Thermopower in Andreev Interferometers: Supercurrents and Persistent Currents

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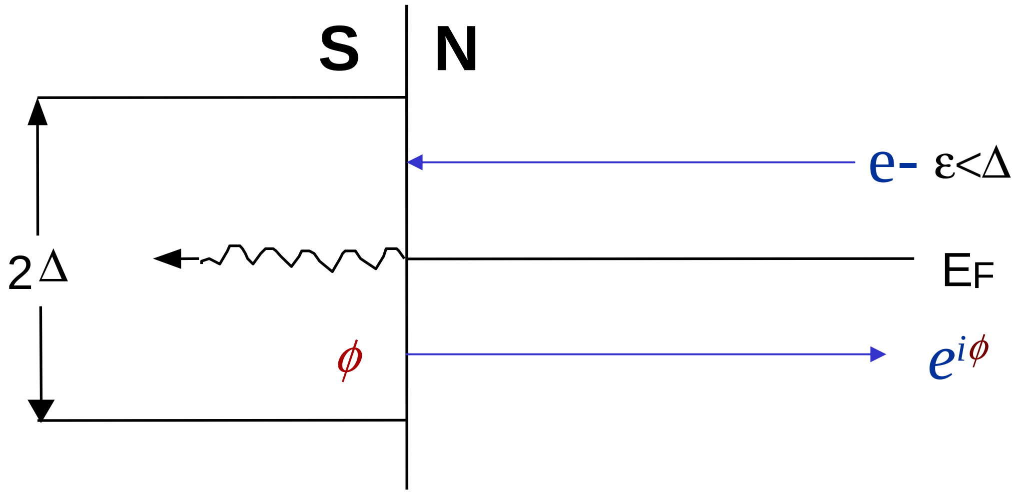
http://www.meso.northwestern.edu

Microscopic Picture

Andreev Reflection

Energy dependence of transport across NS interface



Electron with energy ε<Δ 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 ϕ from superconductor

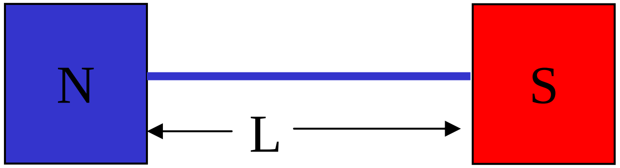
Clean normal metal: factor of 2 increase in conductance of NS junction

Proximity effect in diffusive normal metals

Reentrant behavior in temperature dependent resistance or differential conductance

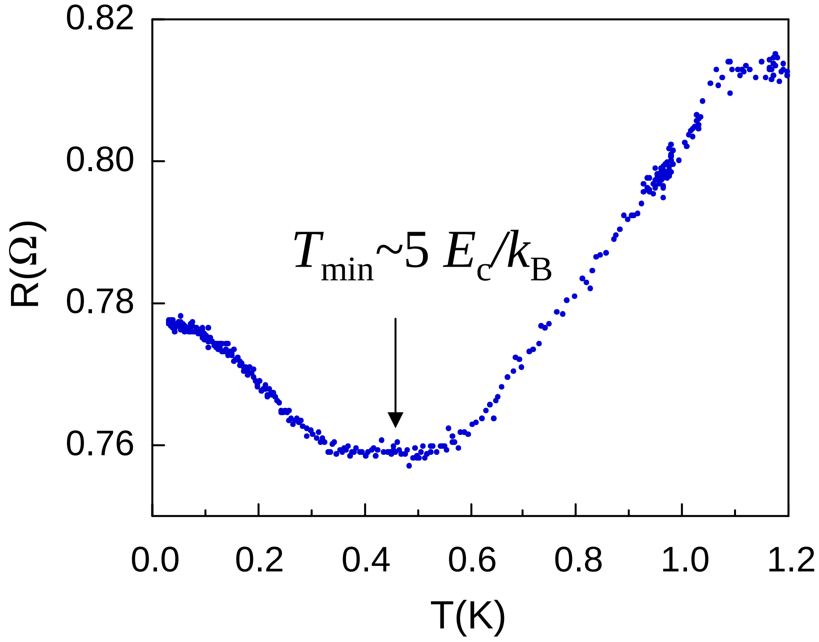
Resistance first decreases, then increases as temperature or voltage is decreased

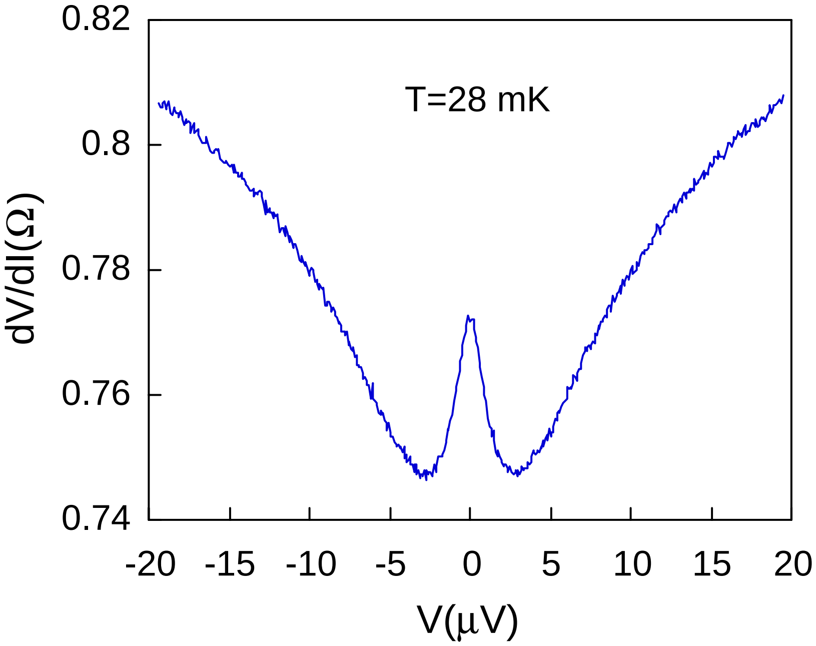
Charlat et al, PRL, 1996



*0.75 μm long Au wire in contact with Al reservoir (M. Black and V. Chandrasekhar EPL **50**, 257 [2000])*

$$E_c = \frac{S D}{L^2}$$



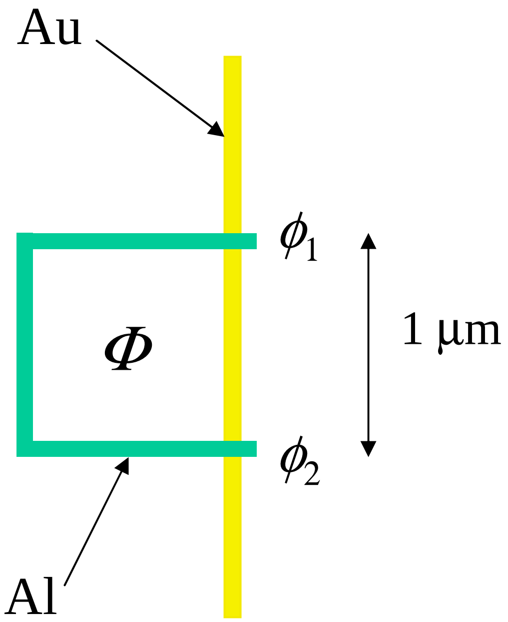


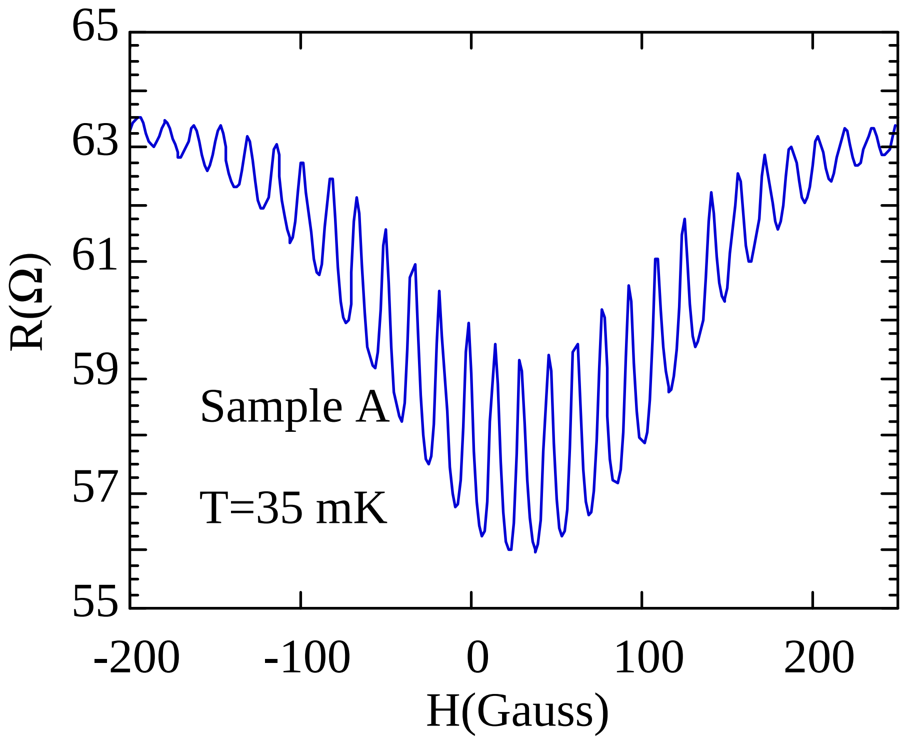
Interference effects

Andreev interferometers

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

C.-J. Chien and V. Chandrasekhar (Phys. Rev. B 60, 15356 (1999))





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

$T+\Delta T,$
ΔV

$T, V=0$

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 $I=0$

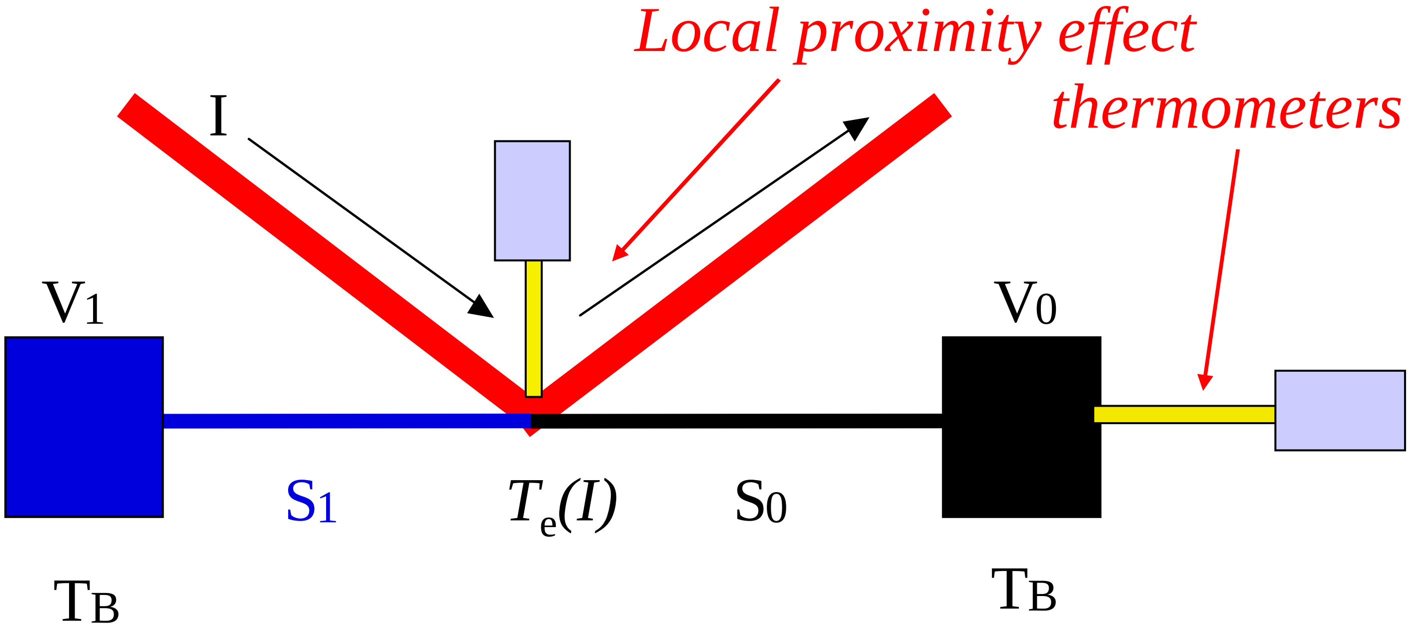
$$S = \Delta V/\Delta T = \eta/G$$

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



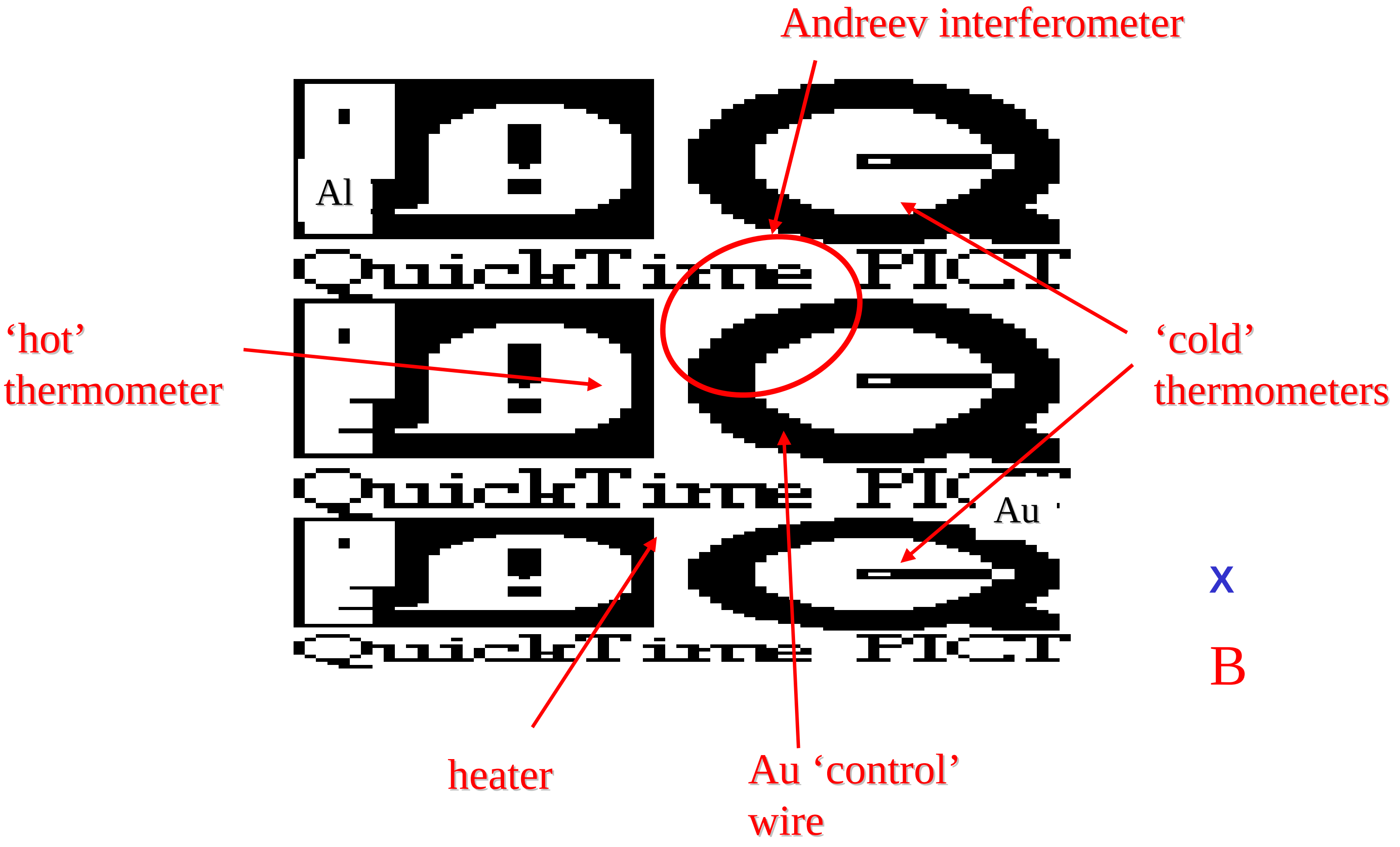
Local proximity effect thermometers

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

‘cold’
thermometers

heater

Au ‘control’
wire

x

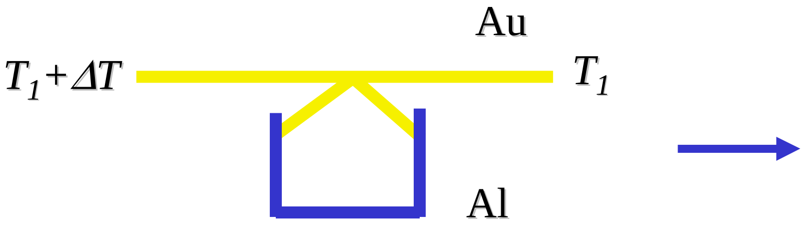
B

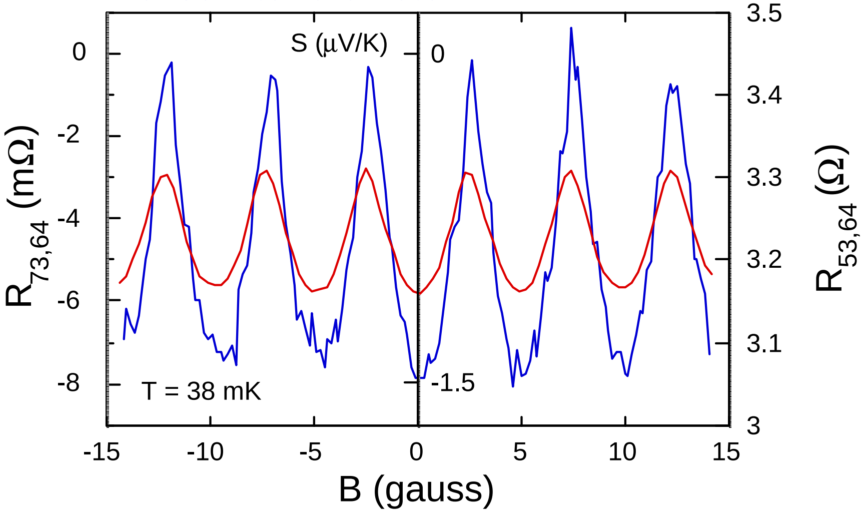
Sample parameters

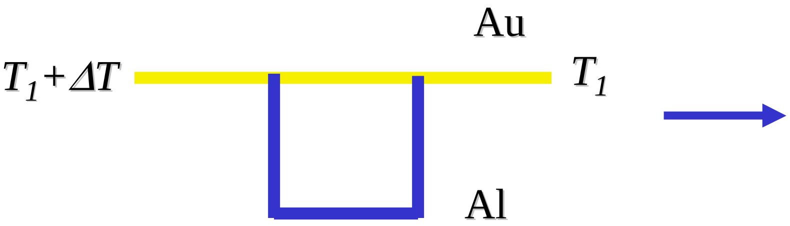
$L_T \sim 0.5\ \mu\text{m}$ at T=1 K
$L_\phi \sim$ 3-7 μm at base temperature

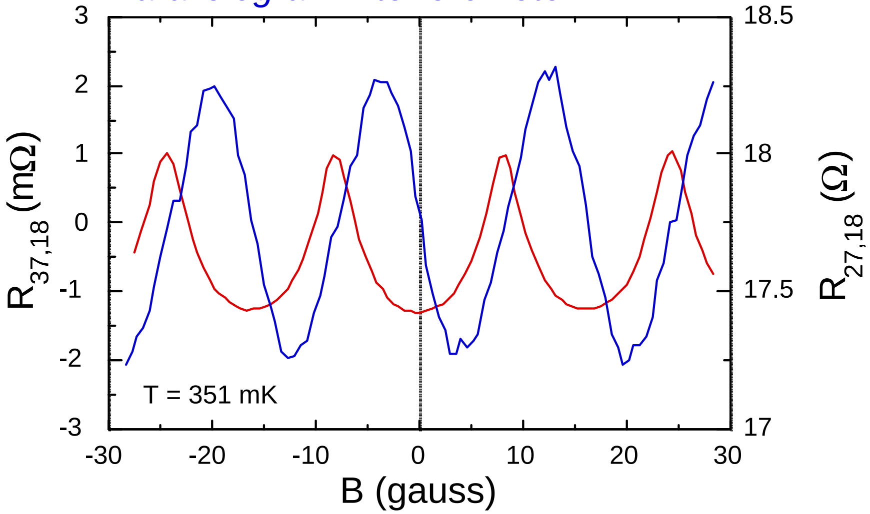
Symmetry of thermopower oscillations

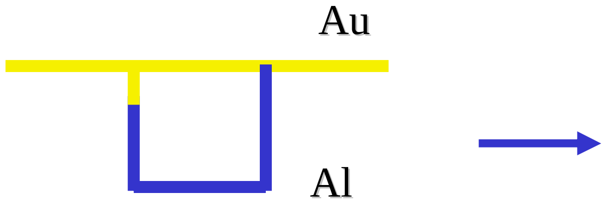
Resistance is always symmetric, but thermopower depends on topology




House interferometer




Parallelogram interferometer



antisymmetric thermopower

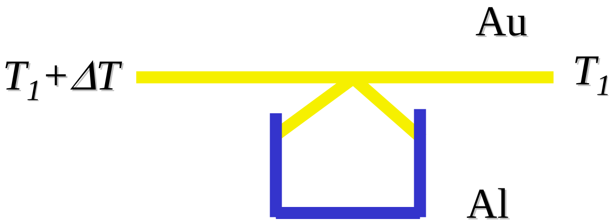
Symmetry of thermopower oscillations

Origin of antisymmetry?

Differences between sample topologies

House interferometer

Oscillations are symmetric in flux

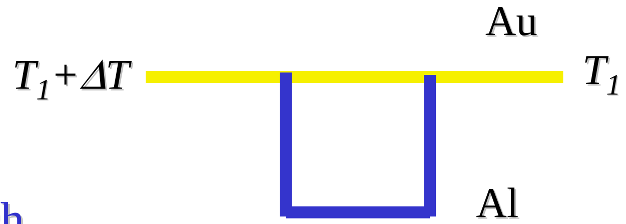


No temperature gradient across superconductor

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

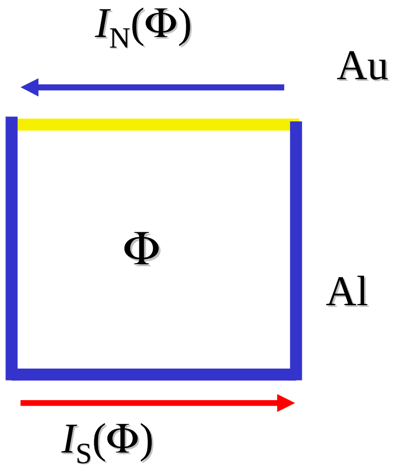
No thermal voltage developed across loop- thermal voltage must arise from normal parts outside loop

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

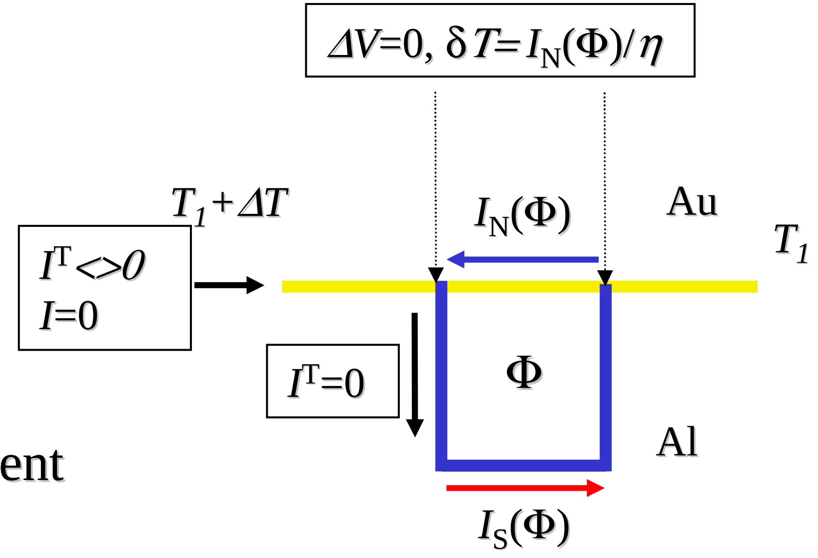
Persistent current is present to higher temperatures if $L_\phi > \xi_N = L_T$

Antisymmetric in magnetic field

Symmetry of thermopower oscillations

Interplay of electrical and thermal currents

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



Persistent current drags along a thermal current

Across normal part of loop:

$$I_N(\Phi) = \cancelto{0}{G\delta V} + \eta\delta\ T \longrightarrow \qquad \delta\ T = I_N(\Phi)/\eta$$

$$\delta I^T = \cancelto{0}{\zeta\delta V} + \kappa\delta\ T \qquad \qquad \delta I^T = \kappa I_N(\Phi)/\eta$$

Difference in thermal voltage between normal control wire and Andreev interferometer

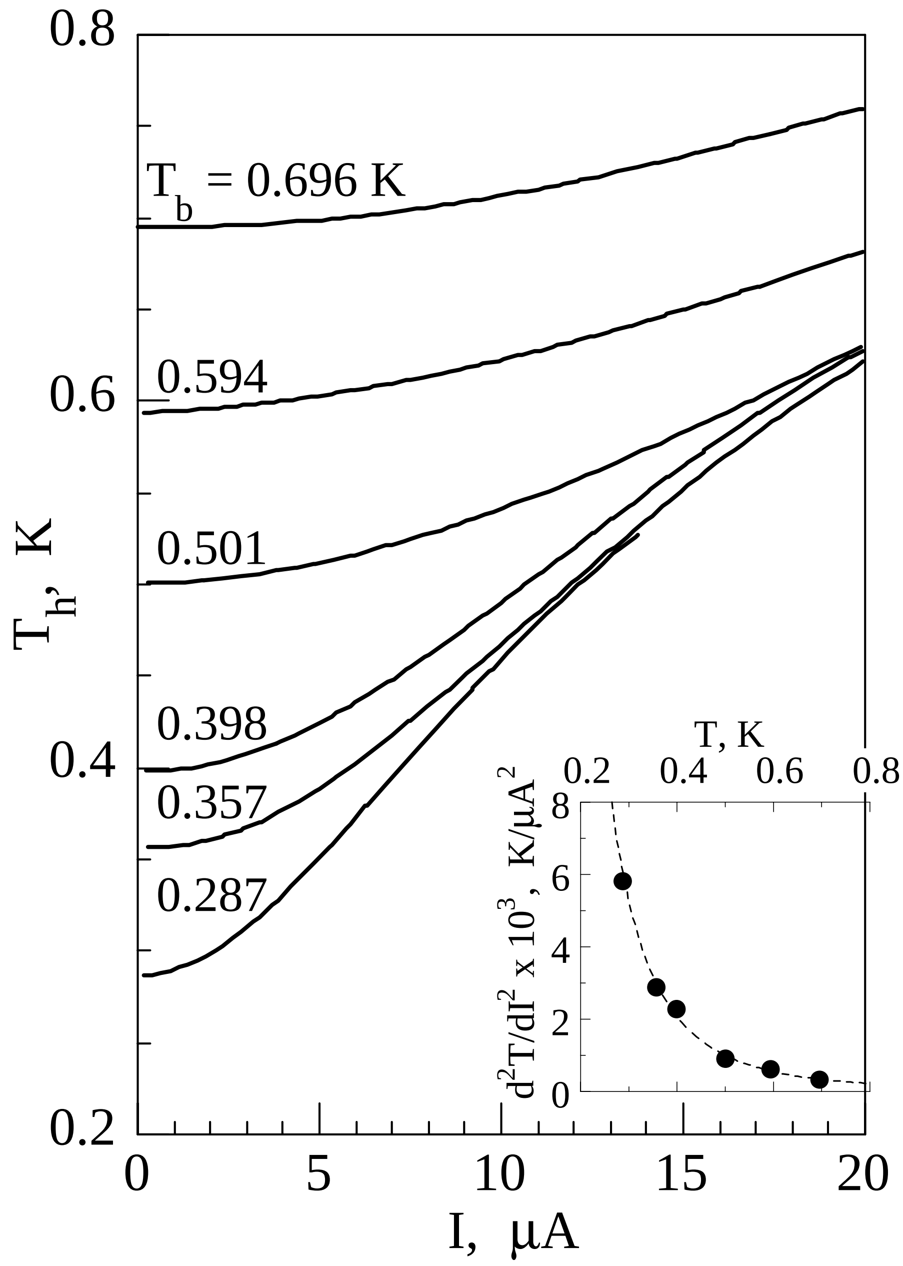
$\sim\Delta V = S_A - S_N \sim (\eta_{side}/G_{side})\,(\kappa_{arm}/\eta_{arm})\, I_N(\Phi)$, *antisymmetric in* Φ

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

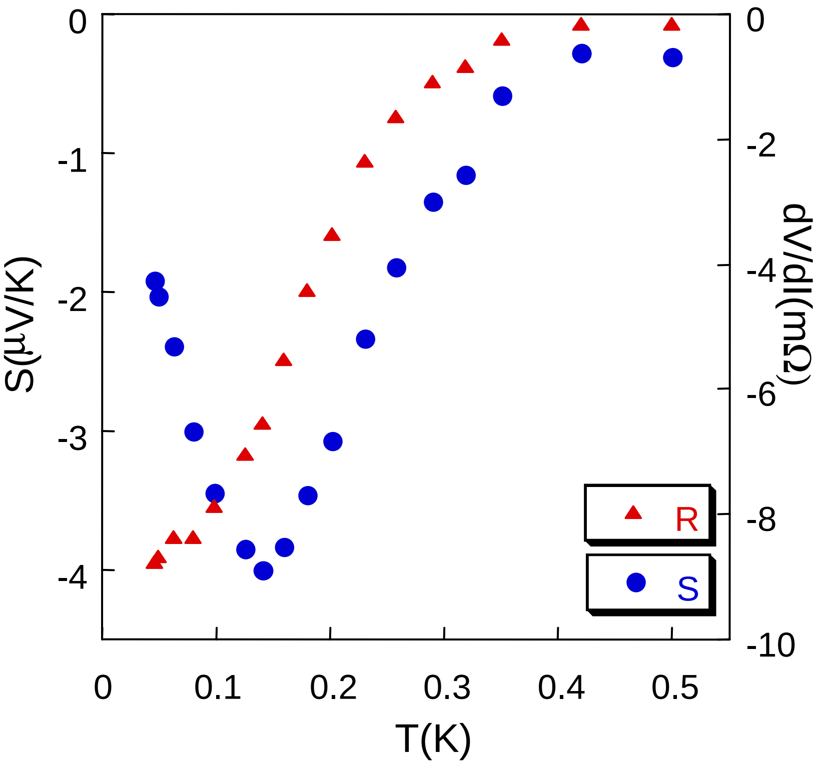


Temperature dependence of thermopower oscillations

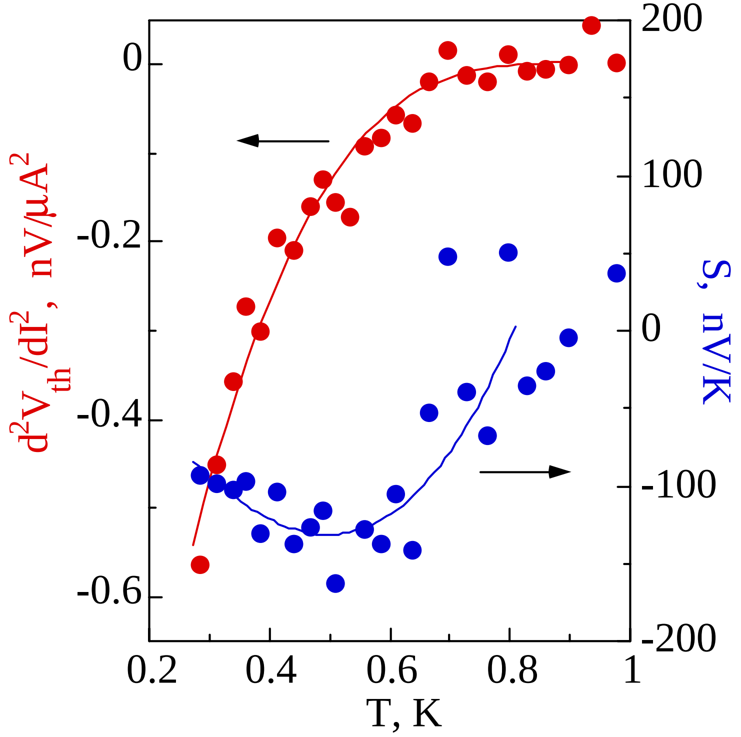
T_{min} appears to depend on dimensions of interferometer

related to temperature dependence of persistent currents?

‘House’ interferometer,
Eom et al., PRL (1998)
L~7 μm, T_{min}~0.14 K



‘Hook’ interferometer,
Dikin et al., EPL (2002)
L~2.7 μm, T_{min}~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

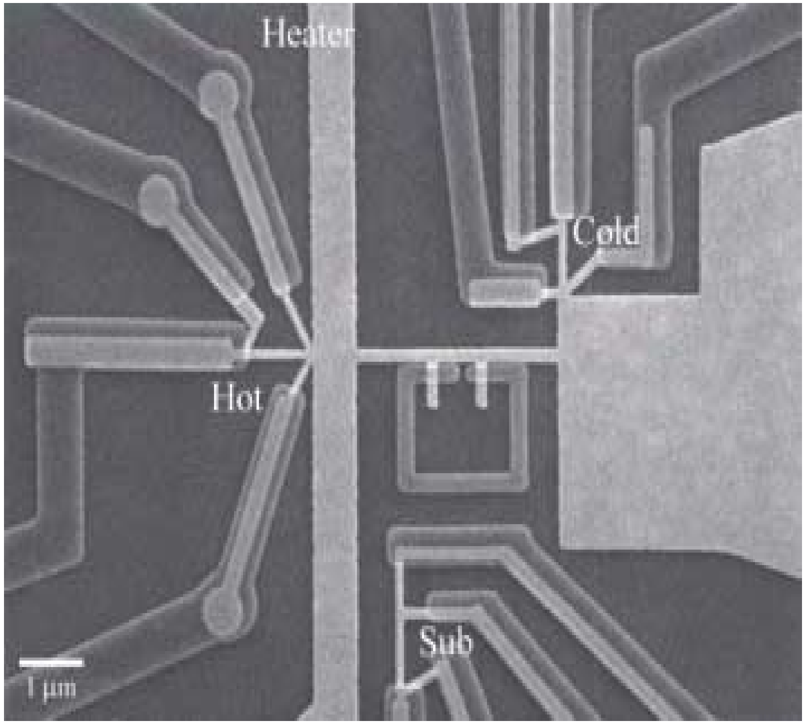
Non-monotonic temperature dependence

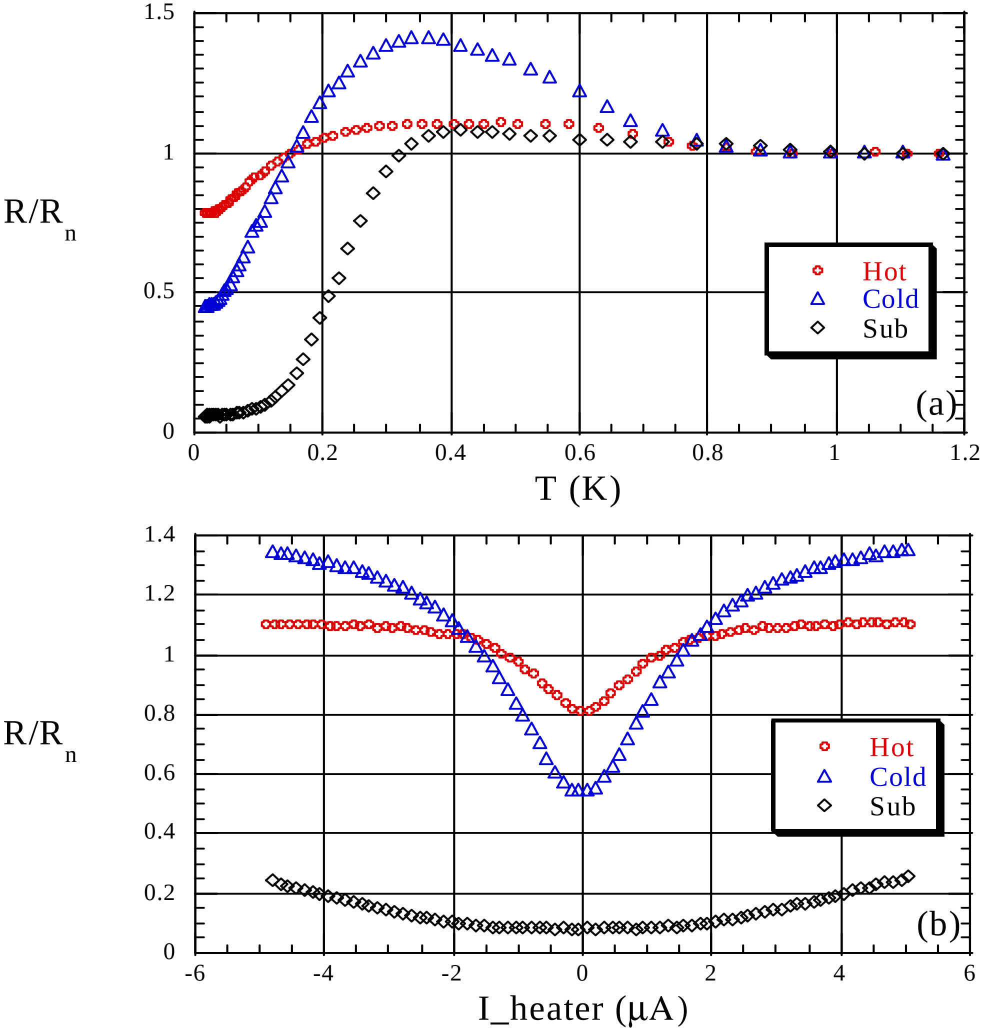
--not associated with reentrance in resistance

Different energy scale involved?

Quantitative theory of thermopower in NS systems

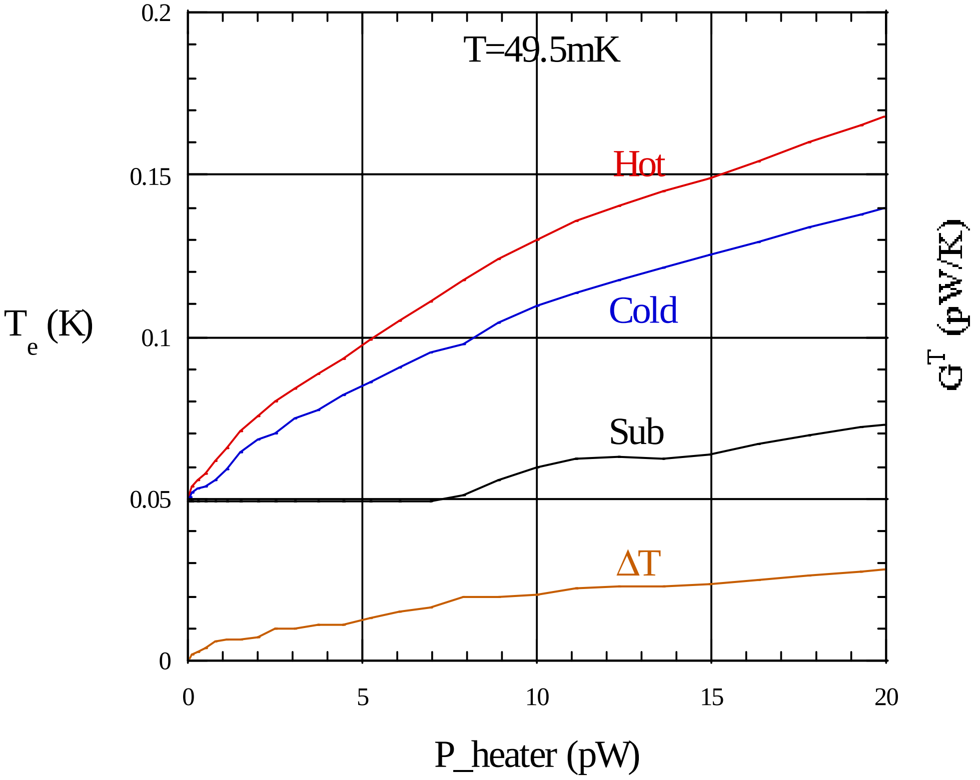
Thermal conductance of Andreev interferometer

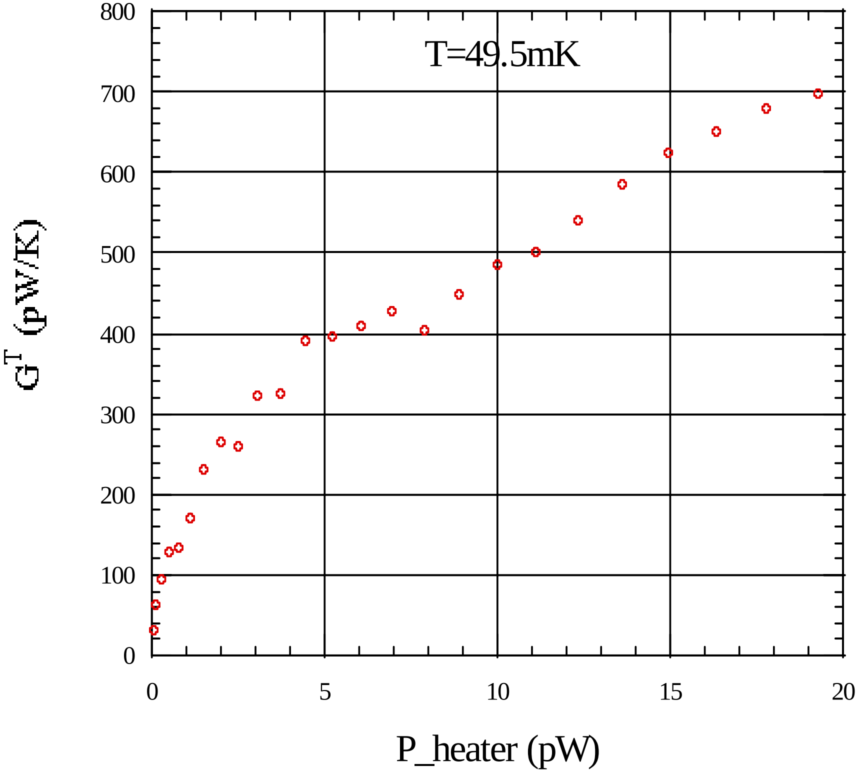




Jiang et al, cond-mat

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

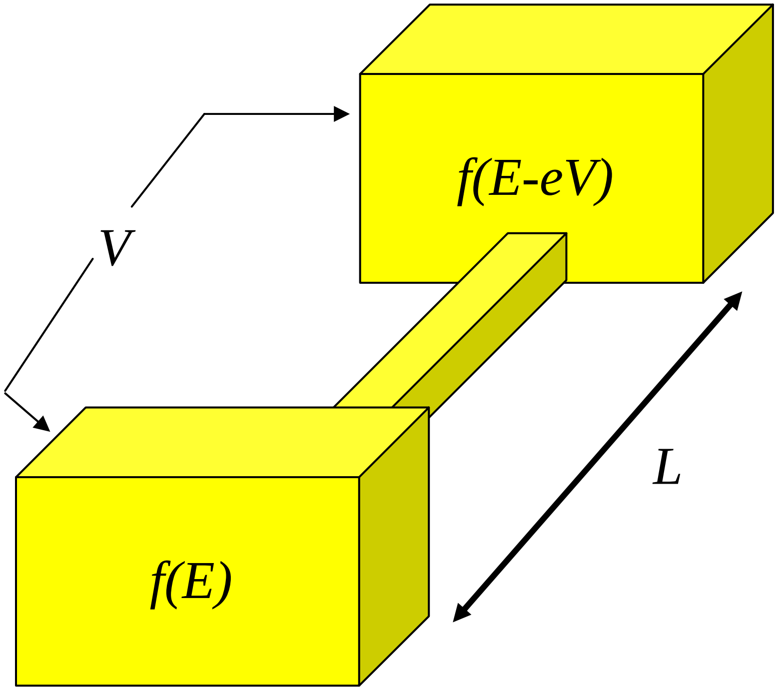
Thermal transport in normal metal systems

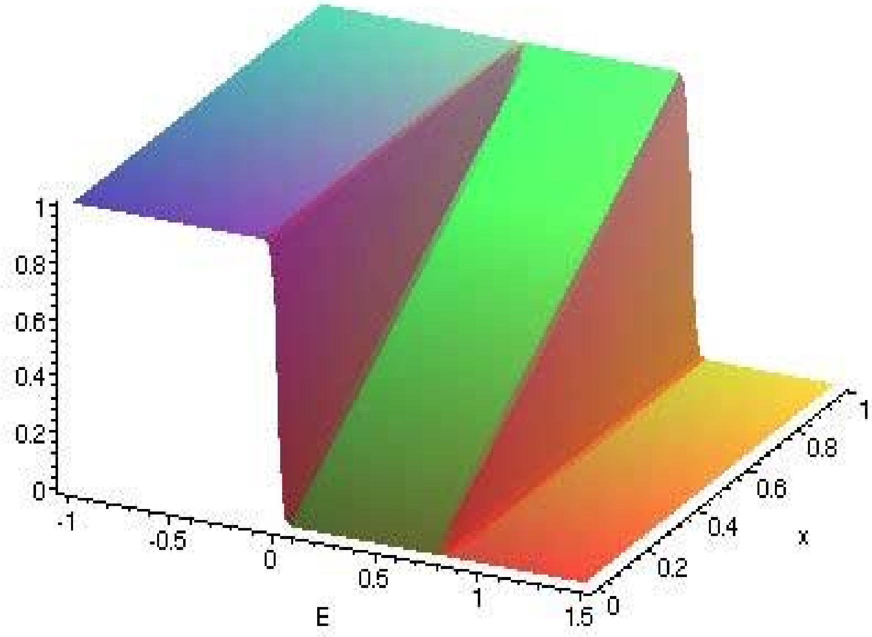
Nonequilibrium transport in mesoscopic devices

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

ID wire with voltage V applied

$$f(x,E)=[(f_R-f_L)(x/L)] + f_L$$



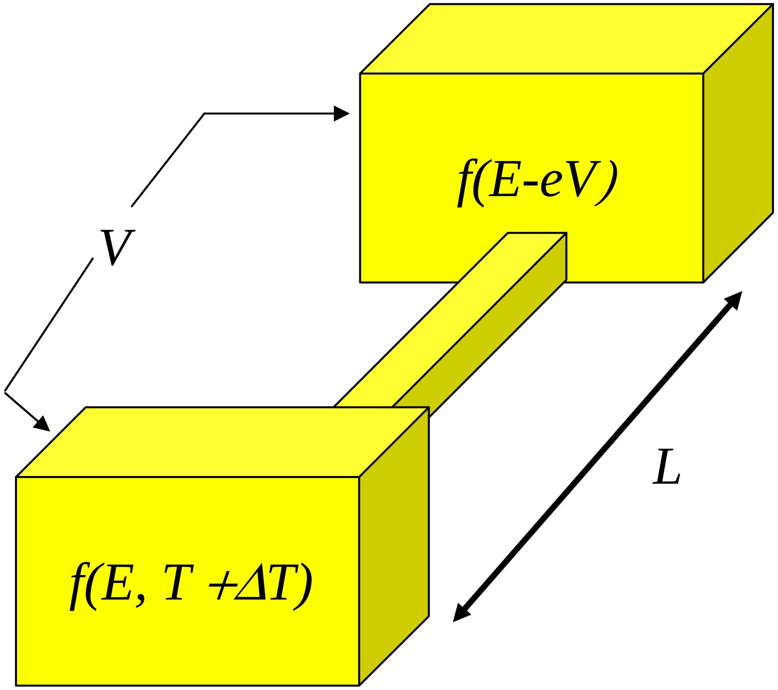


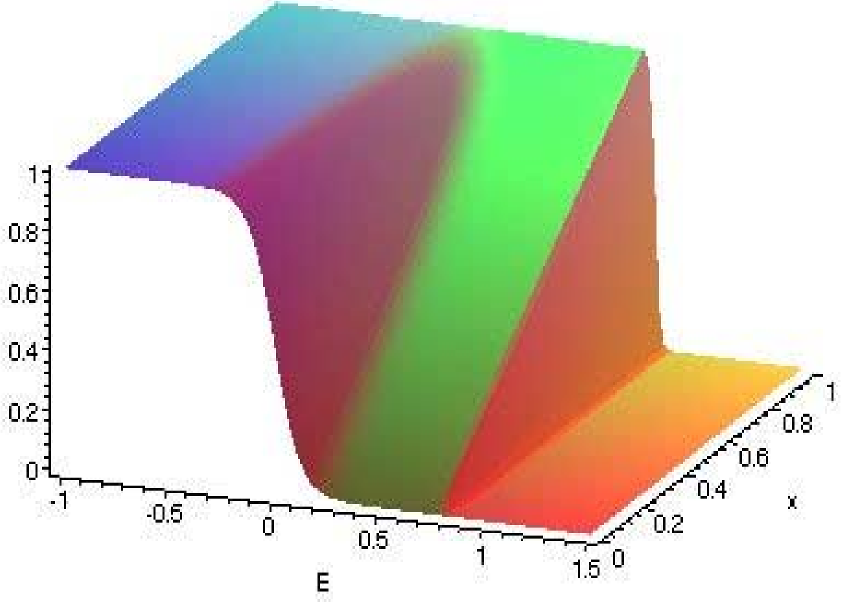
Nonequilibrium transport in mesoscopic devices

Thermal effects

ID wire with temperature differential applied,generates a thermal voltage

$$f(x,E)=[(f_R-f_L)(x/L)]+f_L$$





Diffusive Metals

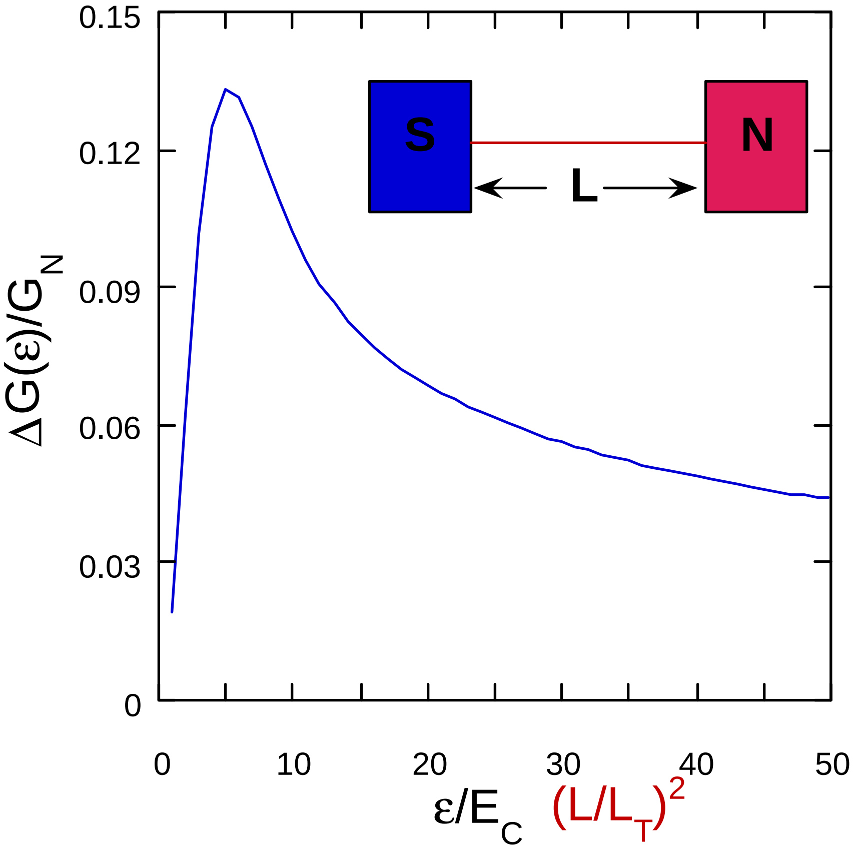
Energy dependent enhancement of diffusion coefficient

Characteristic *energy* scale

$$E_c = \frac{SD}{L^2}$$

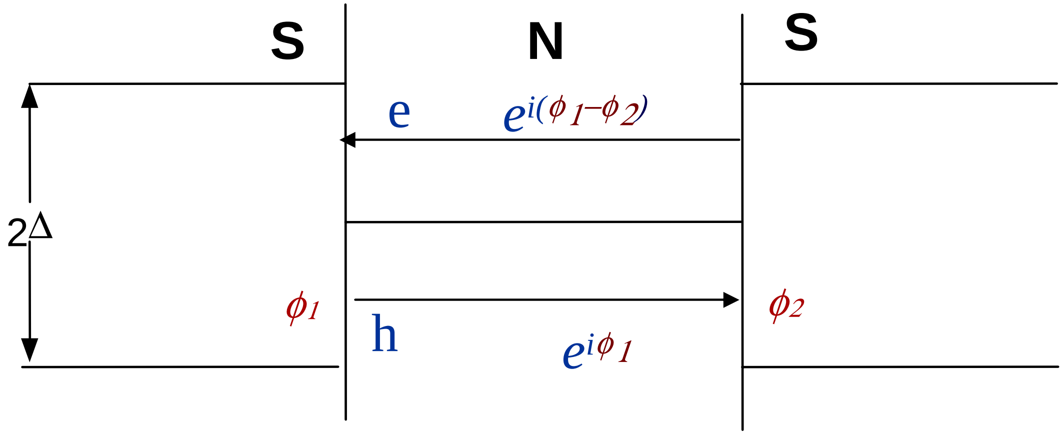
Characteristic *length* scale

$$L_T = \sqrt{\frac{SD}{k_B T}}$$



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