Disorder Goes Coherent

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May 28, 2013 (HP59). Per our invitation, this New Paper Highlight was submitted by the authors of the highlighted paper which appeared in Nature [1]. We believe the paper deserves special interest (Editors' comment).

To summarise, in their paper the authors demonstrated experimentally the existence of a weird property of heat. Such a property manifests itself within a small fraction of the heat current flowing through Josephson junctions between superconductors. First of all, and against all the rules, this anomalous fraction of the heat current is normally transmitted from the cold to the hot source. Last but not least, it is phase coherent. The latter has enabled the authors to realize a Josephson heat interferometer, i.e., the thermal version of a superconducting quantum interference device (SQUID). This discovery has opened the door for a completely new research line; that of coherent caloritronics.

This effect had its origins when two physicists, Kazumi Maki and Allan Griffin [2] realized almost 50 years ago one of the deepest consequences of the Josephson effect, capable of transferring quantum phase coherence to heat currents. This property implied that, just as electric currents do, heat currents are able of interfering. Such a surprising prediction went however unnoticed until very recently when a Josephson heat interferometer has been finally realized at NEST laboratories, Italy.

Physically, this device is very similar to a conventional electric SQUID. It consists of two superconducting electrodes weakly connected through two Josephson junctions forming a ring threaded by a magnetic field (see Fig. 1). The main practical difference lies in the way the system is biased. In a conventional SQUID biasing is usually done by applying a current or a voltage. By contrast, the Josephson heat interferometer must be temperature biased. For this purpose one of the two SQUID branches was heated up to approximately 500 mK while keeping the other one at the minimum temperature, i.e., 250 mK. By varying the magnetic field threading the loop it was possible to play with the macroscopic phase difference between the two condensates, inducing heat interference. The latter was practically reflected into a Φ_0-periodic variation of the temperature of the hot branch as shown in Fig. 2, Φ_0 being the flux quantum. In addition, the experiment revealed unequivocally that the phase dependent fraction of the heat current is indeed transmitted from the cold to the hot SQUID branch. It is however worth highlighting that the total heat current - which results when one also considers the conventional quasiparticle heat current – always flows from the hot to the cold source, in accordance with the second law of thermodynamics.

Besides these striking consequences it is also surprising to observe experimentally how heat, which we usually associate with disorder, behaves coherently. This is further complicated by the fact that, under static conditions, heat flowing through Josephson junctions is transported exclusively by quasiparticles since the Cooper pair condensate carries no entropy. The key is precisely the Josephson effect that constrains Cooper pairs to interact with quasiparticles during tunneling events. As a result of this interplay, the quasiparticle ensemble, responsible for heat transport, becomes "contaminated" with quantum coherence.

In conclusion, the experiments realized at NEST have confirmed the veracity of the above-mentioned predictions. Yet, in the same way that the quantum properties of electric charge are being exploited in practical devices, the fascinating properties discussed here could lead to completely new applications. In this regard the realization of coherent heat circuits consisting of, for instance, coherent heat transistors, diodes and splitters can be envisioned. The latter might lead to novel ways of mastering heat in superconducting nanocircuits. Such circuits could represent also an important breakthrough in different research fields of nanoscience such as solid-state cooling, radiation detection and quantum computing.

[1] Francesco Giazotto and María José Martínez-Pérez, Nature. **492**, 11702 (2012); doi:10.1038/nature11702.

[2] Kazumi Maki and Alan Griffin. Phys. Rev. Lett. **15**, 921 (1965).

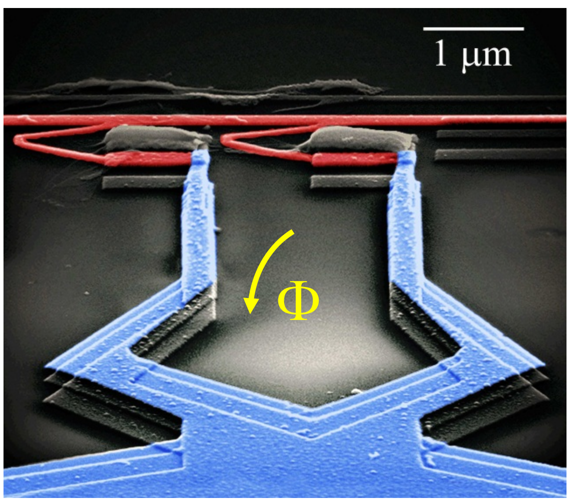

Fig. 1: Pseudo-color scanning electron micrograph of the heat interferometer. The hot (red) branch is heated up to ~ 500 mK through a tunnel-connected source electrode whereas the cold (blue) branch is kept at the bath temperature ~ 250 mK. Under these circumstances, the temperature of a drain electrode tunnel-connected to the hot SQUID branch was measured as a function of the magnetic flux Φ threading the loop.

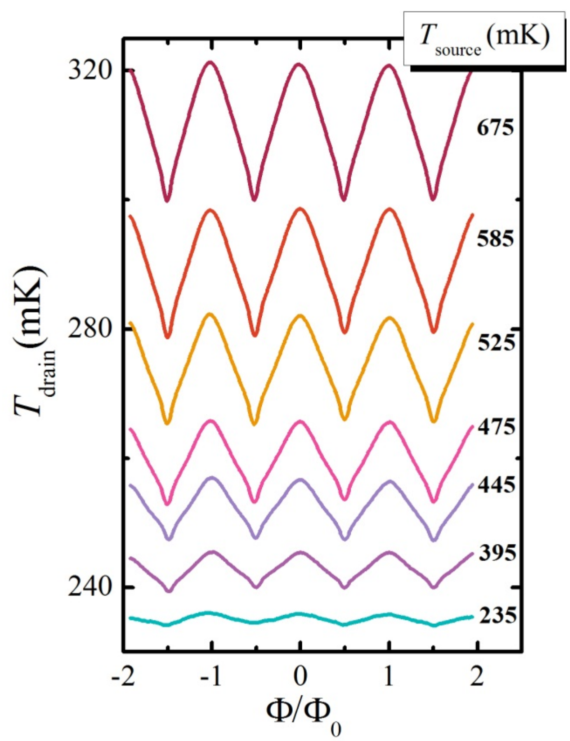

Fig. 2: Temperature modulation of the drain electrode T_{drain} vs. Φ for different values of the temperature of the source electrode T_{source}. As predicted by the theory, T_{drain} is Φ_0-periodic in Φ, like the Josephson critical current.