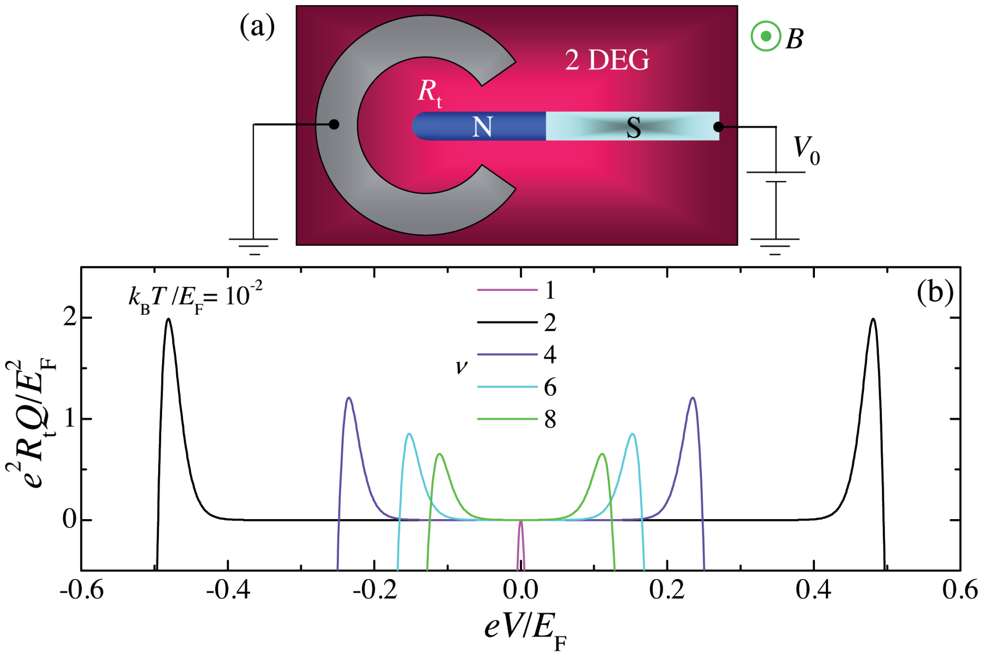
Fig. 1.
(a) Single-electron box with a normal metal (N) island and a superconducting (S) lead. (b) The trajectory on the (n, n_g) plane for the cycle discussed here. (c) Sketch of energy band diagrams of the device showing the tunneling processes in this cycle. (d) The charging energy of the system (solid line, left scale), where discontinuities are observed as electrons tunnel. The gate cycle is shown by the dashed line (right scale).



the cooling power at a given temperature is essentially determined by the value of the superconducting gap, which is fixed by the choice of the metal. Tunable gaps would be highly desirable in view of scalable applications. Motivated by this goal, we have proposed [5] a novel mechanism for refrigeration, based on *Landau-level quantization* (see Fig. 2). Analyzing thermal transport in two-dimensional electron gases (2DEGs) we have been able to show that heat can be efficiently extracted from a metallic nanostructure, thanks to the peculiar *bulk* DOS originating from Landau quantization. We find a large heat current through the system (about 10^{-9} W) yielding a sizable electron cooling also at bath temperatures as high as a few kelvin. Moreover, the possibility to easily set the magnetic field value makes it possible to finely tune and optimize the performance available with this refrigeration principle under different operational conditions. As a further alternative refrigeration schemes, we have reconsidered a cooling principle, originally proposed in the 1930s but mostly unexploited so far, which is based on the adiabatic magnetization of a superconductor. We have presented [6] a detailed dynamic description of the effect, computing the achievable final temperatures as well as the process time scales for different superconductors in various regimes. We have shown that, although in the experimental conditions explored so far the method is in fact inefficient, a suitable choice of initial temperatures and metals can lead to unexpectedly large cooling effect, even in the presence of dissipative phenomena. Our results suggest that this principle can be re-envisaged today as a performing refrigeration method to access the µK regime.

The understanding and manipulation of out-of-equilibrium conditions and their relation to heat dynamics in nanostructures is an important part of our research activity. In this direction we have performed several experiments. On the one hand, we have demonstrated [7] that manipulation of a Josephson current and its generation at temperatures above the critical one can be achieved by varying quasiparticle injection into a small superconducting Ti island tunnel coupled to four Al superconducting electrodes (see Fig. 3). Our results are successfully described within a model

Fig. 2.
(a) A normal metal island (N) is tunnel coupled to a 2DEG in an open pseudo Corbino disk geometry in the presence of a quantizing magnetic field. Grey region represents an ohmic contact to the 2DEG. (b) Heat current *Q* extracted from the N region versus voltage drop *V* across the barrier, for different filling factors υ.



relating the superconducting state of the island to the heat flux originating from quasiparticle injection. From the practical point of view, our experiment demonstrates that quasiparticle injection can cool a metal wire from its normal state deep into the superconducting phase. On the other hand, we have studied quasiparticle energy relaxation at subkelvin temperatures by injecting hot electrons into an Al island and measuring the energy flux from quasiparticles into phonons both in the superconducting and in the normal state [8]. The data show strong reduction of the flux at low temperatures in the superconducting state, in qualitative agreement with the theory for clean superconductors. However, quantitatively the energy flux exceeds the theoretical predictions both in the superconducting and in the normal state, suggesting an enhanced or additional relaxation process. As far as theory is concerned, we have studied the role of the superconducting proximity effect on the electron-phonon energy exchange (a relevant relaxation mechanism for electrons in metals) in diffusive normal metals attached to superconductors [9].

The proximity effect modifies the local density of states in the normal metal leading to a weakening of the electron-phonon energy relaxation. We have shown that the effect is easily observable with modern thermometry methods and predicted that it can be tuned in structures connected to multiple superconductors by adjusting the phase difference between superconducting order parameters at the two NS interfaces.

Finally, we have theoretically investigated the influence of superconducting correlations on the electronic specific heat of a diffusive superconductor-normal metal-superconductor (SNS) Josephson junction [10,11]. We show that, thanks to proximity effect, the specific heat of the *N* region can be dramatically different from that in the absence of superconductivity (see Fig. 4). In particular, at low temperature, it is substantially suppressed with respect to the normal state and turns out to be largely tunable in magnitude by changing the phase difference between the *S* reservoirs. Such peculiarity of mesoscopic SNS Josephson junctions may have an impact for the implementation of devices, for instance,

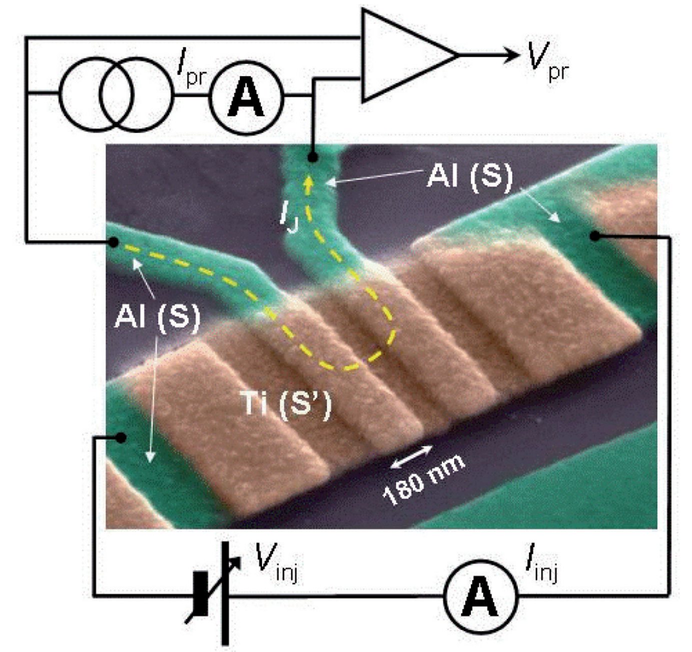
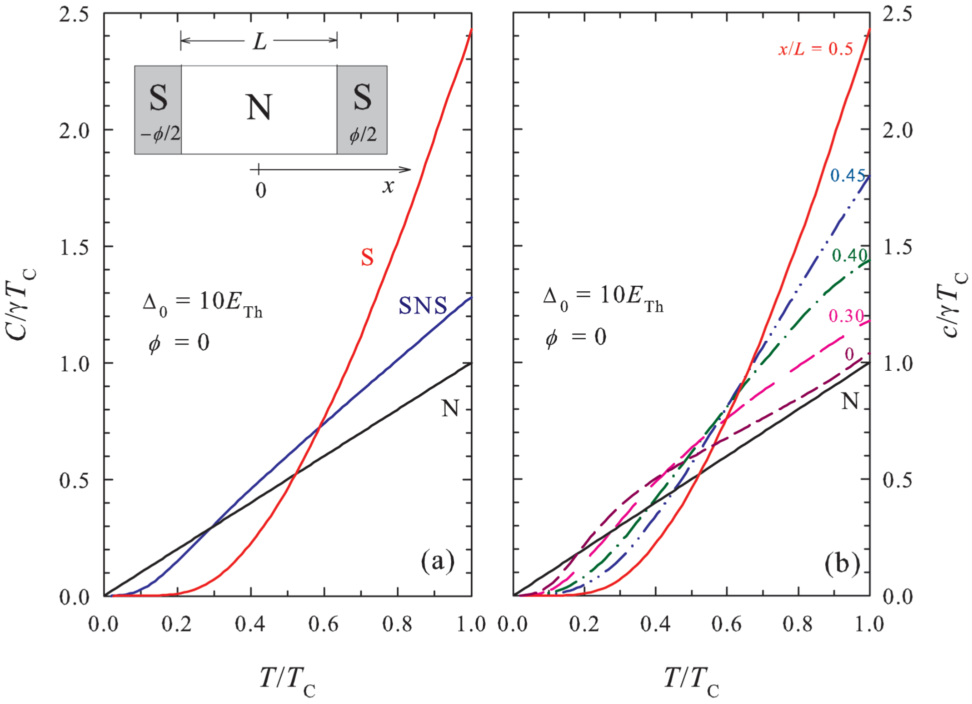


Fig. 3.
A typical structure showing a schematic of the measurement setup. In the middle, a Ti superconducting island (S') is connected to four Al electrodes (S) through tunnel junctions. I_J denotes the Josephson current flowing through the two inner Al-AlOx-Ti tunnel junctions.

ultrasensitive single-photon detectors based on proximity effect. We have also considered the influence of nonidealities occurring in an actual experiment, such as the presence of barriers at the normal metal-superconductor interfaces, the spin-flip, the inelastic scattering in the N-metal region, and quasiparticle subgap states in the superconductors.

Fig. 4.
(a) Comparison of the SNS electronic specific heat *C* vs temperature *T* with that in the normal state (*N*) and in the superconductor (*S*) calculated for $\Delta = 10\ E_{Th}$ and $\phi = 0$. The inset shows a scheme of the SNS junction of length *L*. The point $x = 0$ denotes the middle of the junction and the system is assumed quasi one dimensional. (b) Specific heat per unit length *c* vs *T* at different positions *x* along the *N* wire, calculated for $\Delta = 10\ E_{Th}$ and $\phi = 0$. Also shown is the specific heat in the absence of superconductivity (N). T_C is the critical temperature of the superconductor, and E_{Th} is the Thouless energy.



References

[1] F. Giazotto, T. Heikkilä, A. Luukanen, A. M. Savin, J. P. Pekola, Rev. Mod. Phys. 78, 217 (2006).
[2] J. P. Pekola, F. Giazotto, O-P Saira, Phys. Rev. Lett. 98, 037201 (2007).
[3] O-P. Saira, M. Meschke, F. Giazotto, A. M. Savin, M. Möttönen and J. P. Pekola, Phys. Rev. Lett. 99, 027203 (2007).
[4] N. B. Kopnin, F. Taddei, J. P. Pekola, F. Giazotto, Phys. Rev. B 77, 104517 (2008).
[5] F. Giazotto, F. Taddei, M. Governale, R. Fazio, and F. Beltram, New J. Phys. 9, 439 (2007).
[6] F. Dolcini and F. Giazotto, Phys. Rev. B 80, 024503 (2009).
[7] S. Tirelli, A. M. Savin, C. Pascual Garcia, J. P. Pekola, F. Beltram, and F. Giazotto, Phys. Rev. Lett. 101, 077004 (2008).
[8] A.V. Timofeev, C. Pascual Garcia, N. B. Kopnin, A. M. Savin, M. Meschke, F. Giazotto, and J. P. Pekola, Phys. Rev. Lett. 102, 017003 (2009).
[9] T. T. Heikkilä and F. Giazotto, Phys. Rev. B 79, 094514 (2009).
[10] H. Rabani, F. Taddei, O. Bourgeois, R. Fazio, and F. Giazotto, Phys. Rev. B 78, 012503 (2008).
[11] H. Rabani, F. Taddei, F. Giazotto, and R. Fazio, J. Appl. Phys. 105, 093904 (2009).