Thermopower in Andreev Interferometers: Supercurrents and Persistent Currents

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http://www.meso.northwestern.edu
**Microscopic Picture**

**Andreev Reflection**

Energy dependence of transport across NS interface

Electron with energy $\epsilon < \Delta$ in N cannot be transmitted as a quasiparticle into S

*Retroreflected as a hole with concurrent generation of a Cooper pair in the superconductor*

Phase coherent, hole picks up phase $\phi$ from superconductor

Clean normal metal: factor of 2 increase in conductance of NS junction
Proximity effect in diffusive normal metals

Reentrant behavior in temperature dependent resistance or differential conductance
Resistance first decreases, then increases as temperature or voltage is decreased

Charlat et al, PRL, 1996

0.75 \( \mu \text{m} \) long Au wire in contact with Al reservoir (M. Black and V. Chandrasekhar, EPL 50, 257 [2000])

\[ E_c = \frac{SD}{L^2} \]

\[ T_{\text{min}} \sim 5 \frac{E_c}{k_B} \]
Interference effects
Andreev interferometers

Modify phase of superconductors by applying magnetic flux
Resistance is periodic, with period $h/2e$

Thermal transport in the proximity regime

Mesoscopic phase coherent thermal properties of Andreev interferometers

**Thermopower $S$**

*Phase-coherent oscillations of thermopower with magnetic field*

Open questions:
- Phase of oscillations depends on sample topology
- Amplitude of thermopower
- Non-monotonic temperature dependence

**Thermal conductance $G^T$**

Much smaller than normal-metal thermal conductance
Thermal properties of mesoscopic devices

Transport equations:

Electrical current

\[ I = G \Delta V + \eta \Delta T \]

Thermal current

\[ I^T = \zeta \Delta V + \kappa \Delta T \]

Thermopower: ratio \( \Delta V/\Delta T \) measured with \( I=0 \)

\[ S = \Delta V/\Delta T = \eta/G \]

Thermal conductance: ratio \( I^T/\Delta T \) measured with \( I=0 \)

\[ G^T = I^T/\Delta T = S \zeta + \kappa \sim \kappa \]

Small for typical metals
Mesoscopic thermopower measurements

Local proximity effect thermometers

Aumentado et al, APL (1999), Jiang et al., cond-mat

Calibrate by measuring $R(T)$, $R(I)=(dV/dI)$ and correlating $T(I)$

Measure effective local electron temperature $T_e(I)$ on the scale of ~100 nm
Sample Geometry

Andreev interferometer

'hot' thermometer

heater

Au 'control' wire

'cold' thermometers

Sample parameters

$L_T \sim 0.5 \, \mu m$ at $T=1 \, K$

$L_\phi \sim 3-7 \, \mu m$ at base temperature
Symmetry of thermopower oscillations

Resistance is always symmetric, but thermopower depends on topology

House interferometer

Parallelogram interferometer

Resistance is always symmetric, but thermopower depends on topology

antisymmetric thermopower
Symmetry of thermopower oscillations

**Origin of antisymmetry?**
Differences between sample topologies

**House interferometer**
Oscillations are symmetric in flux

No temperature gradient across superconductor
No possible field induced supercurrent in normal arm which experiences temperature gradient

**Parallelogram interferometer**
Oscillations are antisymmetric in flux

Superconductor experiences temperature gradient
Possibility of field induced supercurrent in normal arm which experiences temperature gradient

*No thermal voltage developed across loop* - thermal voltage must arise from normal parts outside loop

Disordered samples—cannot be due to perfect topological symmetries
Andreev interferometers in a magnetic field

Circulating currents in response to magnetic field

At low temperatures, proximity effect supercurrent through normal-metal arm if $L<\xi_N=L_T$

Additional contribution due to normal-metal persistent current if $L<L_\phi$

Total current through normal metal is proximity effect supercurrent + persistent current=supercurrent in superconductor

Persistent current is present to higher temperatures if $L_\phi>\xi_N=L_T$

Antisymmetric in magnetic field
Symmetry of thermopower oscillations

*Interplay of electrical and thermal currents*

If normal-metal is phase coherent, magnetic flux $\Phi$ induces ‘persistent current’ which is antisymmetric in $\Phi$

Persistent current drags along a thermal current

Across normal part of loop:

$$I_N(\Phi) = G \delta V + \eta \delta T$$

$$\delta I^T = \zeta \delta V + \kappa \delta T$$

Difference in thermal voltage between normal control wire and Andreev interferometer

$$\sim \Delta V = S_A - S_N \sim (\eta_{side}/G_{side}) (\kappa_{arm}/\eta_{arm}) I_N(\Phi), \text{ antisymmetric in } \Phi$$
Temperature dependence of thermopower oscillations

Proximity thermometers enable quantitative measurements of $S$

Current dependence of electron temperature

Can measure electron temperature on both sides of device
Temperature dependence of thermopower oscillations

$T_{\text{min}}$ appears to depend on dimensions of interferometer related to temperature dependence of persistent currents?

‘House’ interferometer, Eom et al., PRL (1998)
$L \sim 7 \, \mu m$, $T_{\text{min}} \sim 0.14 \, K$

‘Hook’ interferometer, Dikin et al., EPL (2002)
$L \sim 2.7 \, \mu m$, $T_{\text{min}} \sim 0.5 \, K$
Summary - Thermopower of Andreev interferometers

Oscillations in thermopower as a function of magnetic field
--influence of quantum mechanical phase on thermopower

Symmetry of thermopower with respect to magnetic field depends on
 topology of the sample--different from symmetry of magnetoresistance

Interplay of thermal and electrical currents
related to normal-metal persistent currents

Non-monotonic temperature dependence
--not associated with reentrance in resistance

Different energy scale involved?

Quantitative theory of thermopower in NS systems
Thermal conductance of Andreev interferometer

Jiang et al, cond-mat
Thermal conductance of Andreev interferometer
Future work

Quantitative measurement of thermal conductance in a mesoscopic NS sample

*NS structures*: temperature dependence of thermal conductance
  - influence of proximity effect

  Observation of oscillations of thermal conductance in an Andreev interferometer

Normal metals: temperature dependence of thermal conductance
  influence of inelastic scattering

Thermal transport in normal metal systems
Nonequilibrium transport in mesoscopic devices

Nonequilibrium distribution function is a linear combination of left and right equilibrium reservoir distribution functions

ID wire with voltage $V$ applied

$$f(x,E) = \left[ (f_R - f_L)(x/L) \right] + f_L$$
Nonequilibrium transport in mesoscopic devices

Thermal effects

ID wire with temperature differential applied, generates a thermal voltage

\[ f(x, E) = \left[ (f_R - f_L)(x / L) \right] + f_L \]
**Diffusive Metals**

*Energy dependent enhancement of diffusion coefficient*

Characteristic *energy* scale

\[ E_c = \frac{SD}{L^2} \]

Characteristic *length* scale

\[ L_r = \sqrt{\frac{SD}{k_B T}} \]
Interference effects

SNS geometries (Andreev interferometer)

Oscillations of the resistance as a function of the phase difference $\phi_1 - \phi_2$ between the superconductors.

Phase can be modified by magnetic field or dc current