Heat interference in Josephson nanocircuits: toward *coherent caloritronics*

F. Giazotto
NEST, Istituto Nanoscienze-CNR and Scuola Normale Superiore, I-56127 Pisa, Italy

The Josephson effect [1] represents perhaps the prototype of macroscopic phase coherence and is at the basis of the most widespread interferometer, i.e., the superconducting quantum interference device (SQUID) [2]. Yet, in analogy to electric interference, Maki and Griffin [3] predicted in 1965 that thermal current flowing through a temperature-biased Josephson tunnel junction is a stationary periodic function of the quantum phase difference between the superconductors. The interplay between quasiparticles and Cooper pairs condensate is at the origin of such phase-dependent heat current, and is unique to Josephson junctions. In this scenario, a temperature-biased SQUID would allow heat currents to interfere [4, 5] thus implementing the thermal version of the electric Josephson interferometer. The dissipative character of heat flux makes this coherent phenomenon not less extraordinary than its electric (non-dissipative) counterpart. Surprisingly, this striking effect has never been demonstrated so far.

In this presentation we shall report the first experimental realization of a heat interferometer [6,7]. We investigate heat exchange between two normal metal electrodes kept at different temperatures and tunnel-coupled to each other through a thermal `*modulator*' [5] in the form of a DC-SQUID. Heat transport in the system is found to be phase dependent, in agreement with the original prediction. With our design the Josephson heat interferometer yields magnetic-flux-dependent temperature oscillations of amplitude up to ~21 mK, and provides a flux-to-temperature transfer coefficient exceeding ~60mK/Φ_0 at 235 mK (Φ_0 is the flux quantum). Besides offering remarkable insight into thermal transport in Josephson junctions, our results represent a significant step toward phase-coherent mastering of heat in solid-state nanocircuits, and pave the way to the design of novel-concept coherent caloritronic devices, for instance, heat transistors, thermal splitters and diodes [8] which exploit phase-dependent heat transfer peculiar to the Josephson effect.

In this latter context, we shall also present the concept for a further development of a Josephson heat interferometer based on a double superconducting loop [9] which allows, in principle, enhanced control over heat transport. We shall finally conclude presenting some preliminary results on a quite different prototypical thermal interferometer which could add complementary flexibility in mastering heat flux at the nanoscale.

References

[1] B. D. Josephson, Phys. Lett. **1**, 251 (1962).
[2] J. Clarke and A. I. Braginski, *The SQUID Handbook* (Wiley-VCH, 2004).
[3] K. Maki and A. Griffin, Phys. Rev. Lett. **15**, 921 (1965).
[4] G. D. Guttman, E. Ben-Jacob, and J. Bergman, Phys. Rev. B **57**, 2717 (1998).
[5] F. Giazotto and M. J. Martínez-Pérez, Appl. Phys. Lett. **101**, 102601 (2012).
[6] F. Giazotto and M. J. Martínez-Pérez, Nature **492**, 401 (2012).
[7] R. W. Simmonds, Nature **492**, 358 (2012).
[8] M. J. Martínez-Pérez and F. Giazotto, Appl. Phys. Lett. **102**, 182602 (2013).
[9] M. J. Martínez-Pérez and F. Giazotto, Appl. Phys. Lett. **102**, 092602 (2013).