Thermal Effects in Andreev Interferometers

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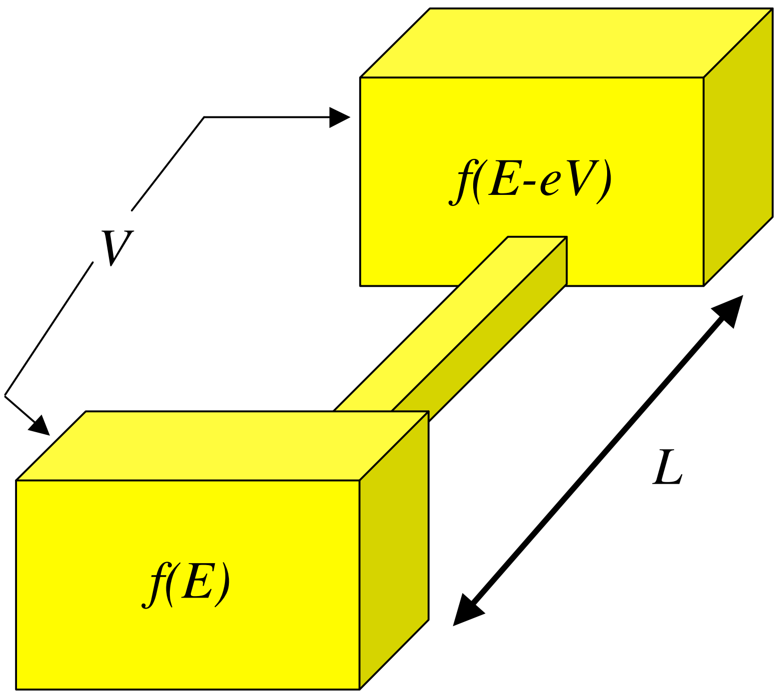
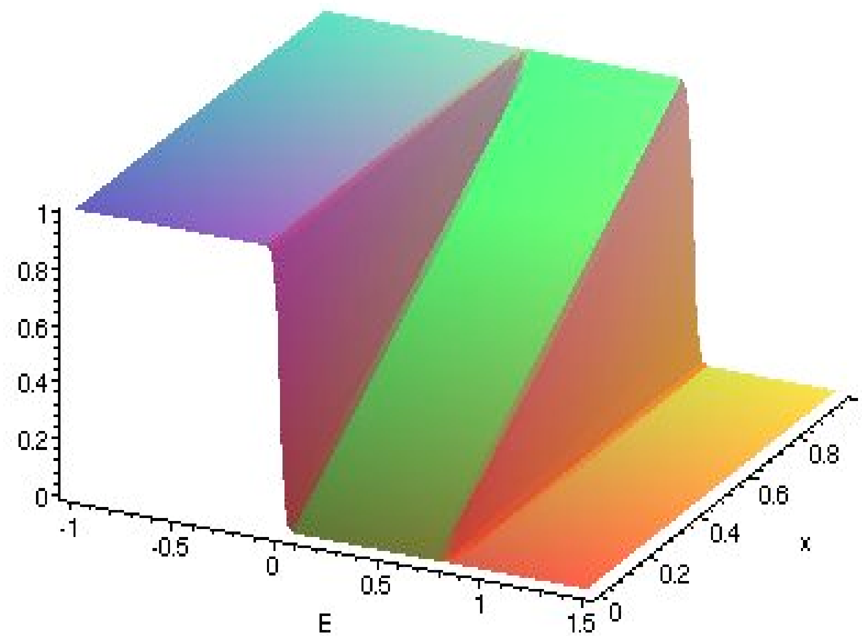
Nonequilibrium transport in mesoscopic devices

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

ID wire with voltage V applied

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



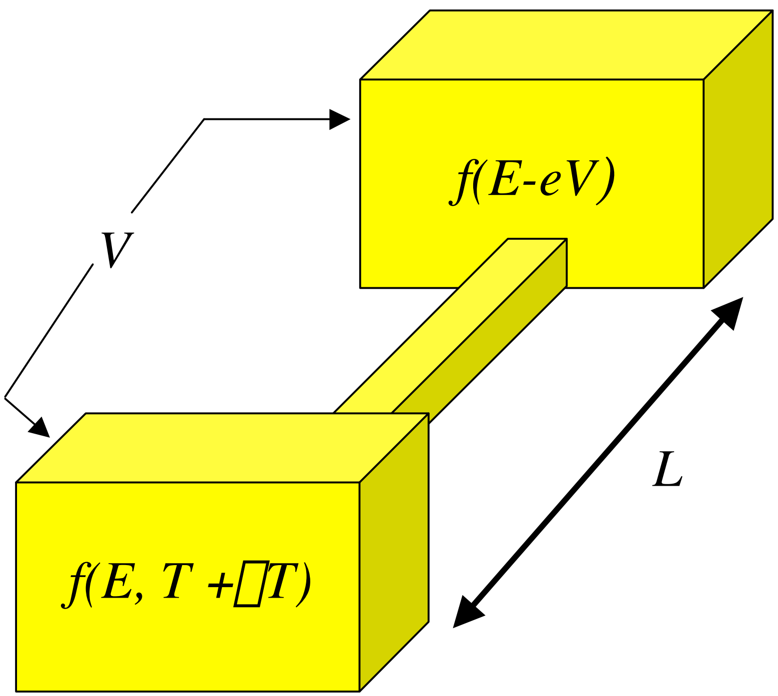


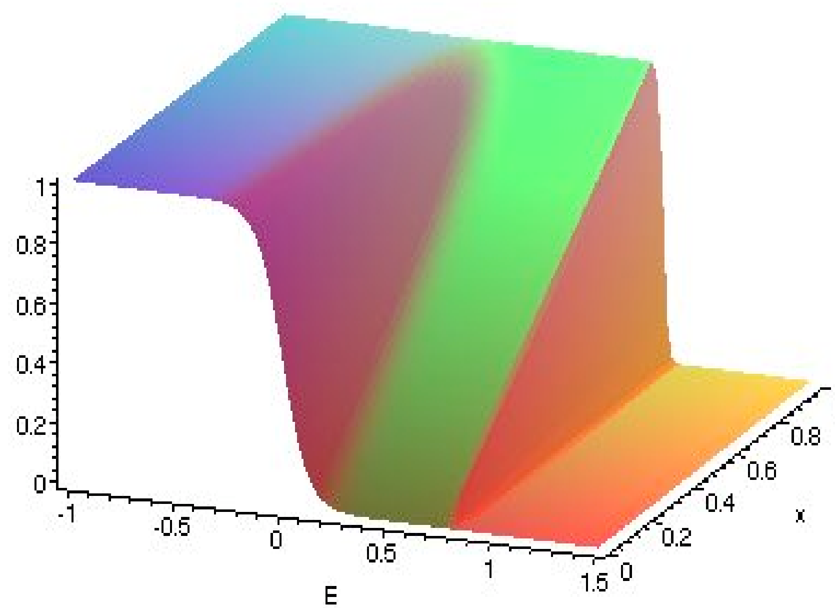
Nonequilibrium transport in mesoscopic devices

Thermal effects

ID wire with temperature differential applied, generates a thermal voltage

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



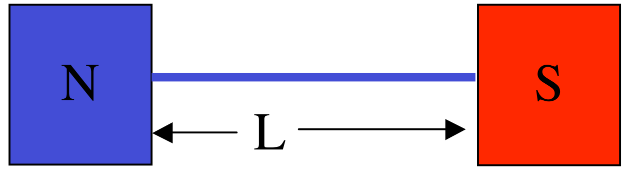


Proximity effect in diffusive normal metals

Reentrant behavior in temperature dependent resistance or differential conductance

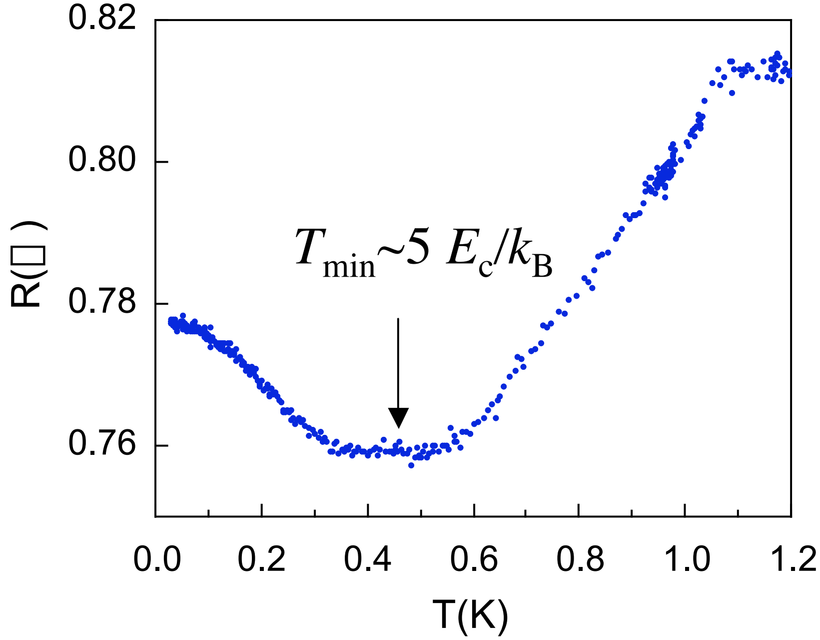
Resistance first decreases, then increases as temperature or voltage is decreased

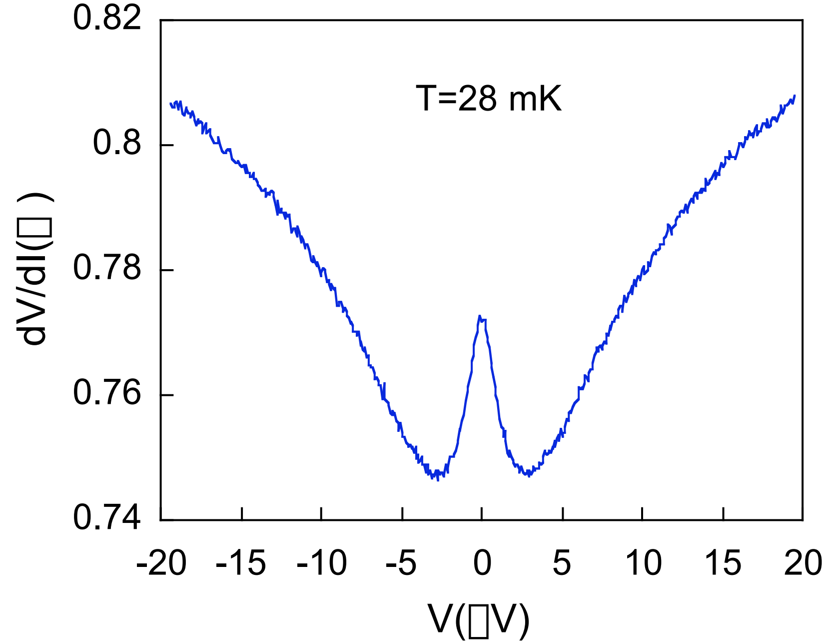
Charlat et al, PRL, 1996



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

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





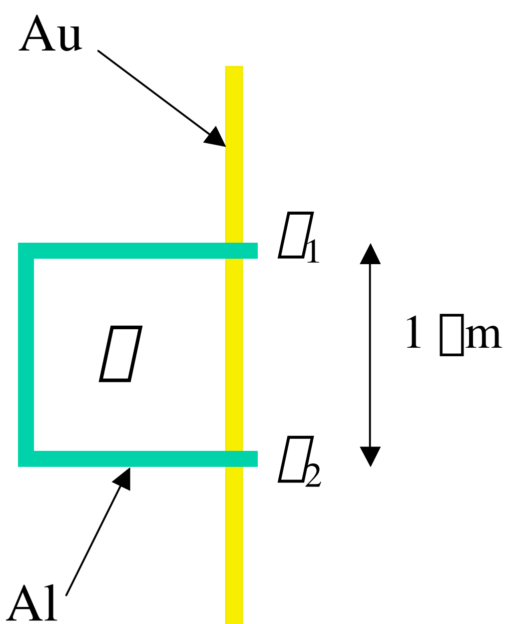
Interference effects

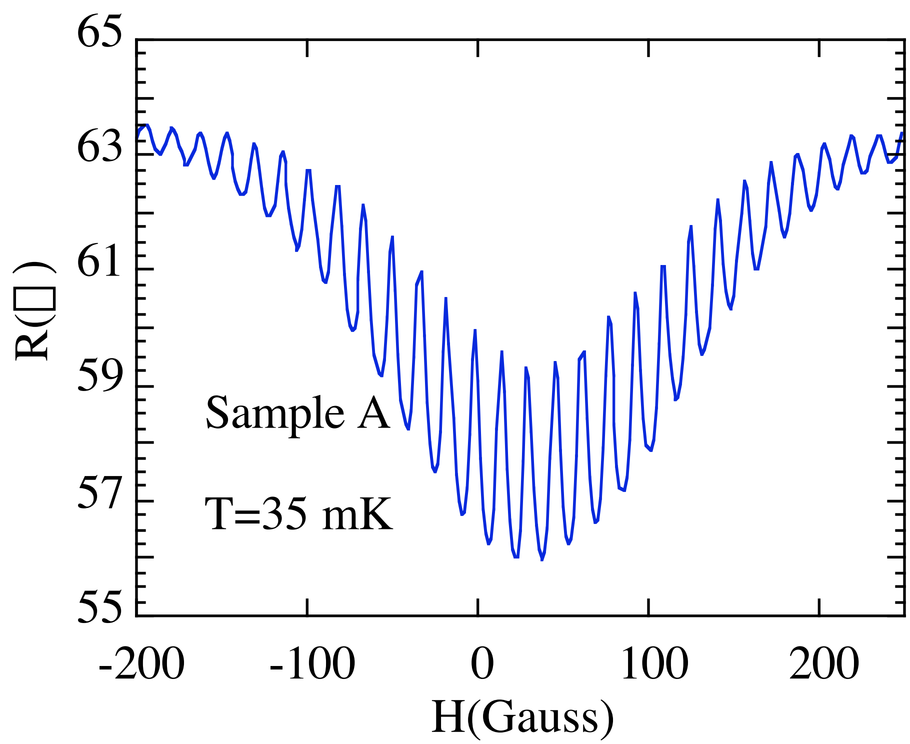
Andreev interferometers

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 properties of mesoscopic devices

Transport equations:

Electrical current $I = G\square V + \square\square T$

Thermal current $I^T = \square\square V + \square\square T$

Thermopower: ratio $\square V/\square T$ measured with $I=0$

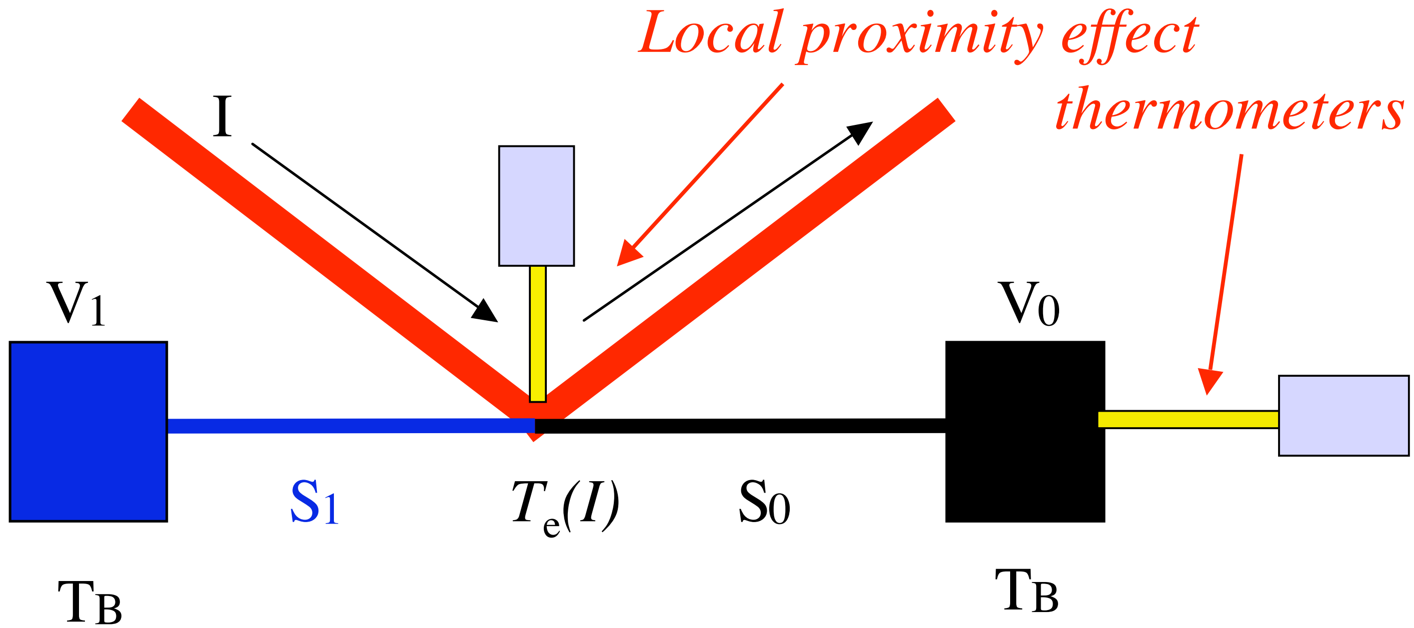
$$S = \square V/\square T = \square/G$$

Thermal conductance: ratio $I^T/\square T$ measured with $I=0$

$$G^T = I^T/\square T = S\square + \square\square\ \square$$

Small for typical metals

Mesoscopic thermopower measurements



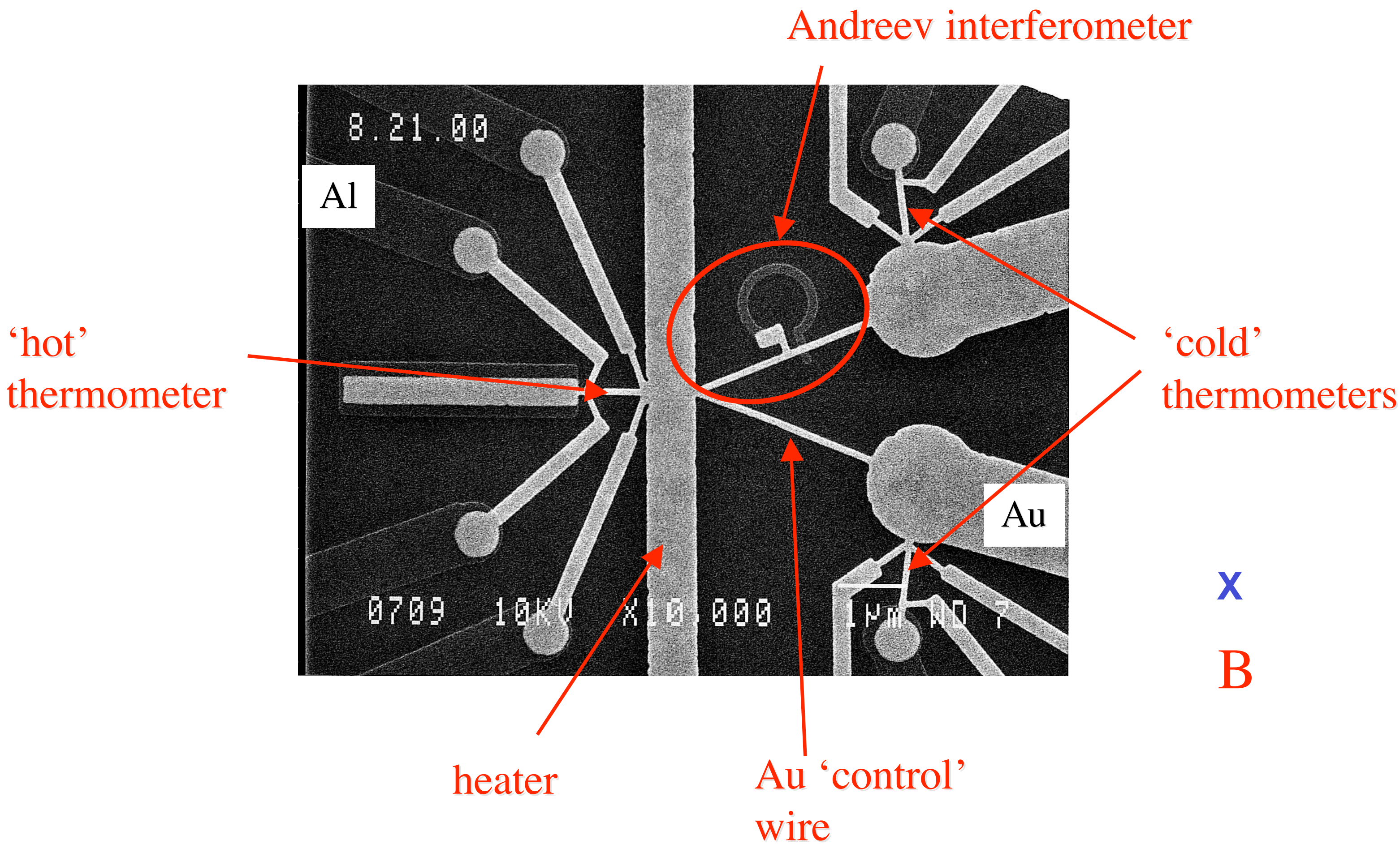
Local proximity effect thermometers

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



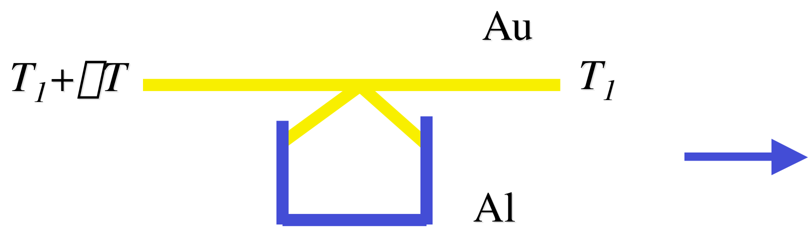
Sample parameters

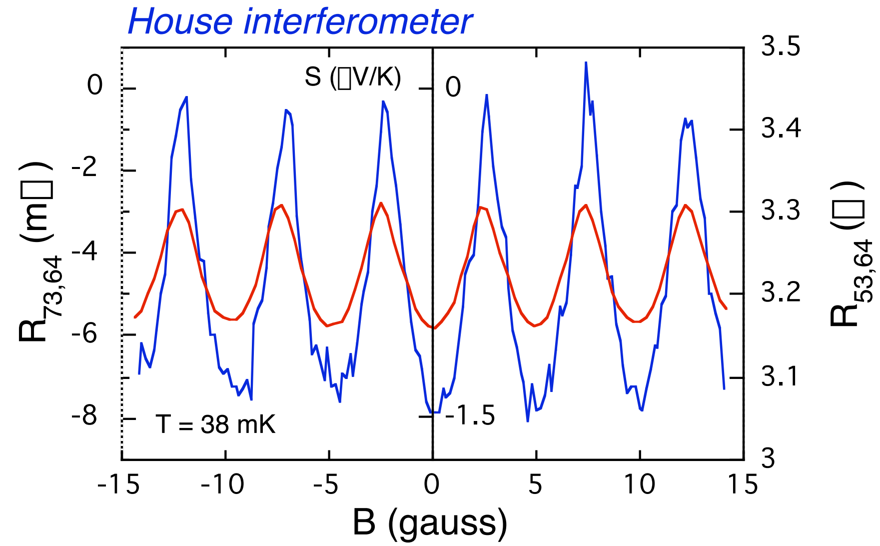
$L_T \sim 0.5$ μm at T=1 K

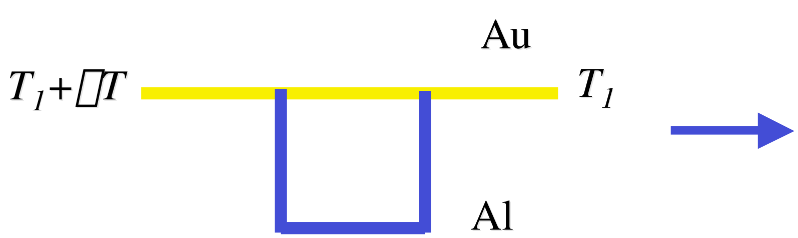
$L_\phi \sim$ 3-7 μm at base temperature

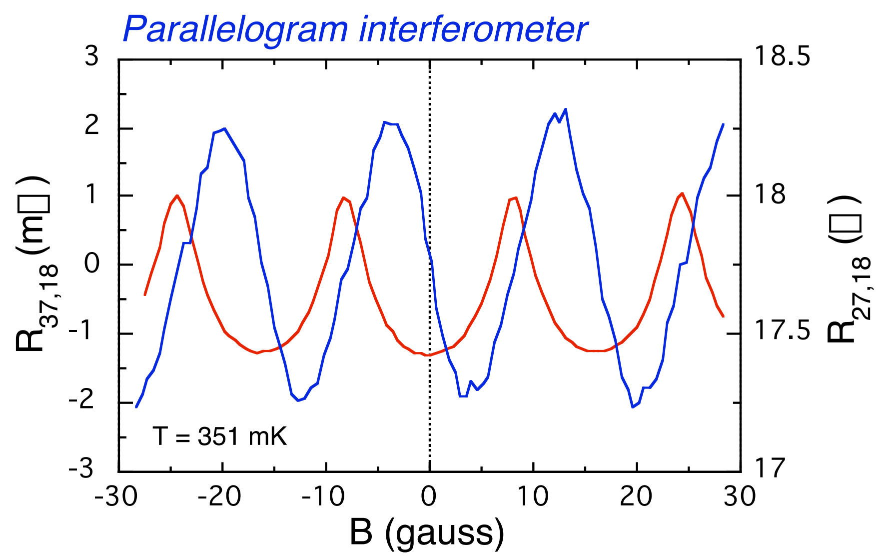
Symmetry of thermopower oscillations

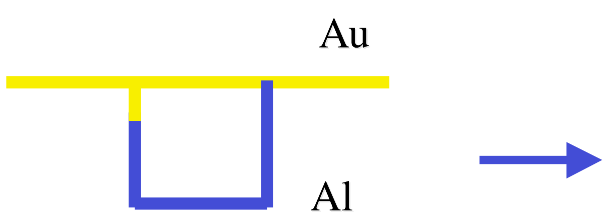
Resistance is always symmetric, but thermopower depends on topology











antisymmetric thermopower

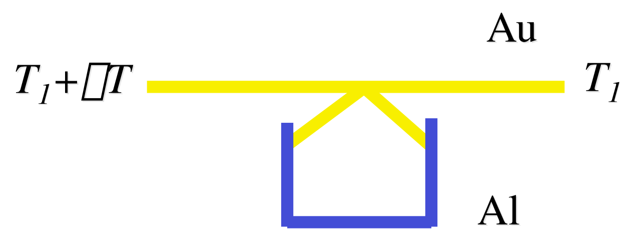
Symmetry of thermopower oscillations

Origin of antisymmetry?

Differences between sample topologies

House interferometer

Oscillations are symmetric in flux

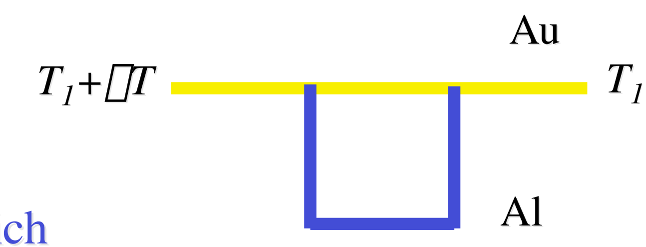


No temperature gradient across superconductor

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

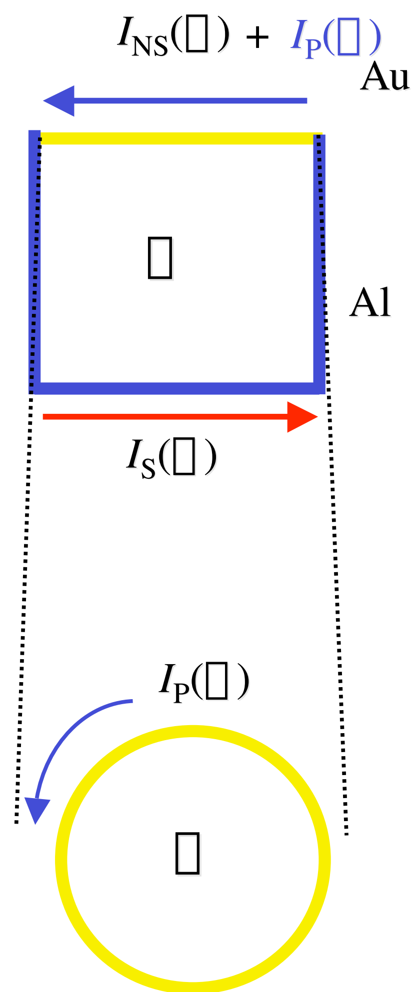
At low temperatures, proximity effect supercurrent I_{NS} through normal-metal arm if

$$L < \square_N = L_T$$

Additional contribution due to normal-metal *persistent* current I_P if $L < L_\square$

Total current through normal metal

$$I_P + I_{NS} = I_S$$

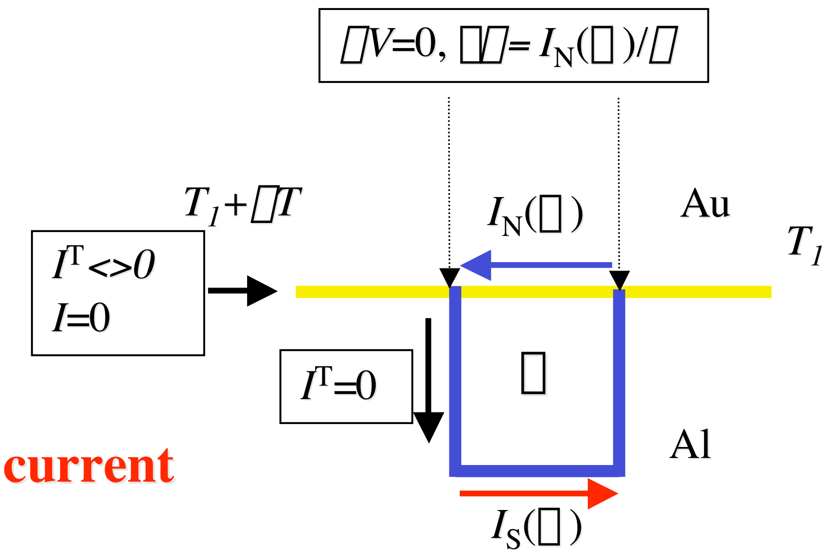


All currents antisymmetric in magnetic field

Symmetry of thermopower oscillations

Interplay of electrical and thermal currents

If normal-metal is phase coherent,
magnetic flux □ induces 'persistent current'
which is antisymmetric in □



Persistent current drags along a thermal current

Across normal part of loop:

$$I_N(\square) = G\square V + \square\square T \quad \longrightarrow \quad \square T = I_N(\square)/\square$$

$$\square I^T = \square\square V + \square\square T \qquad \square I^T = \square I_N(\square)/\square$$

(the $\square V$ terms are struck through and marked 0)

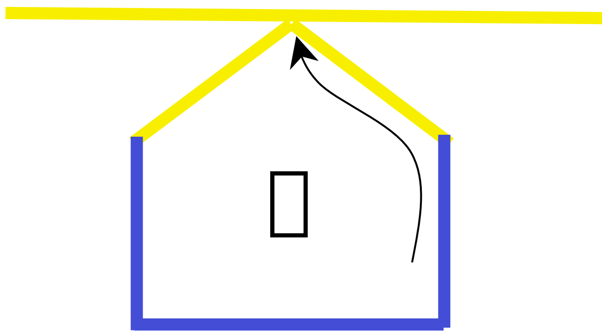
Difference in thermal voltage between normal control wire and Andreev interferometer

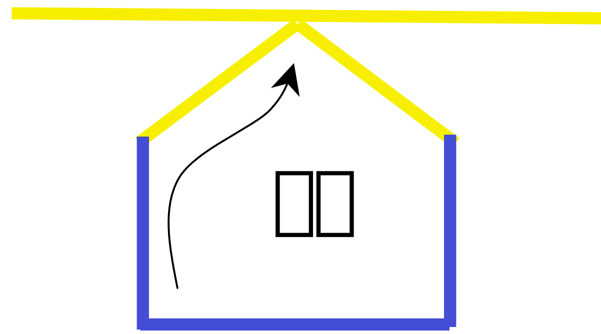
$$\square\square V = S_A - S_N \sim (\square_{side}/G_{side})\,(\square_{arm}/\square_{arm})\, I_N(\square),$$ *antisymmetric in □*

Rough estimates ~ I_N ~ 30 nA

Symmetry of oscillations in house interferometer

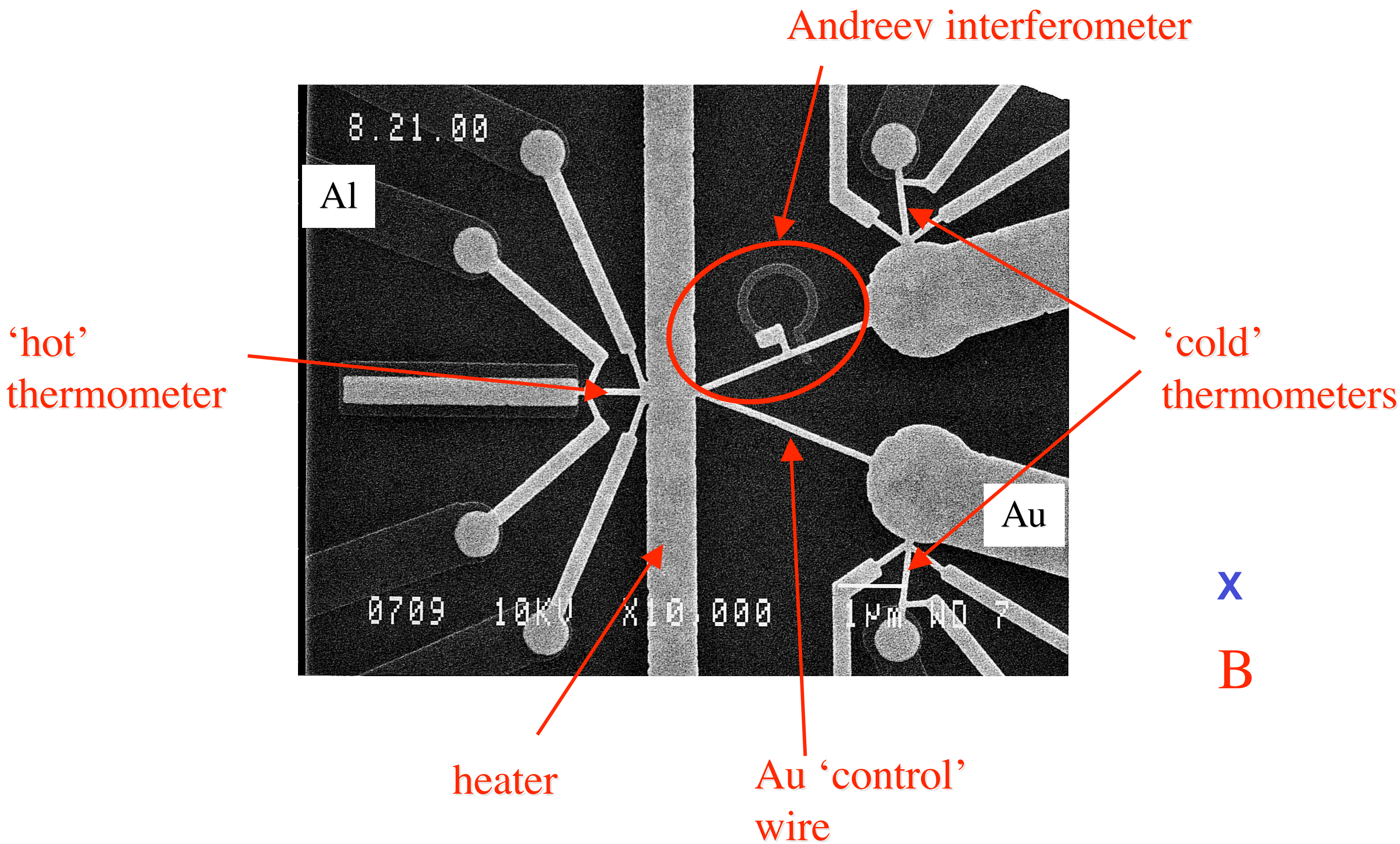
Thermal current cannot enter superconductor





Thermal transport is symmetric with magnetic flux

Temperature Dependence of Thermopower



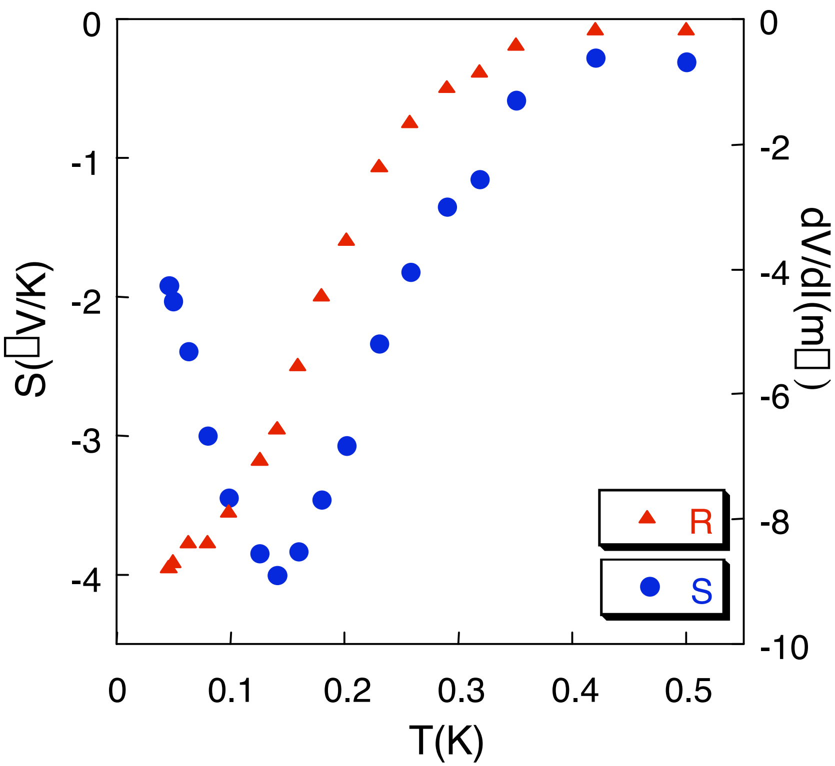
Measure effective electron temperatures with local proximity thermometers

Temperature dependence of thermopower oscillations

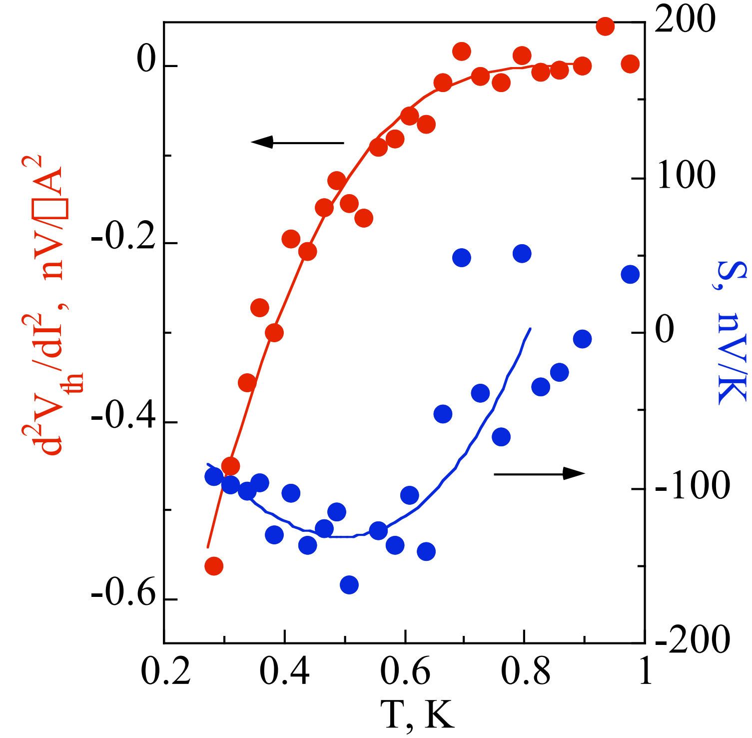
T_{min} appears to depend on dimensions of interferometer

related to temperature dependence of persistent currents?

'House' interferometer,
Eom et al., PRL (1998)
L~7 □m, T_{min}~0.14 K

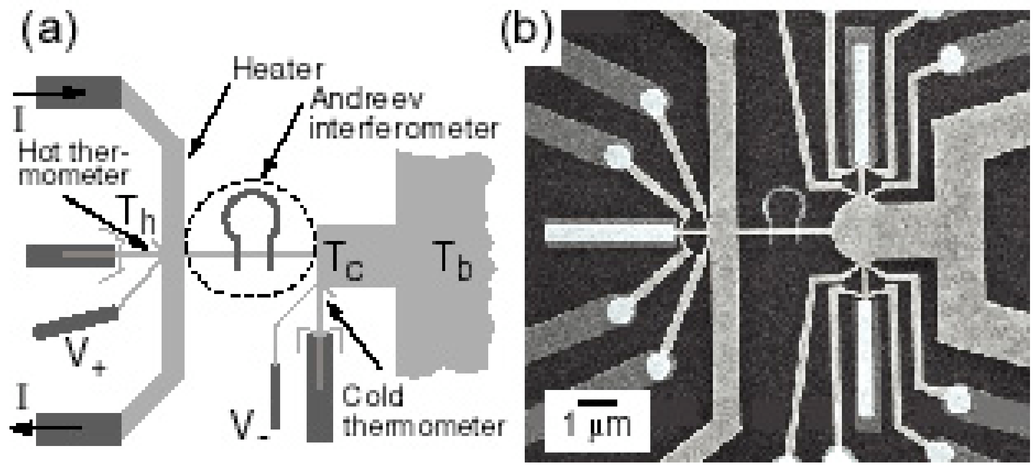


'Hook' interferometer,
Dikin et al., EPL (2002)
L~2.7 □m, T_{min}~0.5 K

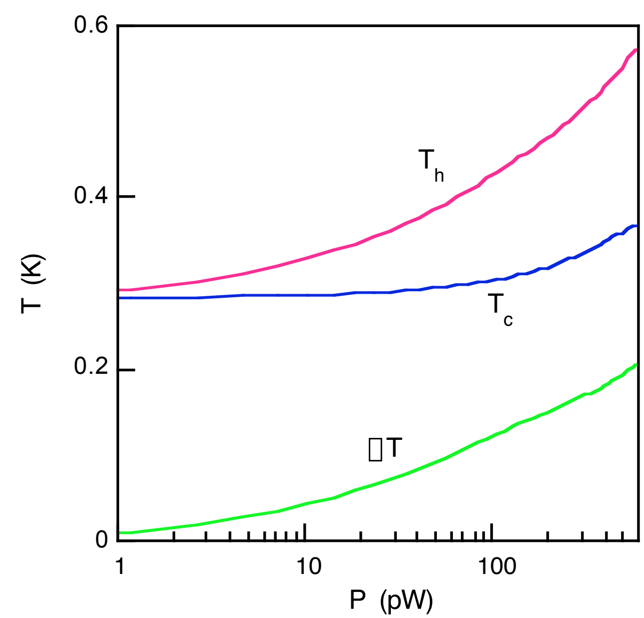


Thermal conductance of mesoscopic devices

Local thermometry technique permits us to make quantitative measurements of temperature differentials (*Dikin et al, PRB, to appear*)



Superconducting contacts on heater permit heat to flow out only through Andreev interferometer



Temperature differential measured by warm and cold thermometers as a function of heater power

Thermal conductance $\kappa=P/\Delta T$

Thermal conductance of ‘parallelogram’ Andreev interferometer

Measured thermal conductance of interferometer at T~0.3 K is G^{T}=0.12 nW/K

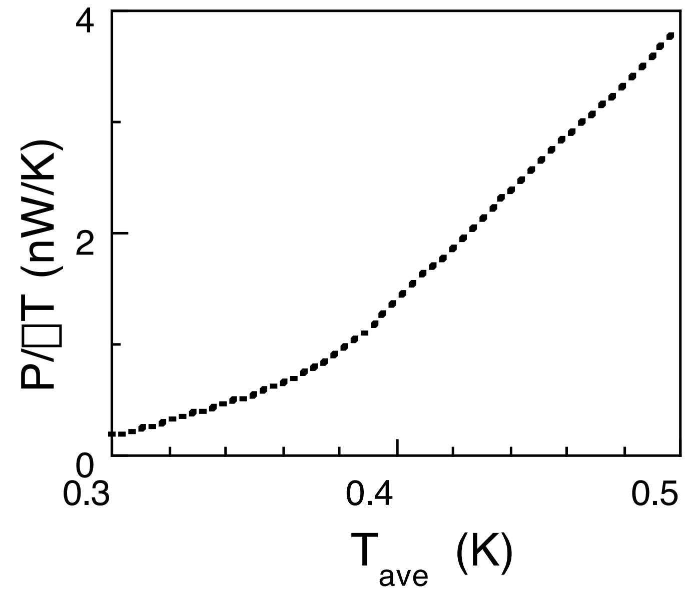
Thermal conductance of equivalent Au wire is
G^{T}= 1.3 nW/K

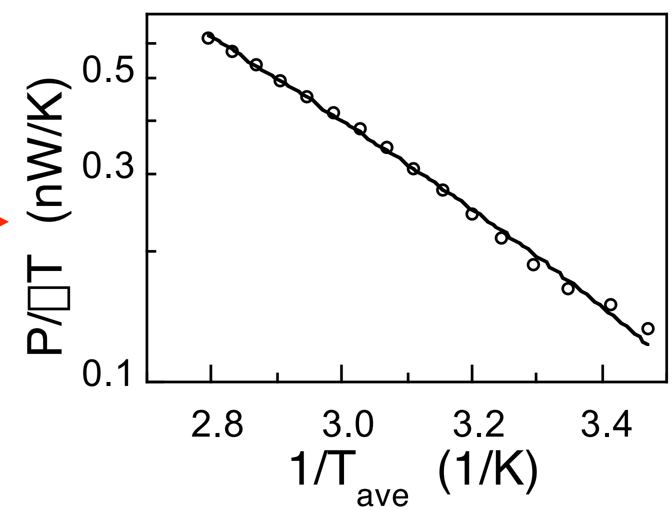
Smaller by factor of 10

Thermal conductance determined by superconducting parts?

$$G_S^T \approx G_N^T \frac{6}{\pi^2}\left(\frac{\Delta}{k_B T}\right)^2 e^{-\Delta/k_B T}$$

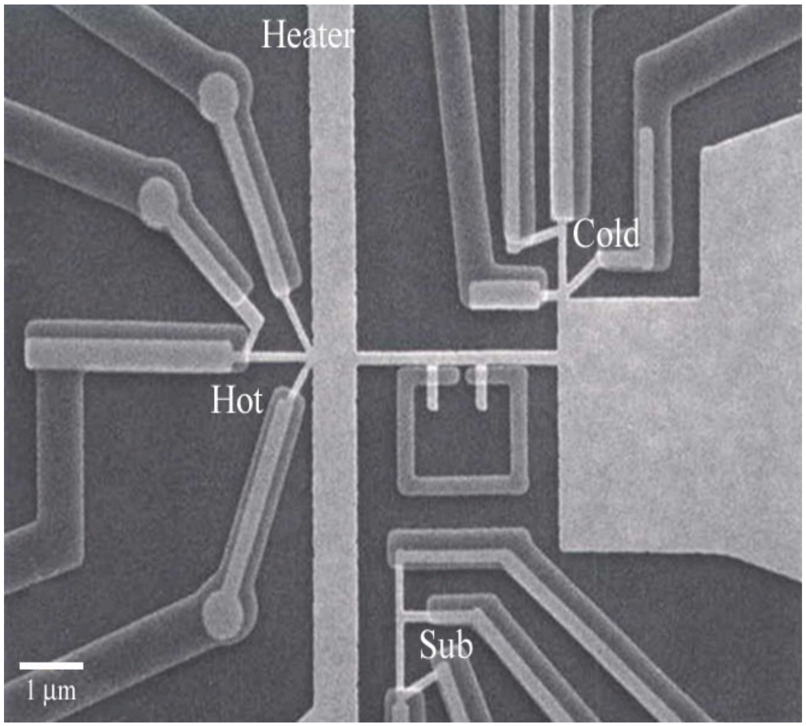
Fit to formula, with Δ~200 μeV
Δ_{Al}~183 μeV

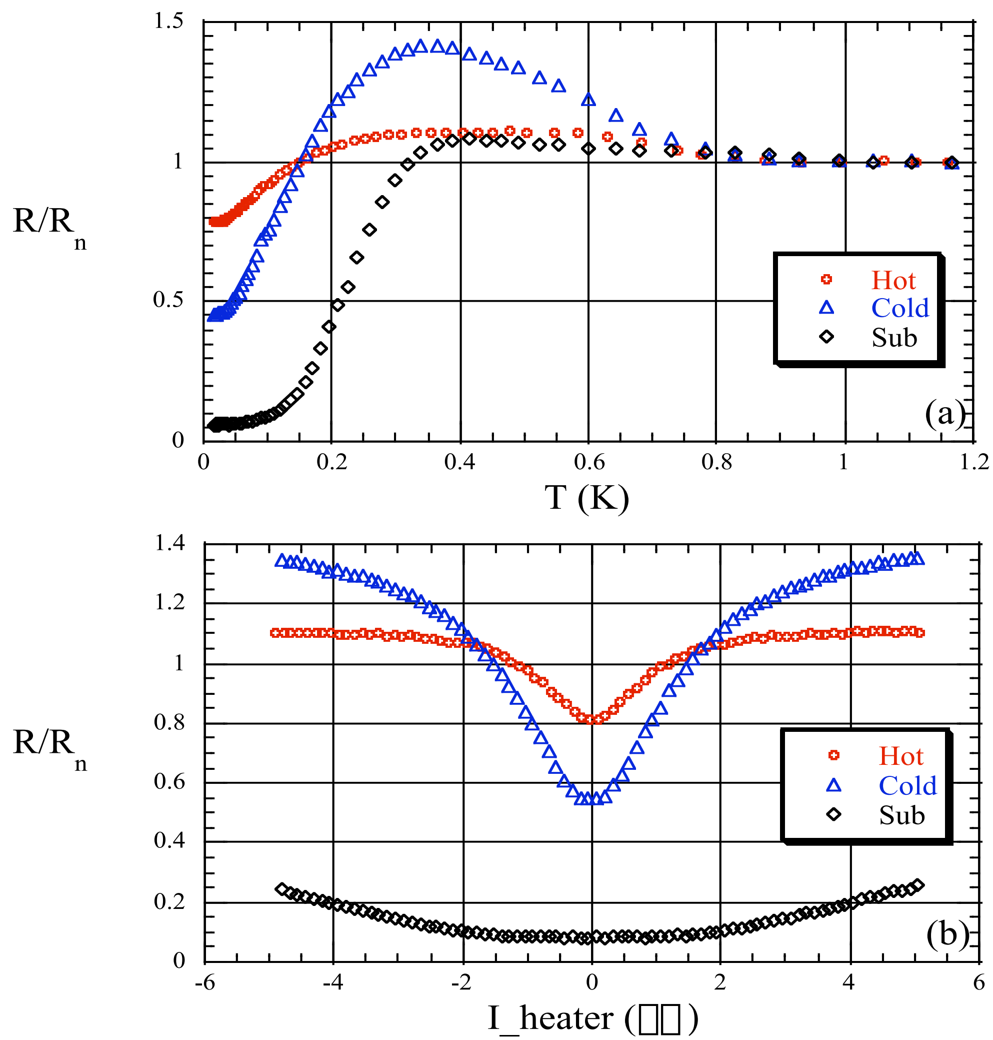




Thermal conductance of Andreev interferometer

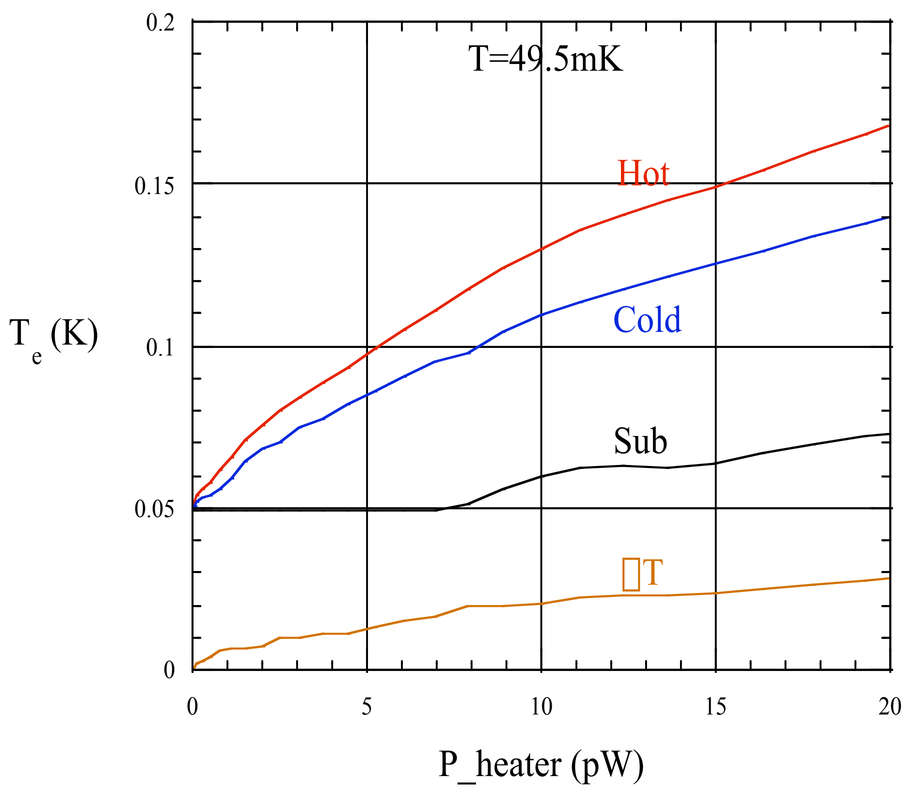
All power dissipated in heater goes through sample

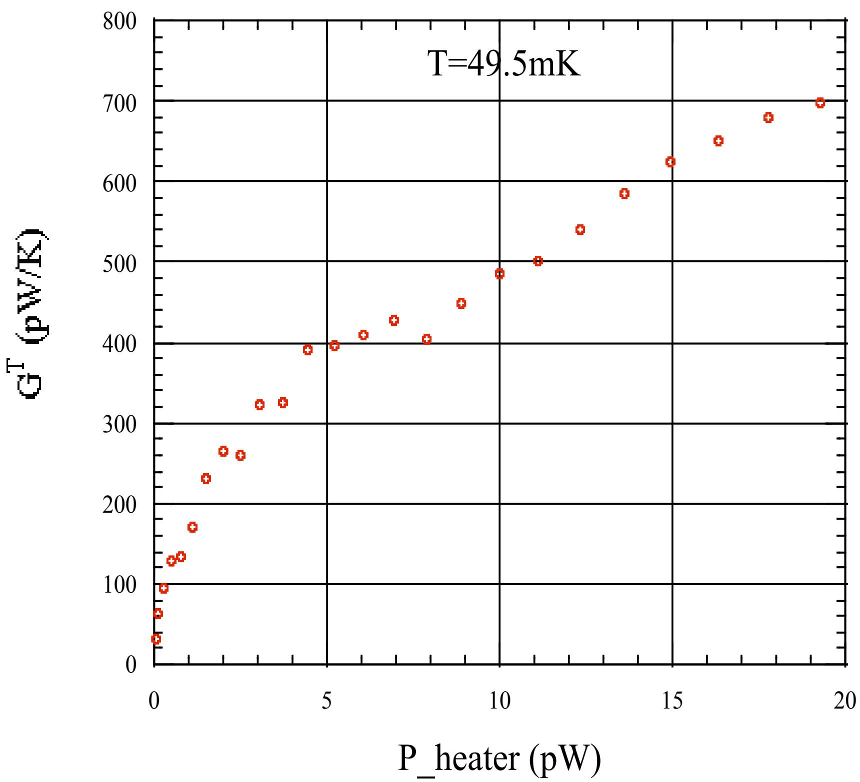




Jiang et al, cond-mat

Thermal conductance of Andreev interferometer

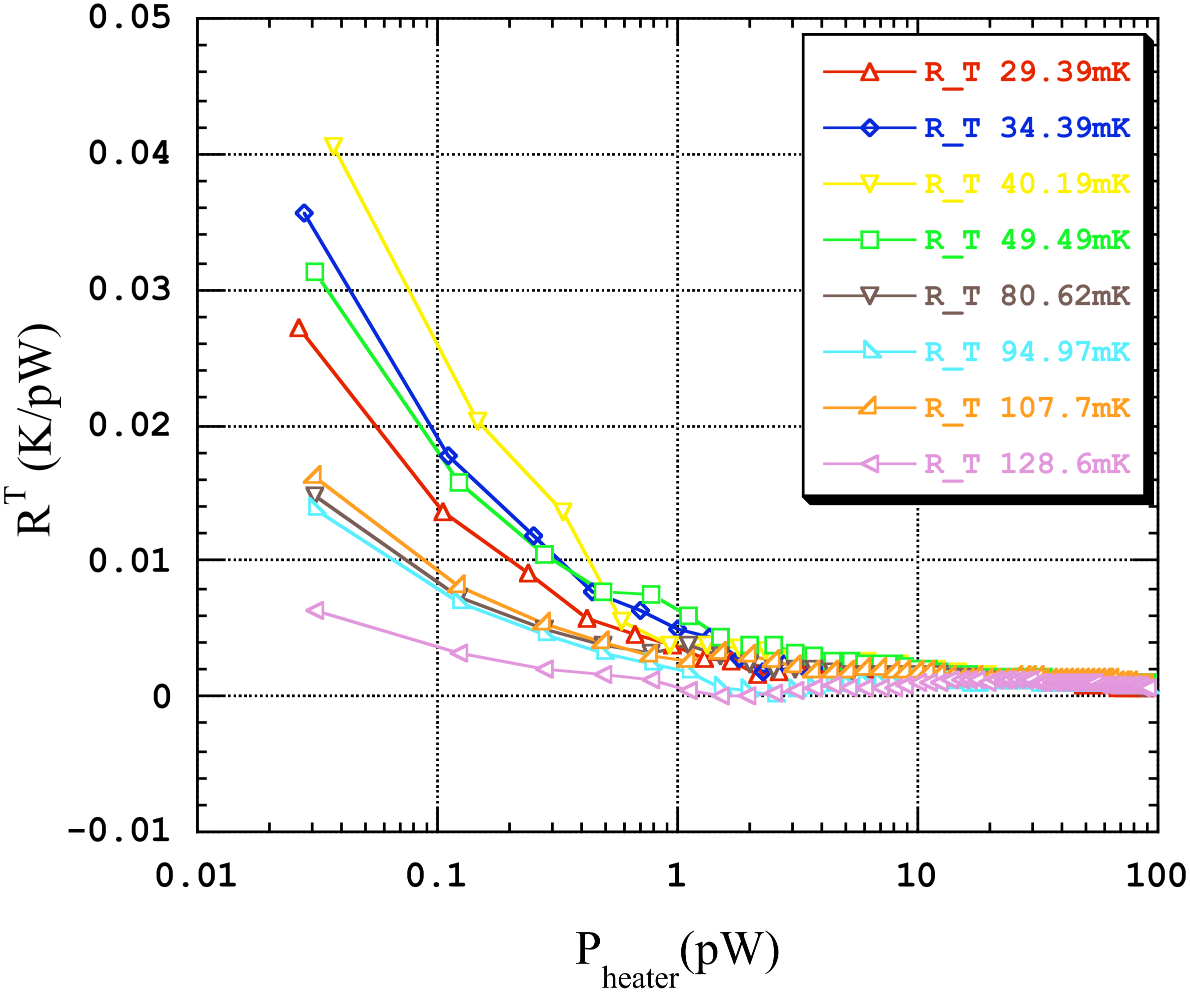




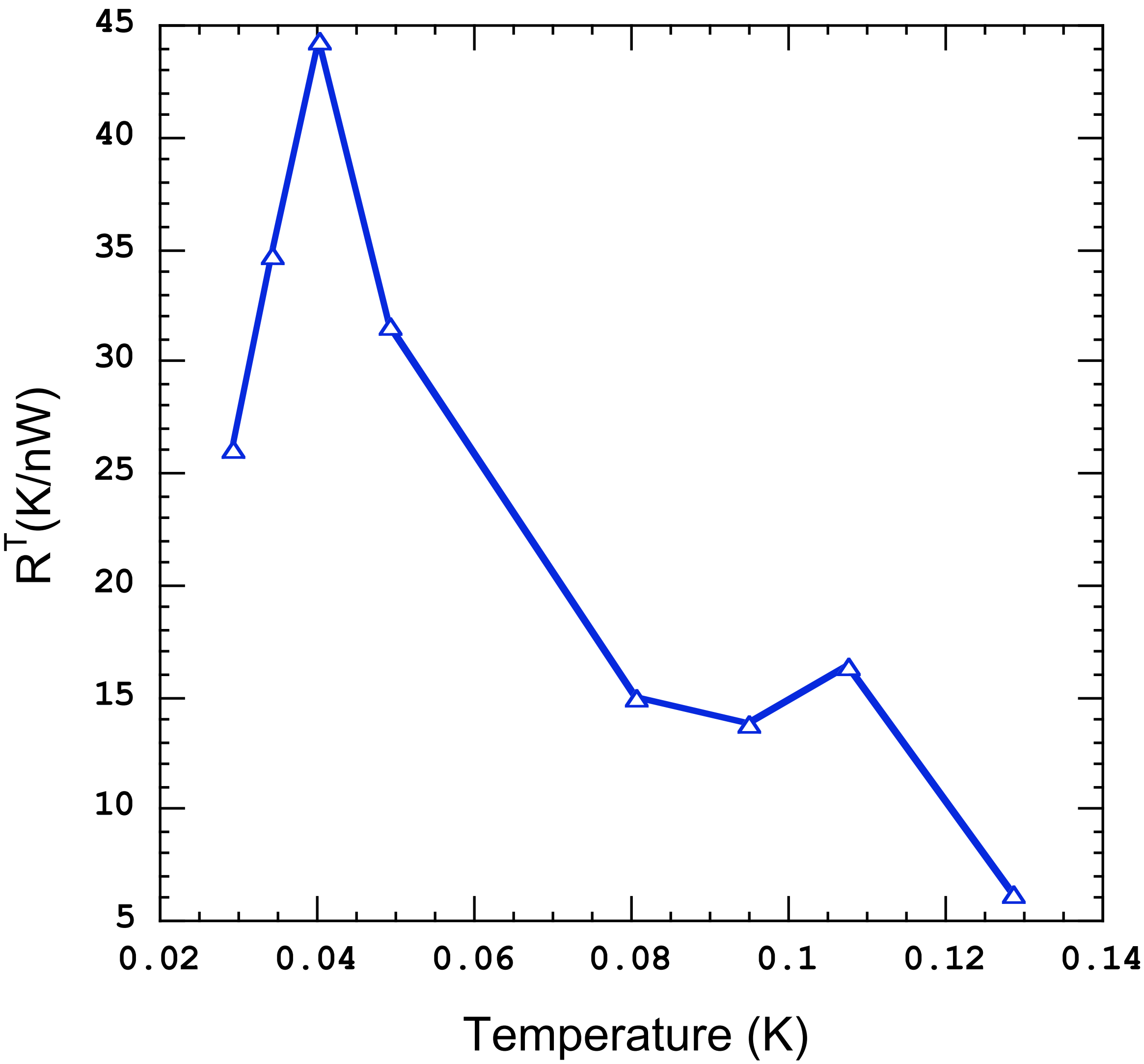
Thermal conductance ~7x smaller than corresponding normal wire at same temperature

Nonlinear thermal conductance

Thermal resistance of an Andreev interferometer



Temperature dependence of the thermal resistance



Future work

Symmetry of thermopower: control of thermal currents by local tunable fields

Detailed quantitative measurement of thermal conductance in mesoscopic samples

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