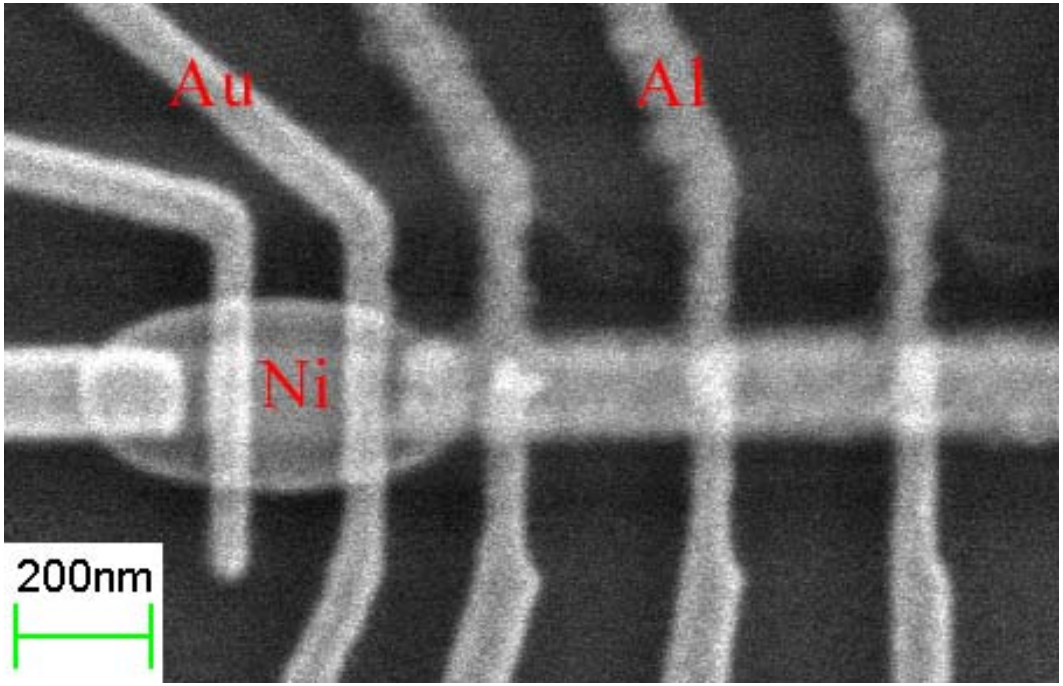
Charge Imbalance, Elastic Cotunneling, and Crossed Andreev Reflection: Non-Local Effects in Normal-Superconducting Systems



Zhigang Jiang,
Paul Cadden-Zimansky,
Venkat Chandrasekhar
Northwestern University

Argonne National Laboratory, May 5, 2005

Funded by the US NSF

Interface Resistance

For NS interfaces, resistance can be described by the BTK model

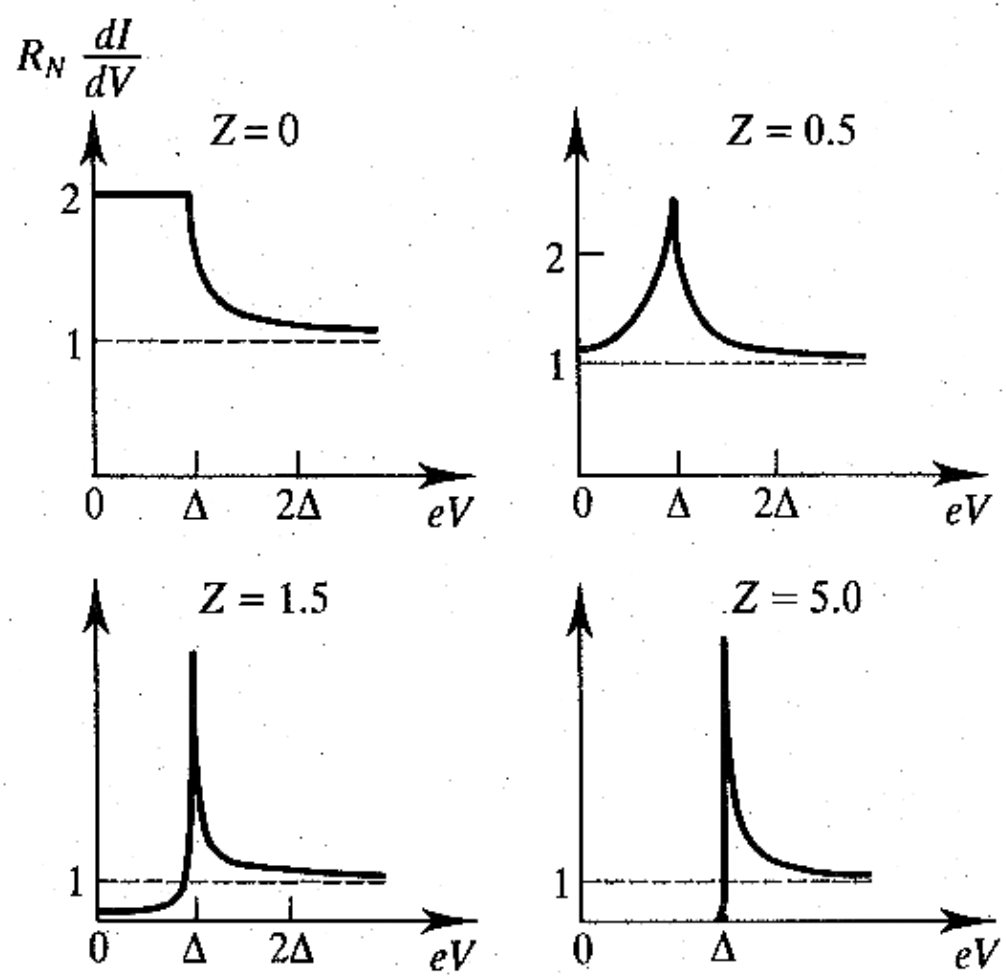
(Blonder, Tinkham and Klapwijk [PRB (1982)]

$$I_{NS} = 2N(0)ev_F A\int_{-\infty}^{+\infty}\left[f_0(E-eV)-f_0(E)\right]\left[1+A(E)-B(E)\right]dE$$

A(E) → *probability of Andreev reflection at NS interface*

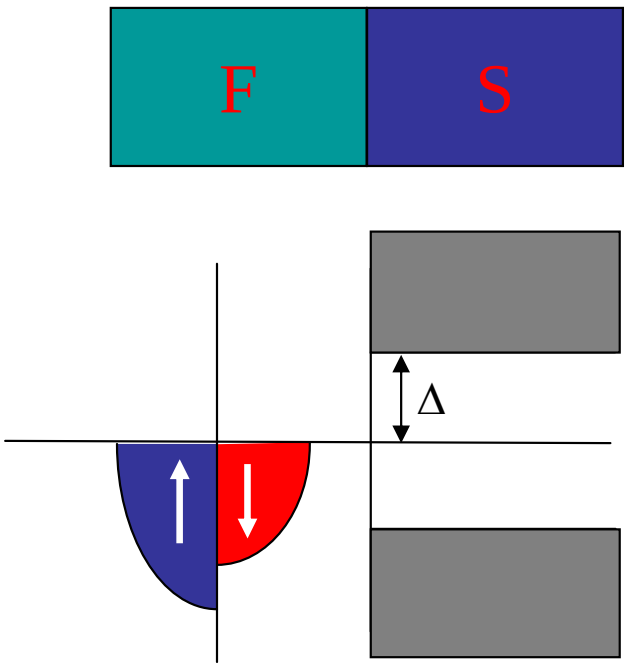
B(E) → *probability of normal reflection at NS interface*

Z → *Strength of interface barrier* $T=(1+Z^2)^{-1}$



Spin-polarized BTK model

Include effects of spin-polarization and Zeeman splitting of quasi-particle spectrum



Fraction *a* of spin-up electrons (2*a*-1=*P*)
(*P for Ni is* 20-30%)

Split currents into *u*npolarized and *p*olarized parts (modified polarized BTK coefficients, A_p=0)

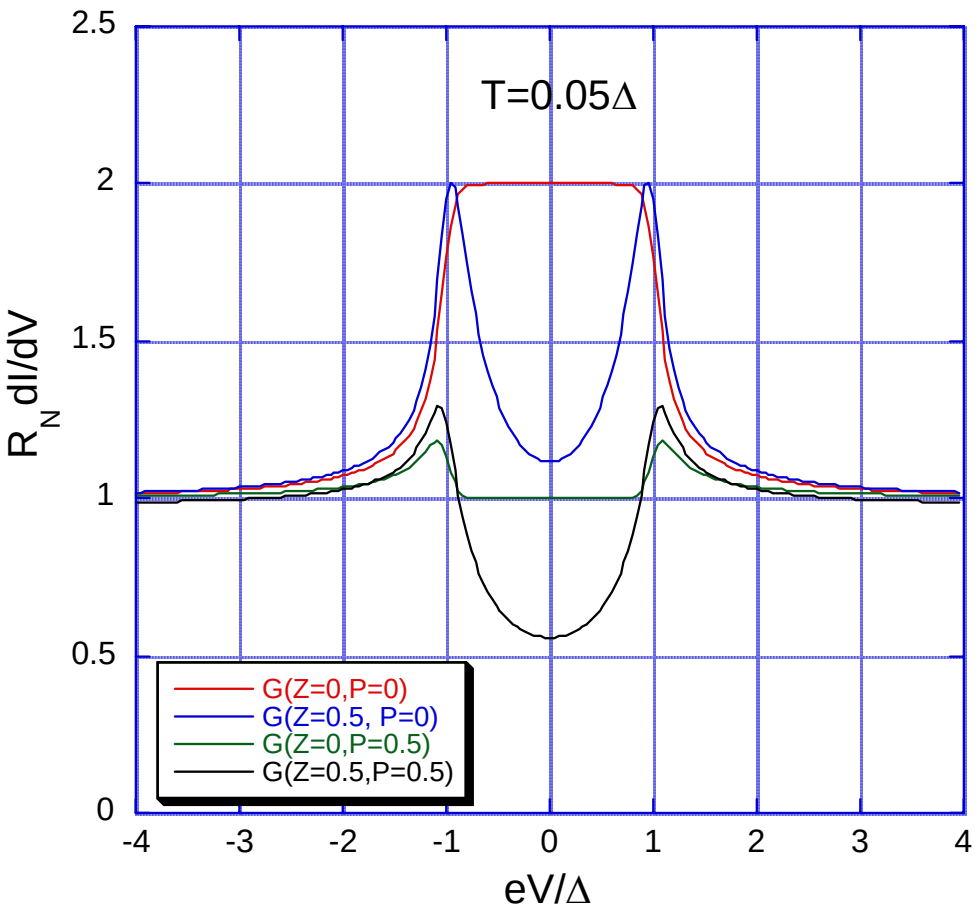
Strijkers et al, Mazin et al, Belzig et al, Golubov

$$I_{NS} \propto \int \{(1-P)[(1+A_u(E-g\mu H)-B_u(E-g\mu H))+ (1+A_u(E+g\mu H)-B_u(E+g\mu H))]+ P(1-B_p(E-g\mu H))\}(f(E-eV)-f(E)\}dE$$

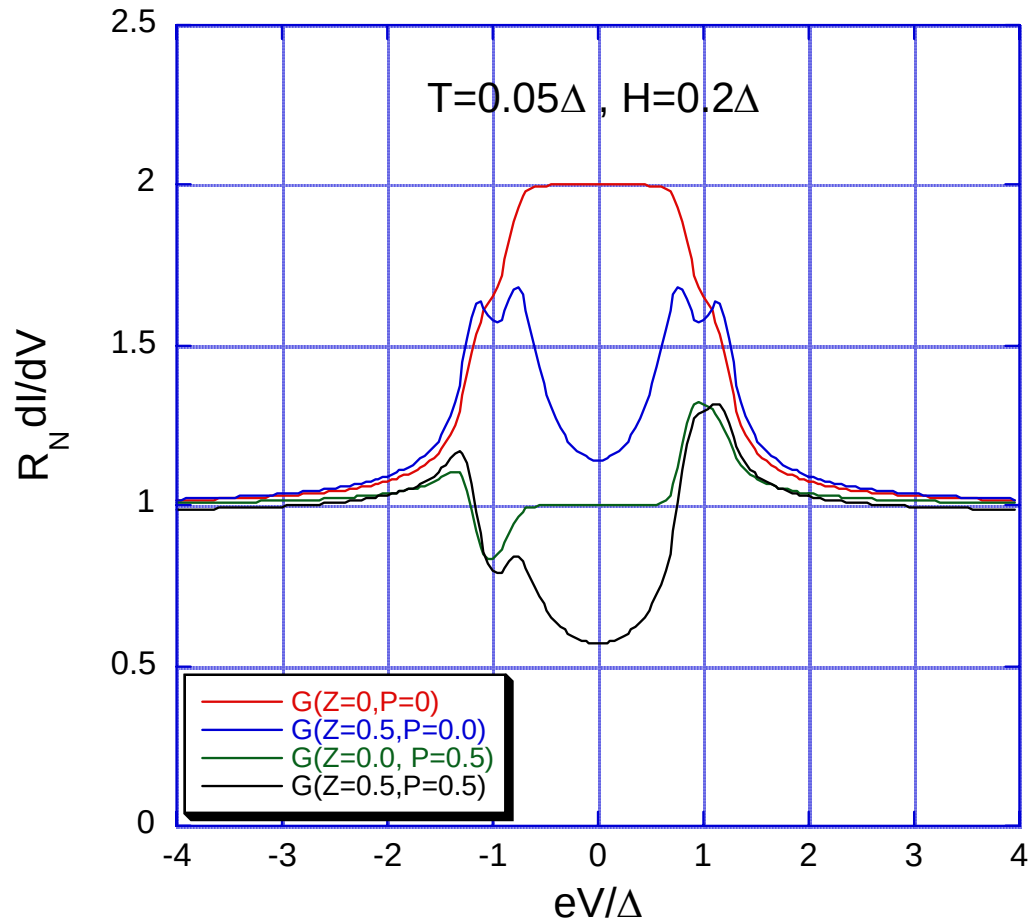
Spin-polarized BTK model

Jiang et al., cond-mat/0311334

BTK with finite spin-polarization

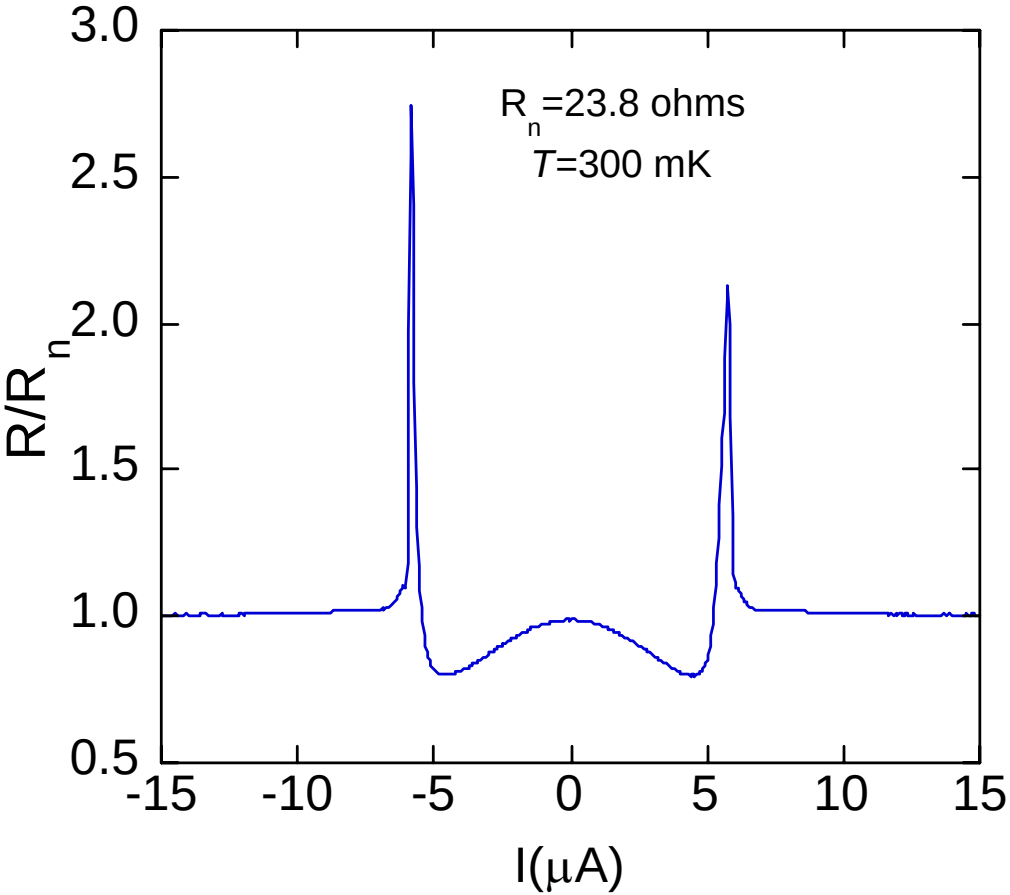


BTK with finite spin-polarization+ Zeeman split quasiparticle spectrum



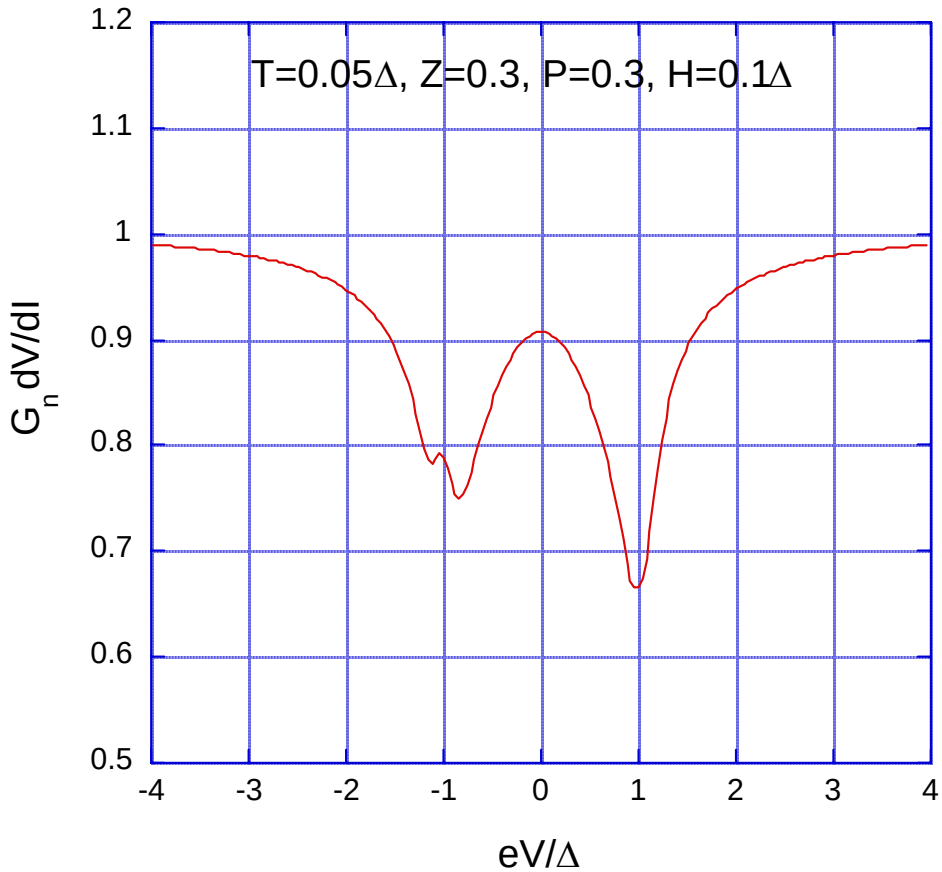
FS interface differential resistance

Experimental FS differential resistance (J. Aumentado, 2001)



BTK spin-polarization simulation

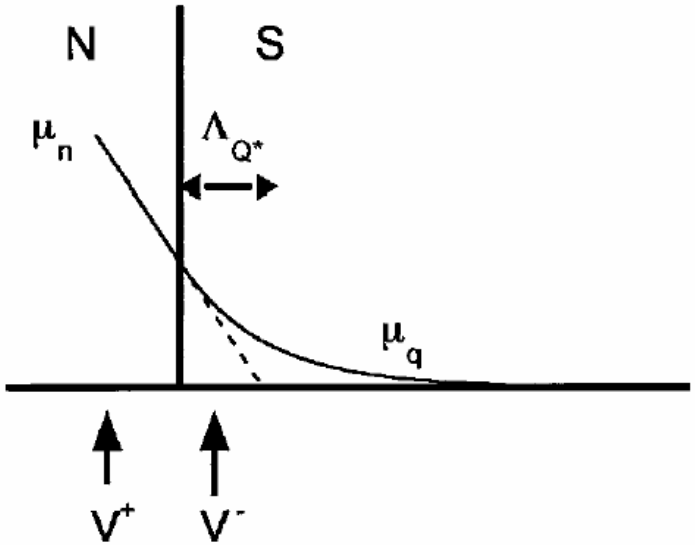
No peaks!

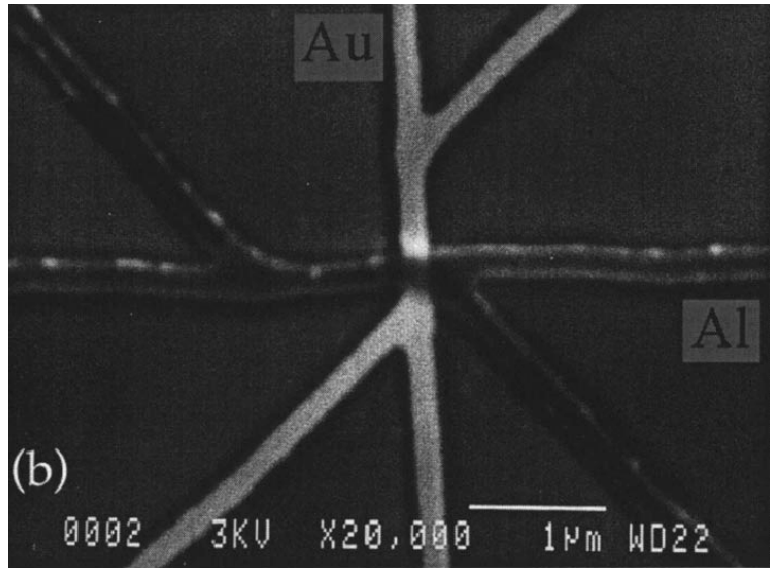


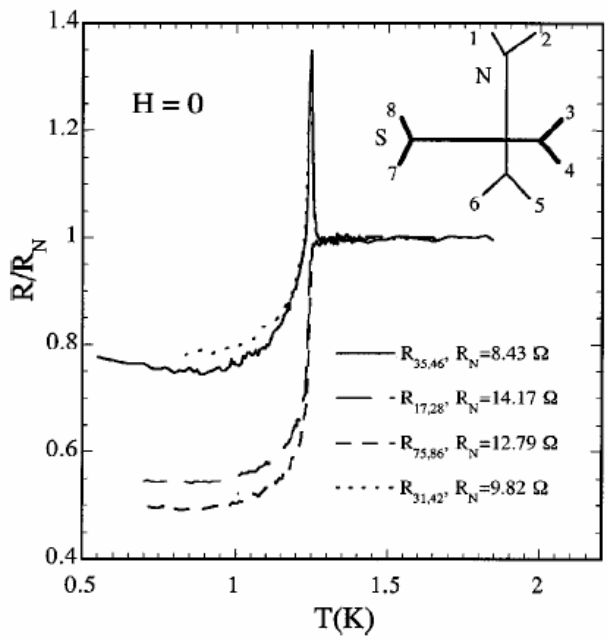
Origin of peaks?

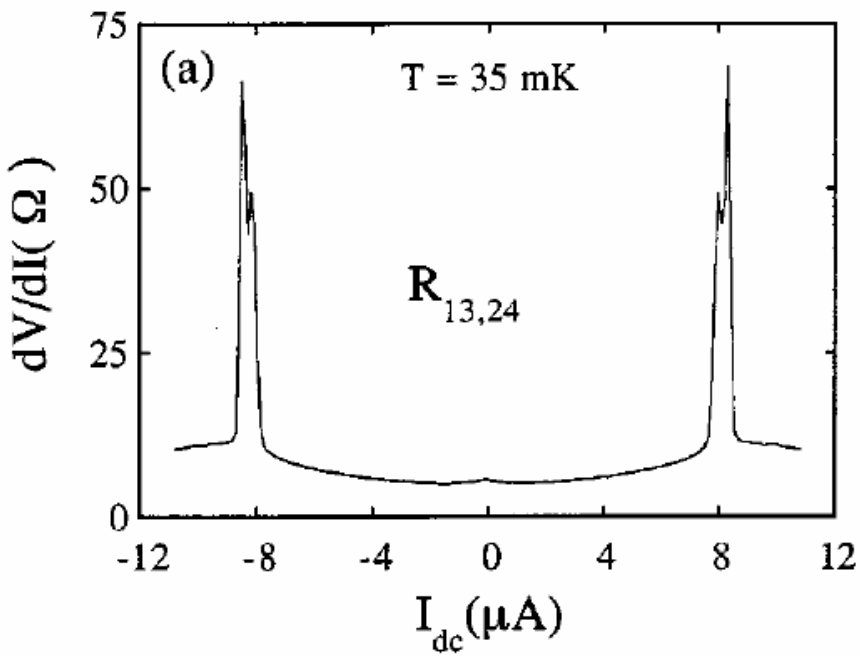
Charge imbalance in superconductor at a NS interface gives rise to excess resistance

Chien and Chandrasekhar, PRB 60, 3655(1999)









Charge imbalance in the BTK approximation

Quasiparticle potential due to charge imbalance

$$\phi = -\frac{Q^*}{N_0 e}$$

Relaxation time approximation for charge imbalance

$$\frac{dQ^*}{dt} = -\frac{Q^*}{\tau_{Q^*}}$$

In BTK approximation, charge imbalance current is given by

$$\frac{dQ^*}{dt} = I_{NS}^* \sim \int [f(E-eV) - f(E)][C(E) - D(E)]N_S^{-1} dE$$

so that excess charge imbalance voltage can be written as

$$V_{imb} \sim \tau_{Q^*} \int [f(E-eV) - f(E)][C(E) - D(E)]N_S^{-1} dE$$

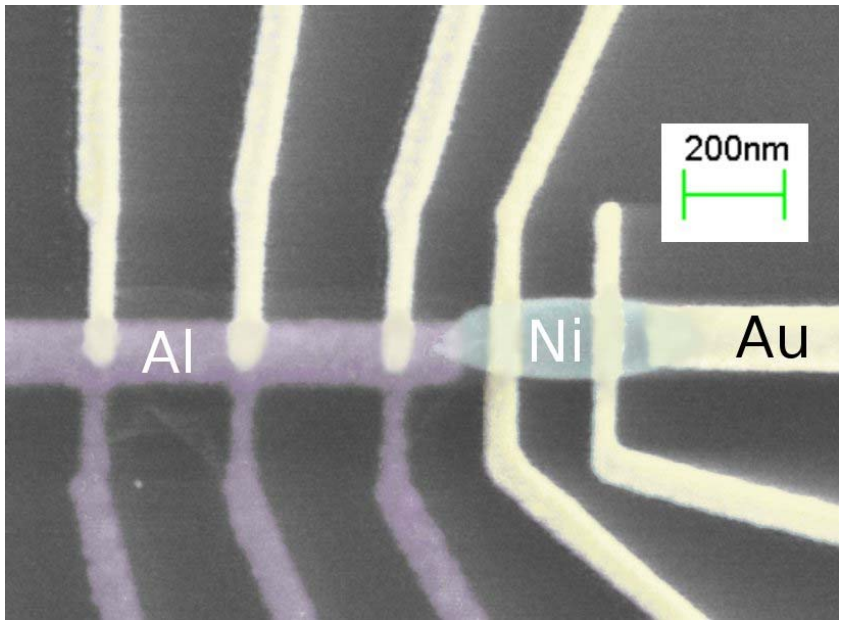
Charge imbalance voltage depends on charge imbalance time τ_Q*

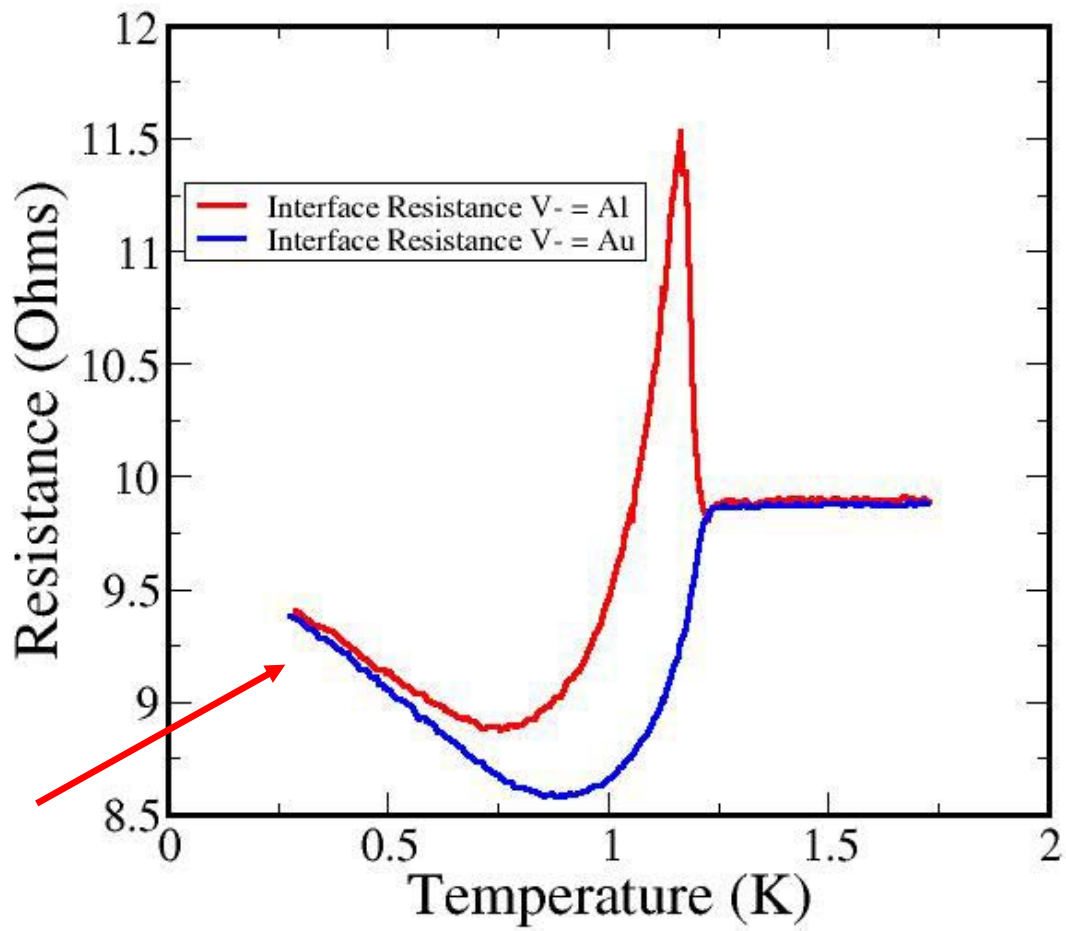
Diverges near T_c....large charge imbalance resistance near T_c

Charge imbalance in FS structures

Z. Jiang, P. Cadden-Zimansky

Multiple probes enable measurement of charge imbalance voltage





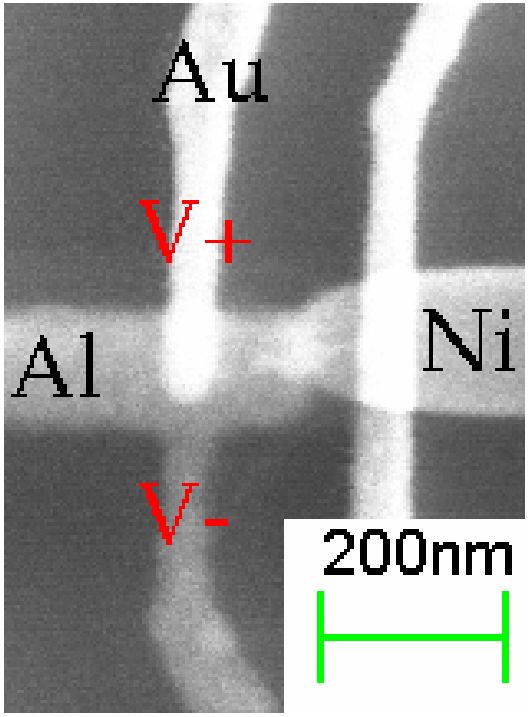
Long decay due to long spin diffusion time ?

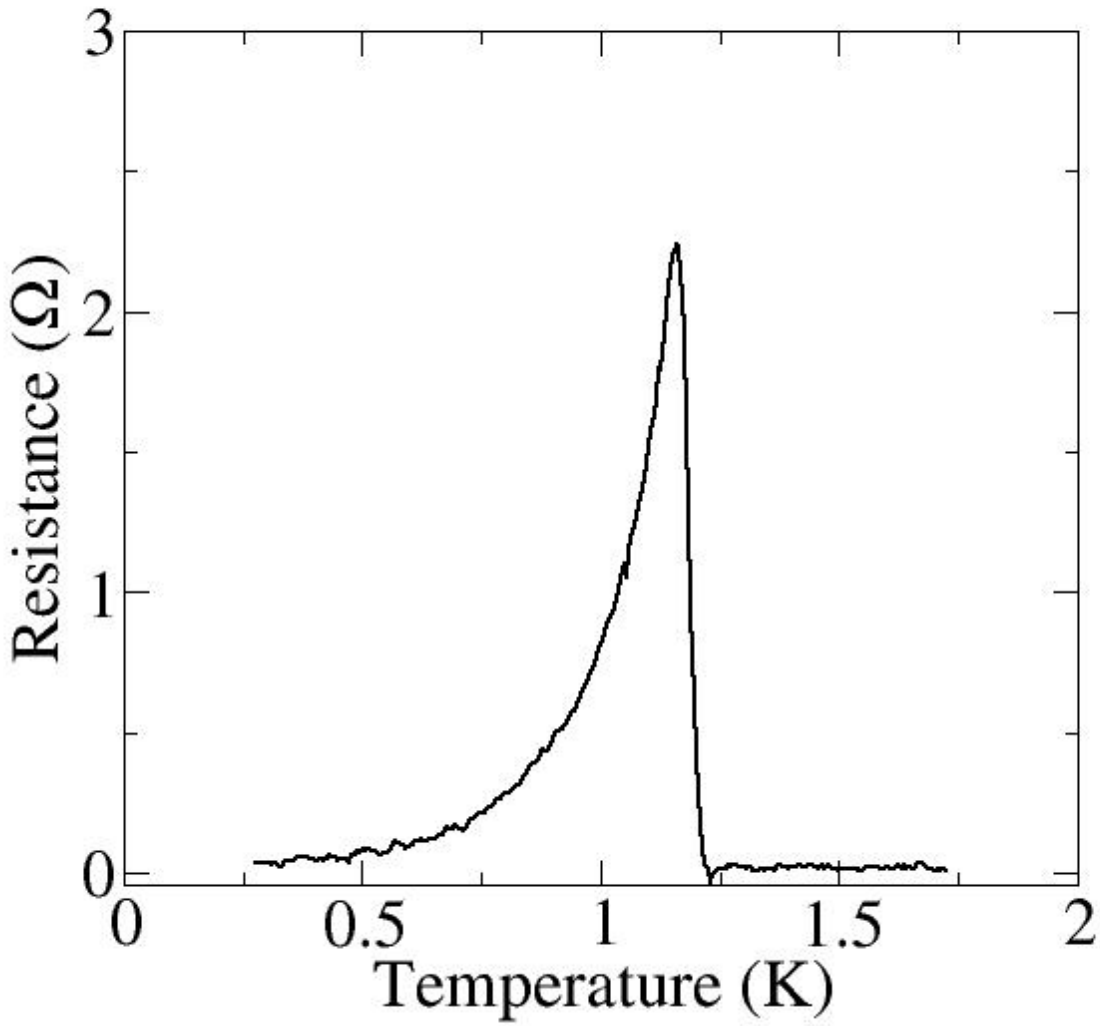
Charge imbalance disappears at low temperature

Charge imbalance in FS structures

Z. Jiang, P. Cadden-Zimansky

Nonlocal voltage, goes to zero at low temperatures



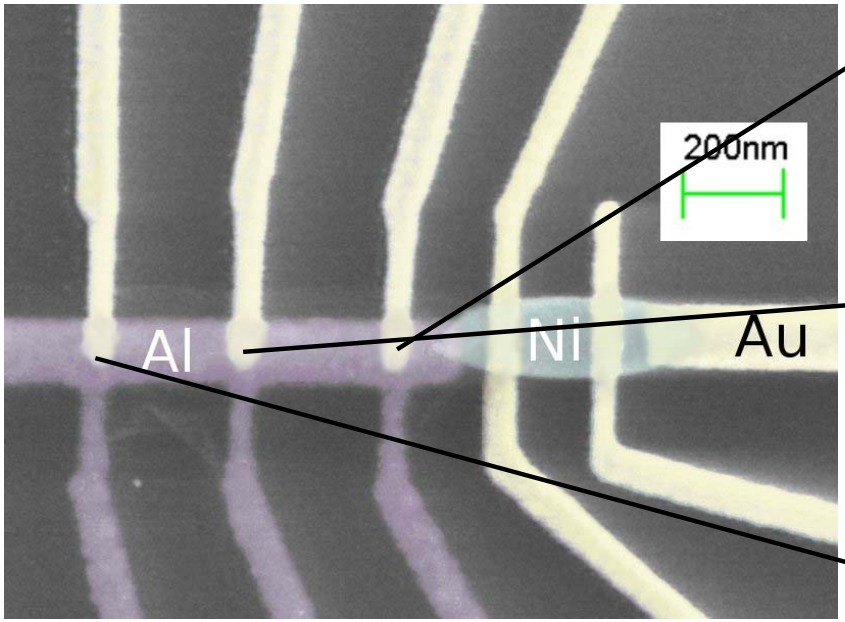


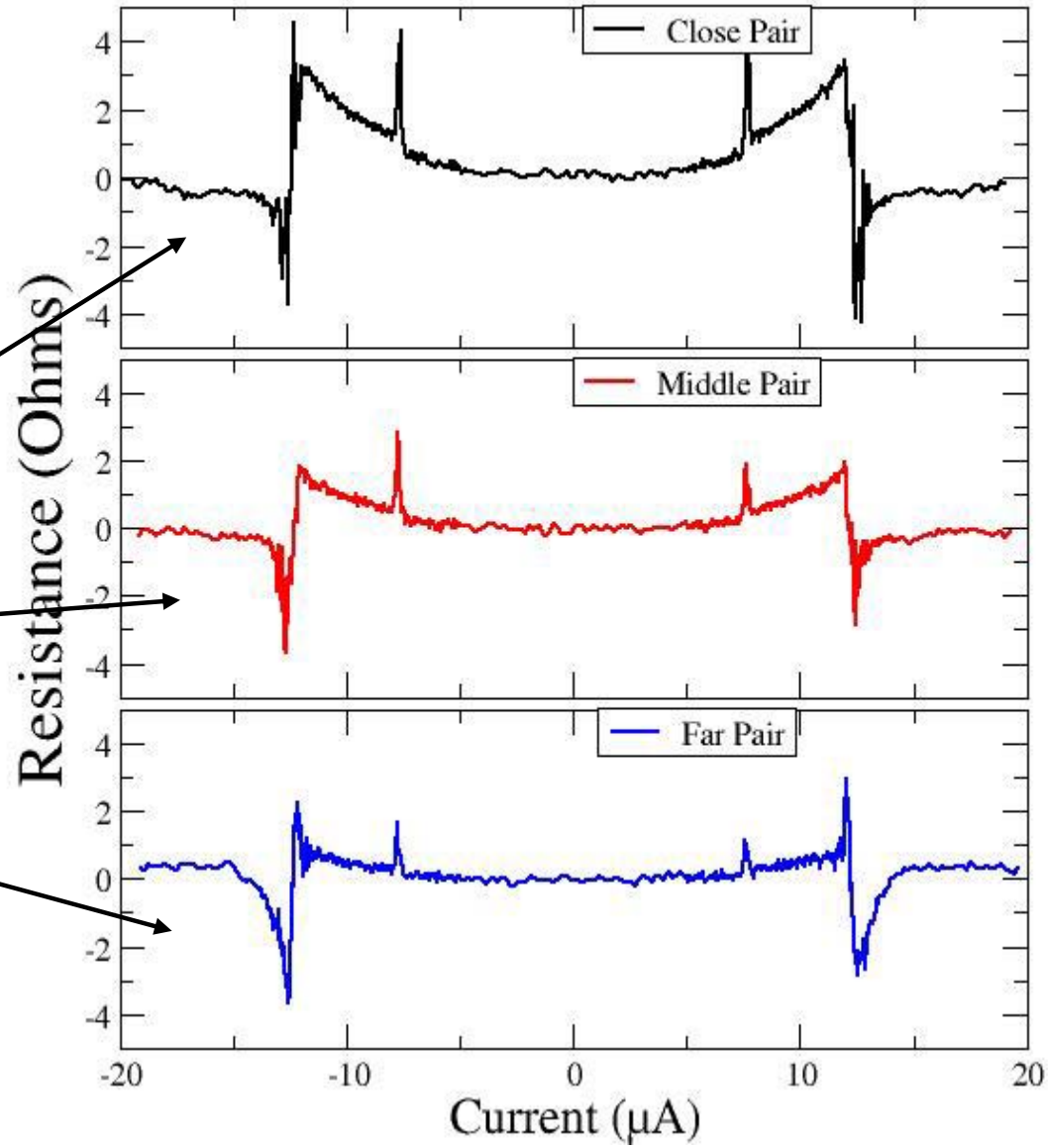
Northwestern Experiments

Z. Jiang, P. Cadden-Zimansky

Charge imbalance signal

Difference between quasiparticle and Cooper pair potential





Amplitude of signal decreases with distance from interface

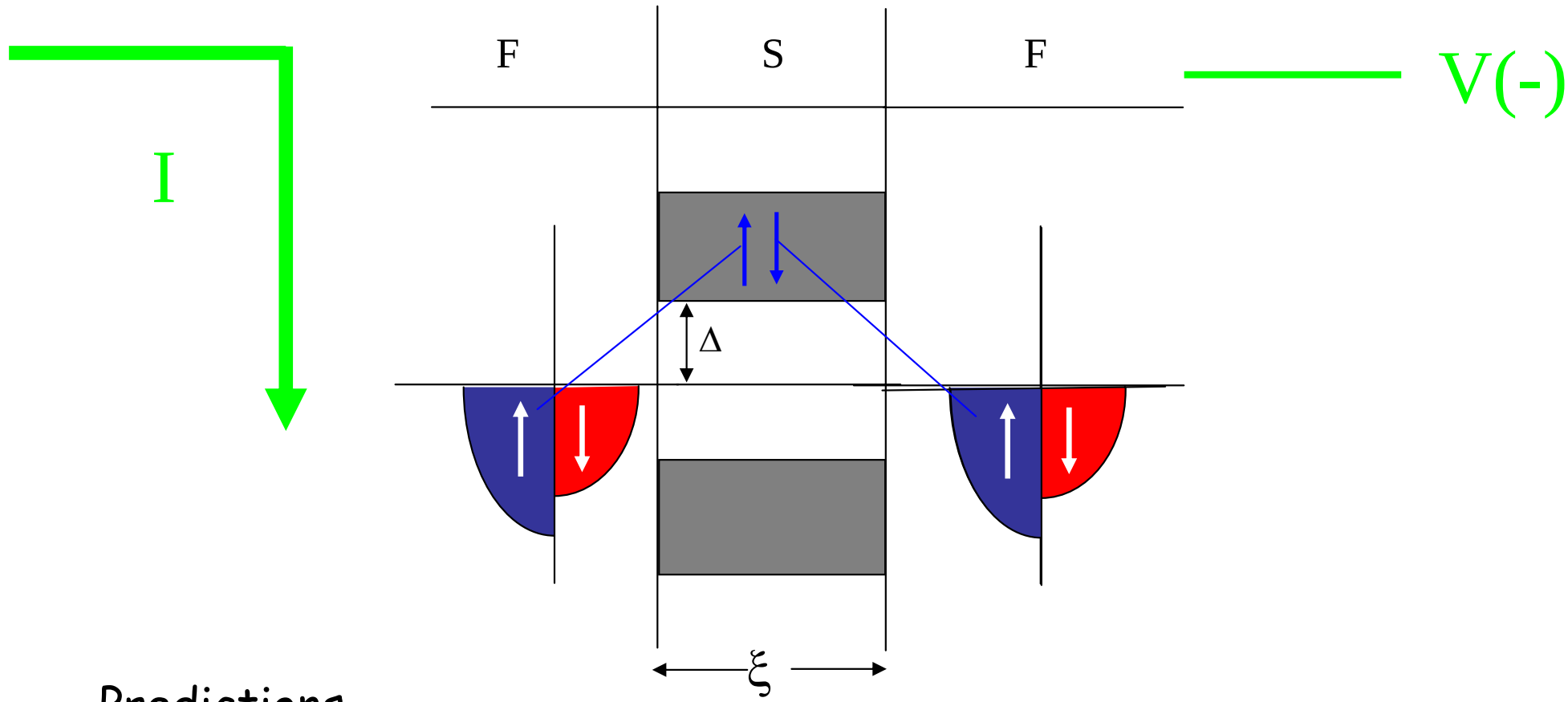
Crossed Andreev Reflection (CAR)

Antiparallel alignment

Andreev reflection enhanced

Parallel alignment

Andreev reflection suppressed



Predictions

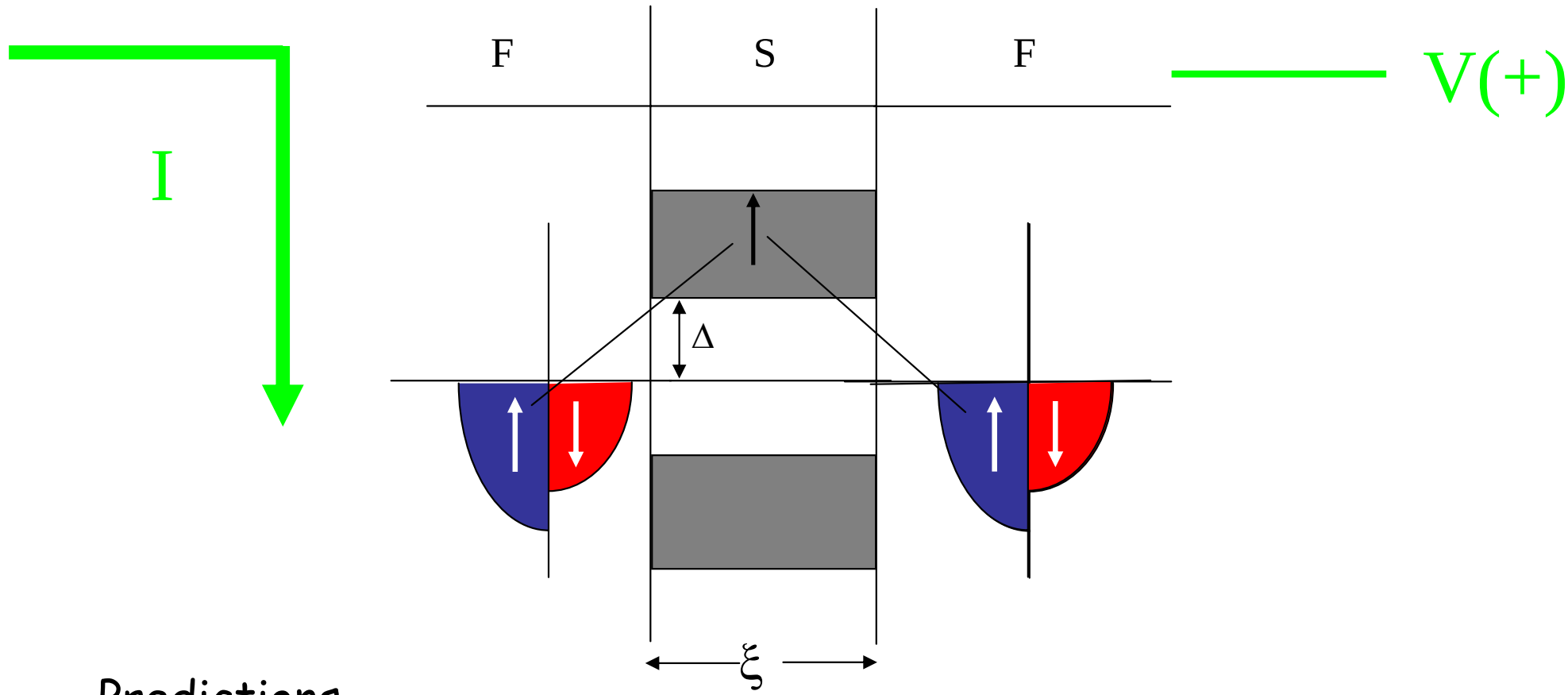
CAR is favored by antiparallel alignment of magnetic moments of contacts

Negative non-local voltage with respect to superconductor

Elastic Co-tunneling (EC)

Antiparallel alignment

Elastic cotunneling suppressed



Predictions

EC is favored by parallel alignment of moments of contact
Results in a *positive* nonlocal voltage

Crossed Andreev Reflection- earlier work

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Evidence for Crossed Andreev Reflection in Superconductor-Ferromagnet Hybrid Structures

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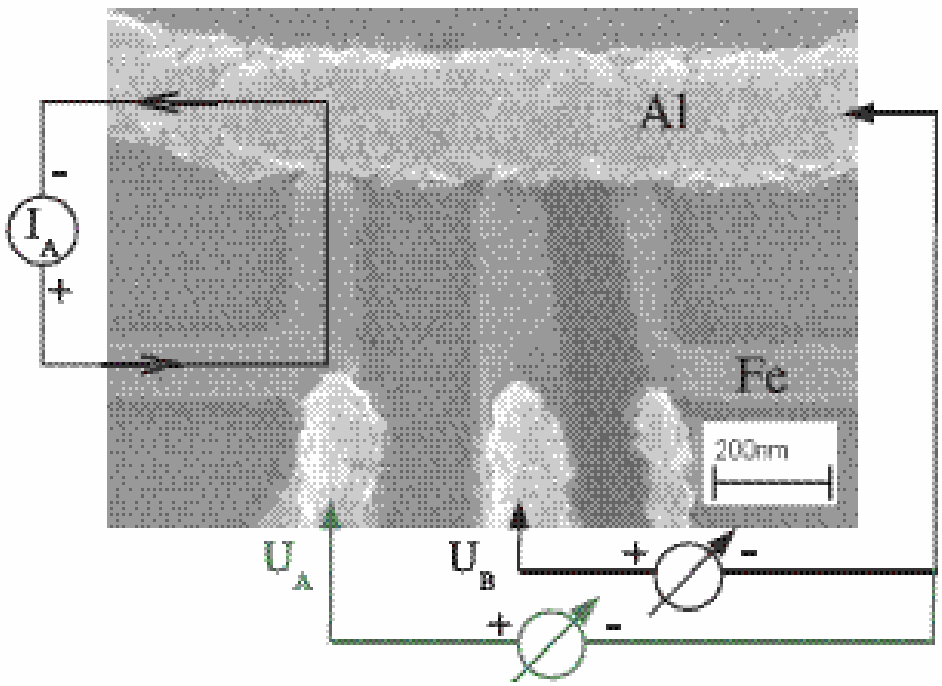
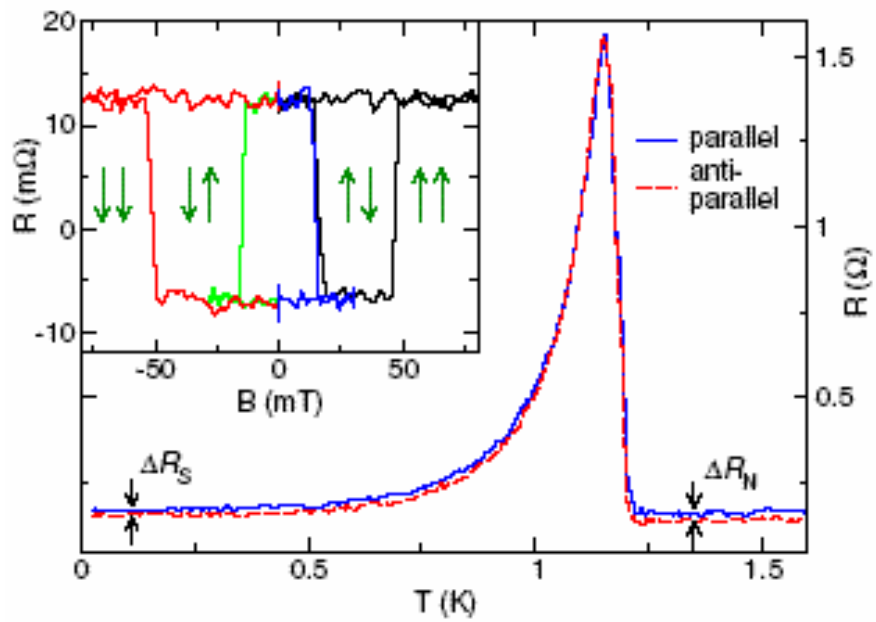
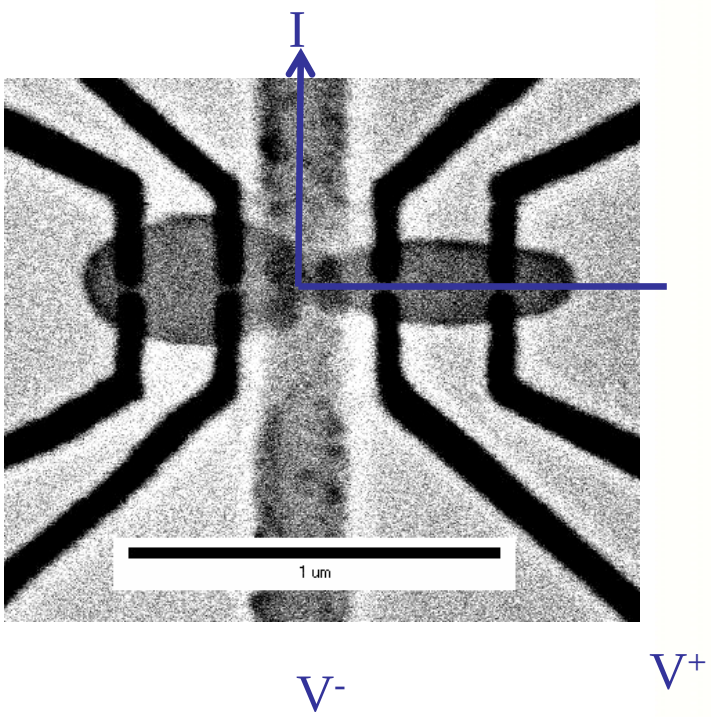
(Received 16 April 2004; published 4 November 2004)

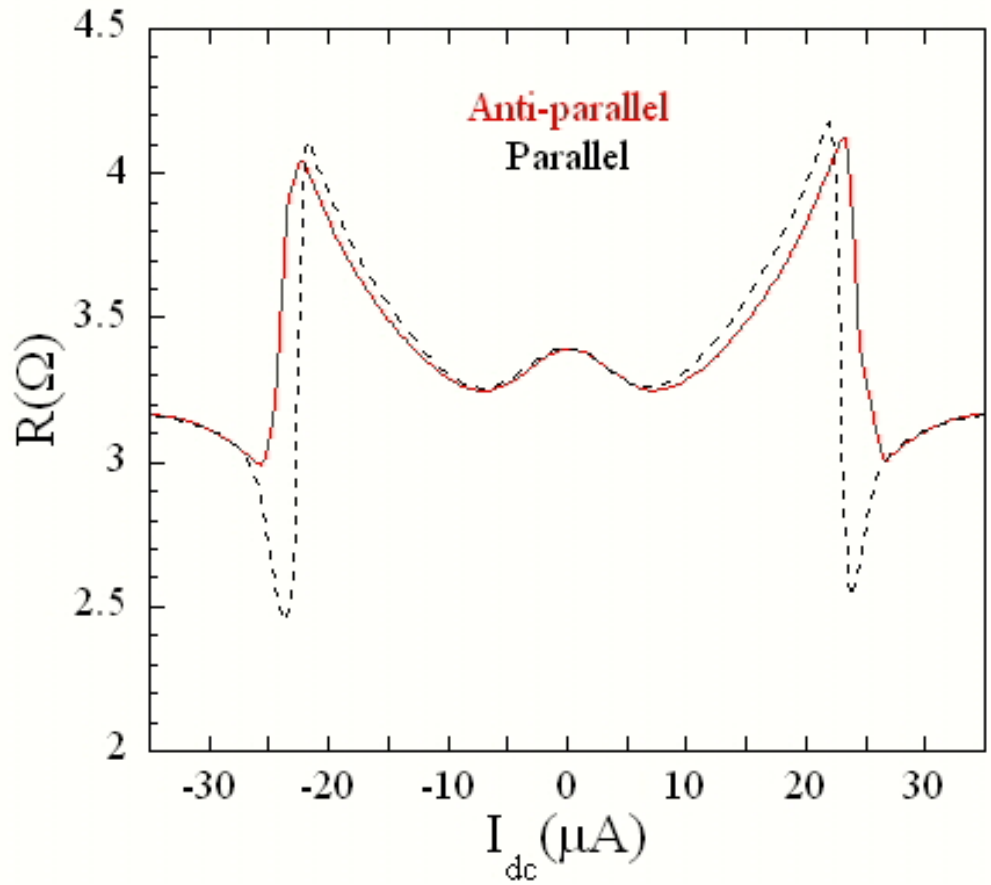




Crossed Andreev Reflection- Northwestern experiments

Nonlocal signal
  Only at intermediate currents

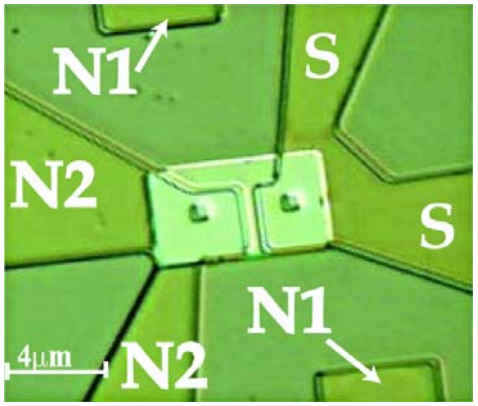


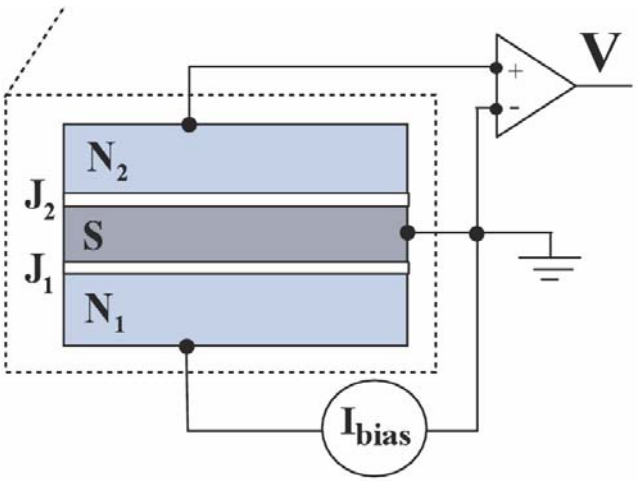


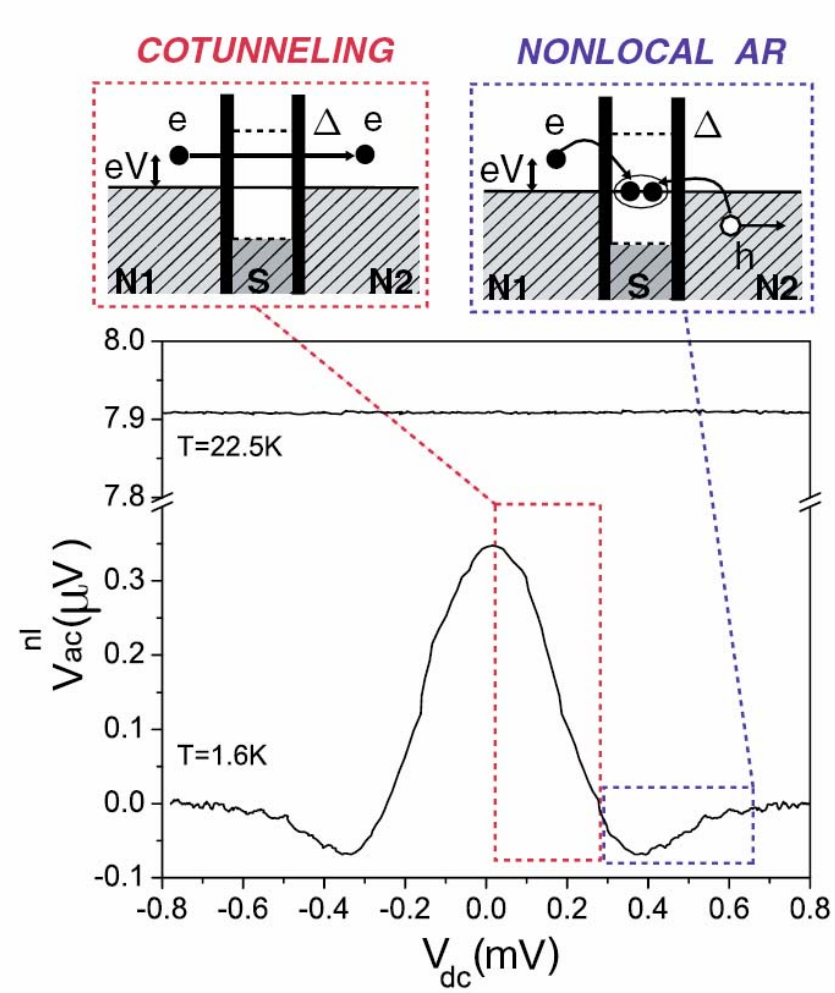
EC and CAR- Delft experiments

Russo et al., PRL 2005

EC at low bias, turns to CAR at high bias, crossover determined by Thouless energy



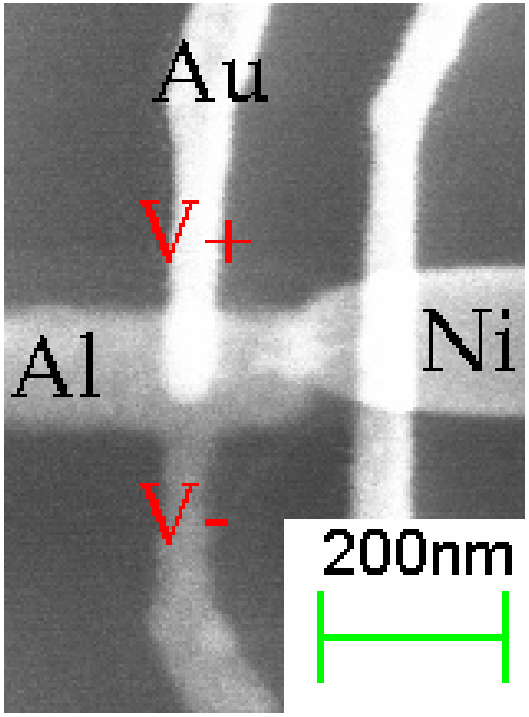


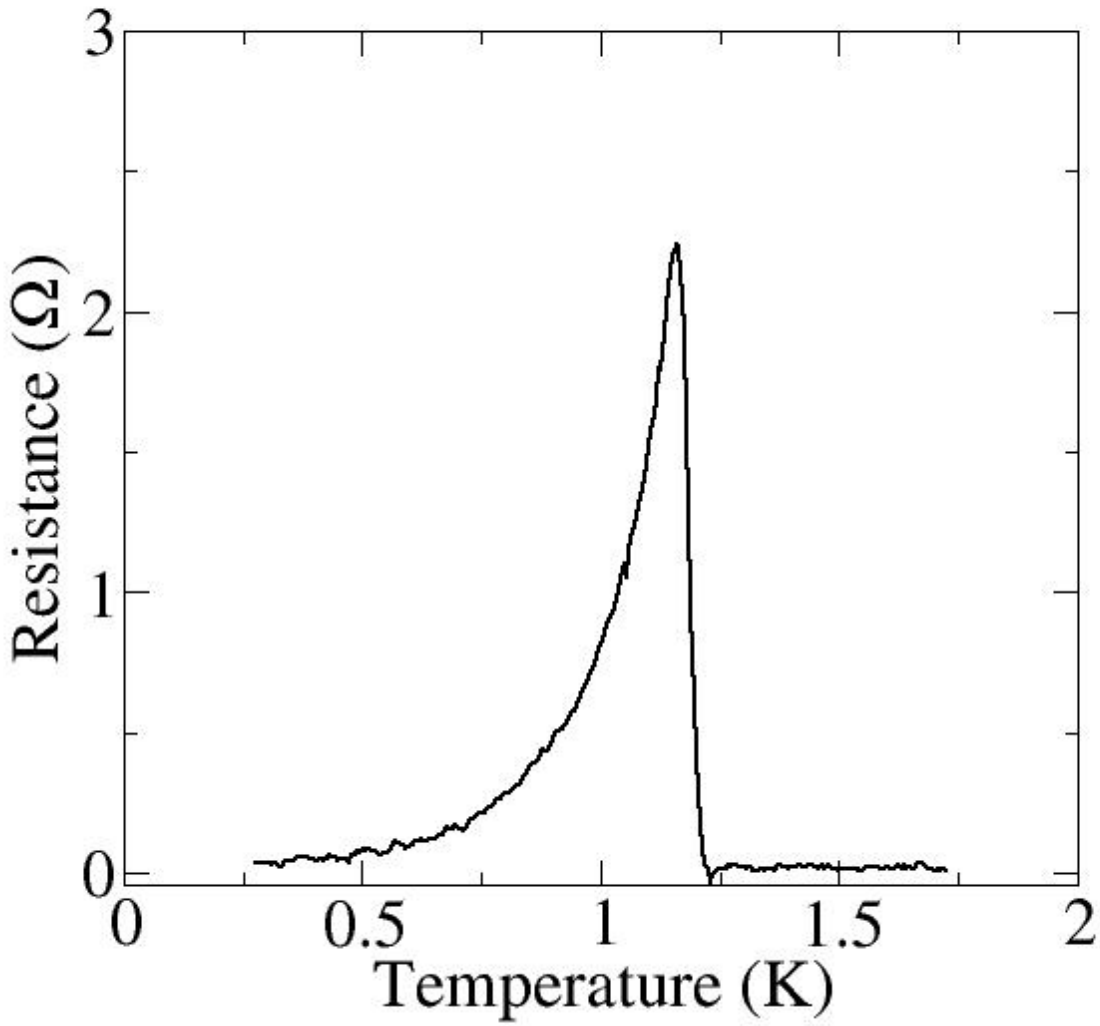


Charge imbalance in FS structures

Z. Jiang, P. Cadden-Zimansky

Nonlocal voltage, goes to zero at low temperatures

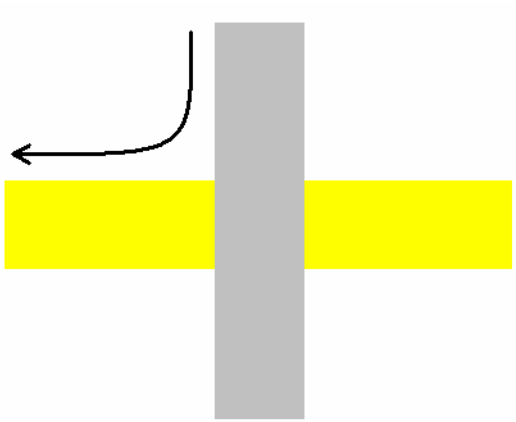


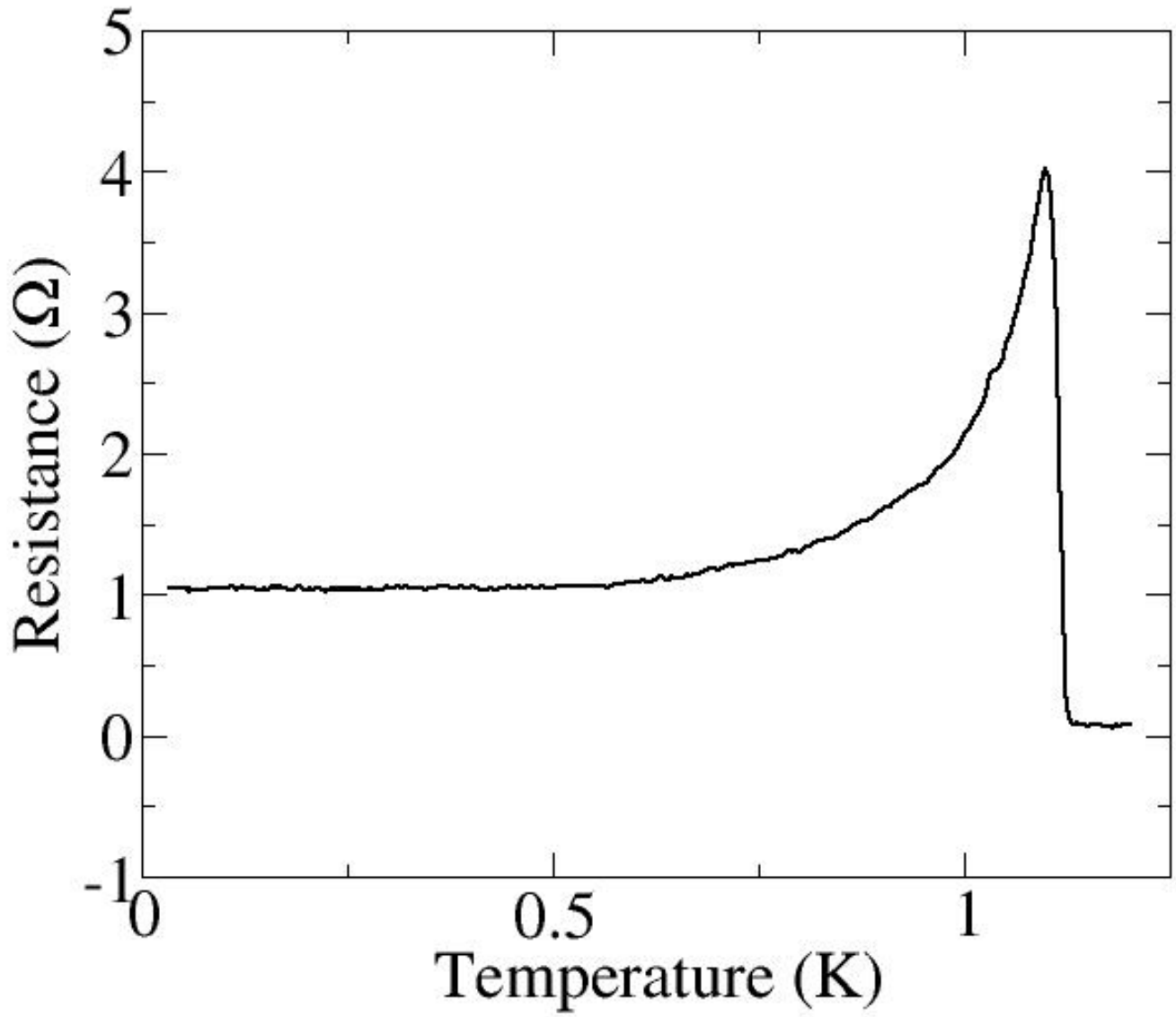


NS cross

Z. Jiang, P. Cadden-Zimansky

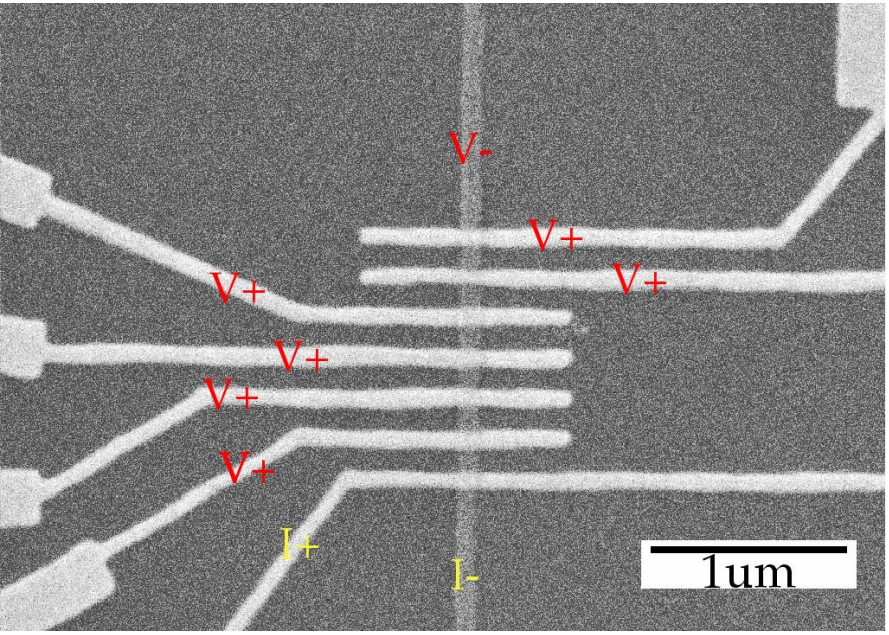
Nonlocal voltage does not go to zero at low temperatures

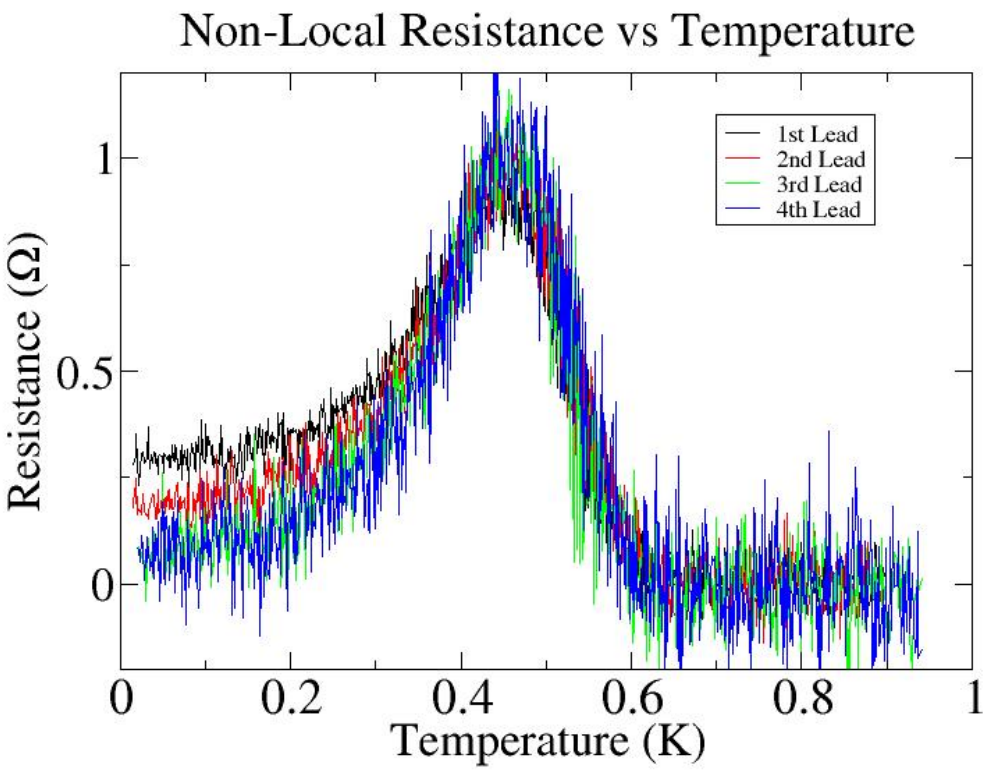




NS device, nonlocal measurements: Temperature

P. Cadden-Zimansky



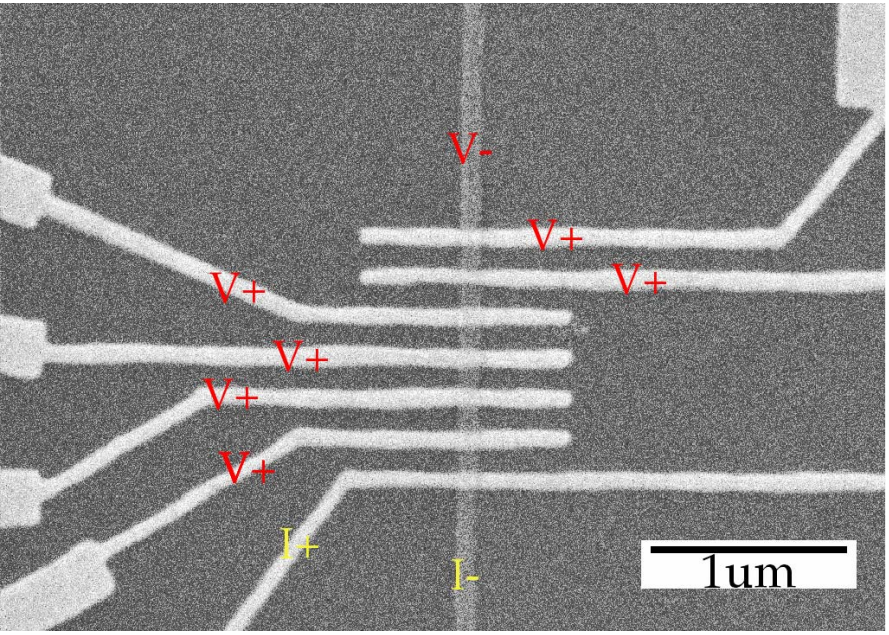


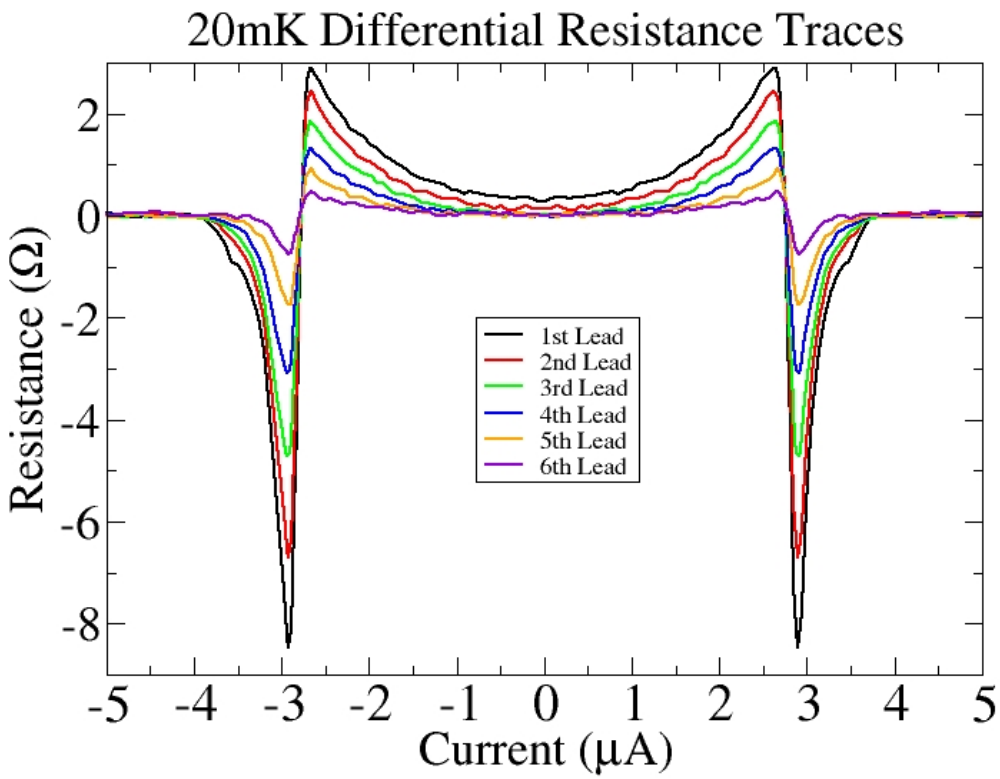
Charge imbalance peak scaled

Zero-bias peak and charge imbalance peak do not scale in the same way
(zero-bias peak decays faster)

NS device, nonlocal measurements: Bias

P. Cadden-Zimansky





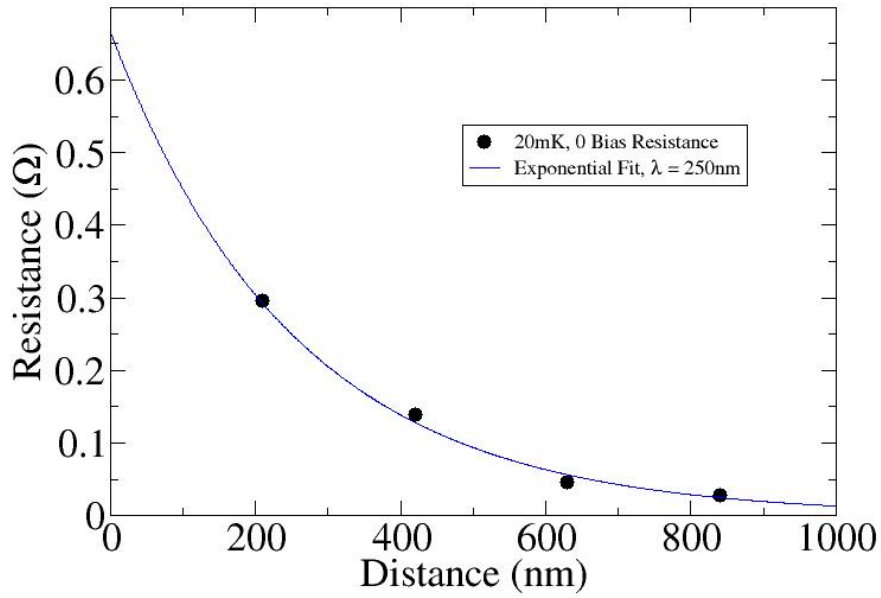
Length dependence

P. Cadden-Zimansky

zero bias peak has a shorter decay length ~ 250 nm

Corresponds well with superconducting coherence length

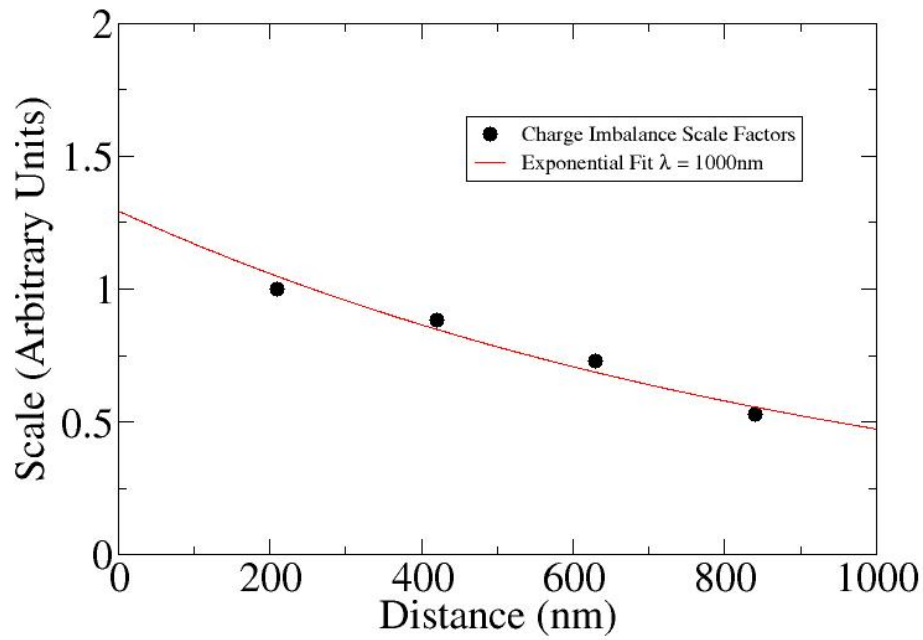
Consistent with EC and CAR contribution



Charge imbalance peak has a longer decay length ~ 1 μm

Shorter than usual charge imbalance length near T_c

Nonlocal charge imbalance?



Summary

Zero bias contribution to nonlocal resistance in NS and FS structures due to combination of EC and CAR

Signal decays on length scale corresponding to superconducting coherence length

Peak in nonlocal resistance at finite bias due to charge imbalance--decays on a longer length scale

Negative differential resistance at finite bias

In FS devices, depends on relative orientation of magnetization

maybe due to CAR

Outstanding issues

Separation of EC and CAR contributions

For tunneling NS contacts, EC and CAR exactly cancel at all energies (biases)

for transparent contacts, EC is predicted to be larger

Need detailed energy dependence of EC and CAR for transparent contacts

Separation of EC, CAR contributions from Charge Imbalance

Charge imbalance usually not discussed in EC, CAR theory

Charge imbalance only discussed near T_c

Need theory of *nonlocal* charge imbalance at low temperatures

Future work

Demonstration of phase coherence in CAR process

Applications to entanglement

Techniques to separate EC and CAR contributions

FS structures, noise measurements