Interference of nonequilibrium quasiparticles in a superconductor

K. Yu. Arutyunov [a,1], T. T. Hongisto [a], J. P. Pekola [a]

[a] *University of Jyväskylä, Department of Physics, PL 35, 40014 Jyväskylä, Finland*

Abstract

We have observed an interference of nonequilibrium quasiparticles, injected from a copper electrode into an aluminium loop through a tunnel barrier. At temperatures below $1K$ the tunnel current at fixed voltage bias is periodically modulated by external magnetic field. The amplitude of the modulation reaches maximum at a bias slightly below the gap energy, and decreases with the further increase of the bias voltage. For a given voltage bias the amplitude of the current oscillations decreases with increase of the temperature and the loop circumference.

Key words: nonequilibrium superconductivity, quasipartices, interference, nanostructures

At low temperatures ($T < 1K$) electric transport in solids is maintained by conducting electrons (normal metals) or paired electrons (superconductors). If the current is not too high, the system is in a quasi-equilibrium state with a certain amount of equilibrium excitations at any finite temperature. However, it is possible to create nonequilibrium quasiparticle excitations. At room temperatures in normal metals the lifetime of corresponding excitations is extremely short ($\sim 10^{-11}s$). One may naively expect that at low temperatures in superconducting state the contribution of nonequilibrium quasiparticles to electric current is negligible. We have experimentally shown that under certain conditions the contribution of nonequilibrium excitations to coherent transport is essential. The phase of the wave function of these nonequilibrium quasiparticles is preserved on distances (times) significantly larger than for 'conventional' conducting electrons in normal metals at same temperatures.

We fabricated a set of nanostructures, which can serve as analogues of an optical interferometer. A superconducting loop (Al) is overlapped at one point by a normal metal bar (Cu) through a tunnel barrier (Fig. 1, inset). Nominal area of the junction is about $100nm \times 100nm$. Depending on the aluminum oxidation procedure, the resulting tunnel resistance R_T varies from $2k\Omega$ to $50k\Omega$. The circumference of the interferometer loop varies from $2\mu m$ to $40\mu m$.

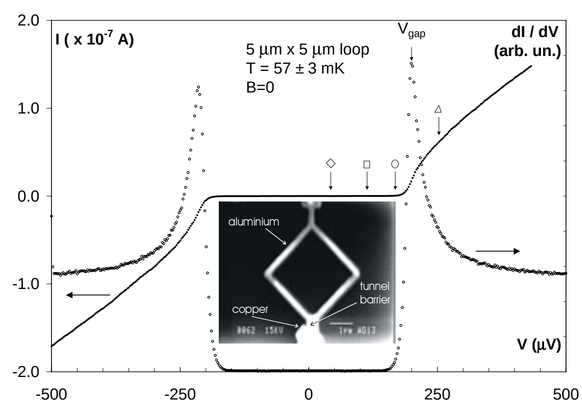

Fig. 1. Typical $I-V$ characteristics at zero magnetic field. Arrows indicate bias voltages at which magnetic field sweeps in Fig. 2 are shown. Inset: SEM image of a typical nanostructure.

At temperatures $40mK < T < 1K$ the dependencies of the tunnel current I measured as a function of the bias voltage V are typical for a normal-insulator-superconductor structure (Fig. 1). Application of a perpendicular magnetic field B at a fixed voltage bias causes periodic modulation of the tunnel current (Fig.

[1] Corresponding author. University of Jyväskylä, Department of Physics, PL 35, 40014 Jyväskylä, Finland E-mail: Konstantin.Arutyunov@phys.jyu.fi

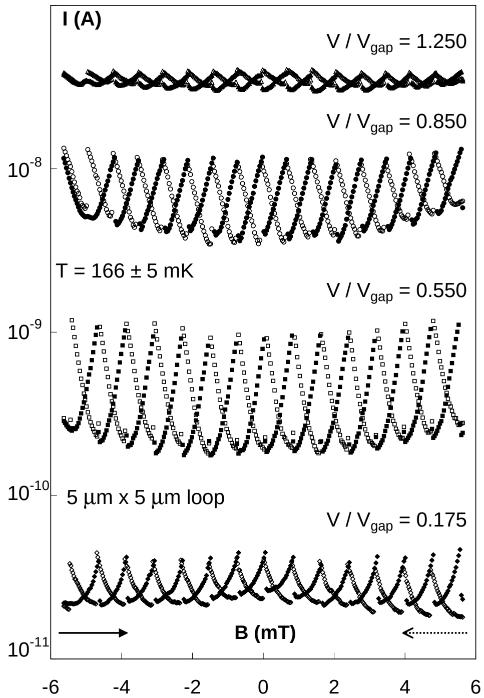

Fig. 2. $I(B, V = const)$ dependencies taken at $T = 166 \pm 5mK$ at various voltage biases, normalised by the gap voltage $V/Vgap$. Arrows show the directions of the magnetic field sweeps.

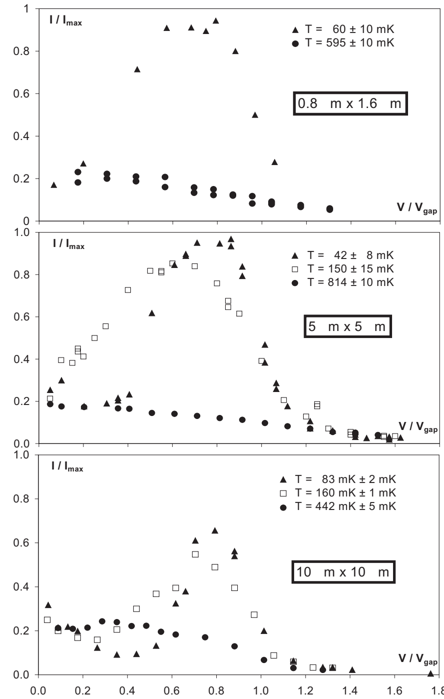

Fig. 3. The normalised magnitudes of the current oscillations $\Delta I/I_{\max}$ vs. normalised bias voltage $V/V_{\rm gap}$ at various temperatures for three samples, which differ by the circumference of the loop.

2). The magnitude of the oscillations depends on the bias voltage, showing a nonmonotonous behavior (Fig. 3). If to define ΔI as the magnitude of the current oscillations and $I_{\max}$ as the maximum current at a given voltage bias, then at the lowest temperatures the function $\Delta I/I_{\max}(V)$ shows a pronounced maximum at energies slightly below the superconducting gap $eV_{\rm gap} = \Delta$. At higher temperatures the function $\Delta I/I_{\max}(V)$ is rather broad, monotonously decreasing at $eV > \Delta$ (Fig. 3).

The dependencies in magnetic field $I(B, V = const)$ are hysteretic. The allowed current states form a set of 'parabolas' (Fig. 2). Defining Φ as magnetic flux through the area of the loop, one may notice that the system switches from one quantum state ($\Phi/\phi_0^* = n$) to the other ($\Phi/\phi_0^* = n \pm 1$) 'jumping' only to / from particular branches of the 'parabolas', depending on the direction of the magnetic field sweep. Within the same quantum state ($\Phi/\phi_0^* = const$) the dependencies in magnetic field are not hysteretic.

The maximum on $\Delta I/I_{\max}(V)$ dependencies close to the gap voltages $V \sim V_{\rm gap}$ is probably an evidence that the quasiparticles are involved in the process, as the density of states of a superconductor has a singularity at the gap edge. The decrease of the magnitude of this maximum with the increase of the loop circumference can be accounted for the finite relaxation length of the nonequilibrium quasiparticles. The most unexpected feature is the absolute value of the effective flux quantum ϕ_0^*, which determines the period of the current oscillations in magnetic field. It equals the normal metal value $\phi_0 = h/e$ only for the very small loops, being noticeably larger (up to 10 times !) for bigger circumferences.

For the moment the experimental data lacks the solid theoretical explanation. Probably, the results can be understood incorporating interference effects originating from the transport of the Cooper pairs [1] -[3] and the injected nonequilibrium quasiparticles.

Authors would like to acknowledge D. Esteve for helpful discussion. The work was supported by the Russian Foundation for Basic Research (Grant 01-02-17427) and the Academy of Finland under the Finnish Center of Excellence Program 2000-2005 No. 44875, Nuclear and Condensed Matter Program at JYFL.

References

[1] H. Nakano, H. Takayanagi, Sol. St. Comm. **80**(1991) 997.

[2] F. W. J. Hekking, Yu. V. Nazarov, Phys. Rev. Lett. **71** (1993) 1625; F. W. J. Hekking, Yu. V. Nazarov, Phys. Rev. B **49** (1994) 6847.

[3] H. Pothier, S. Guéron, D. Esteve, M. H. Devoret, Phys. Rev. Lett. **73** (1994) 2488.