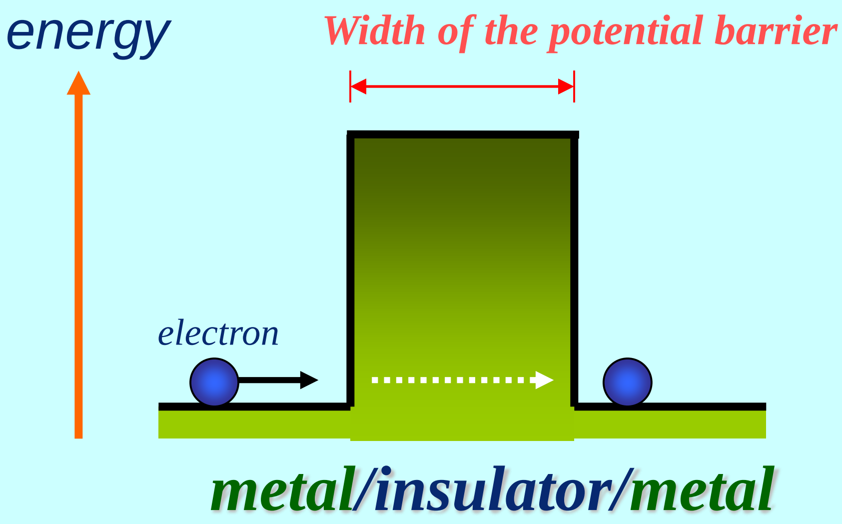
Electron cooling and Andreev reflections in superconducting tunnel junctions

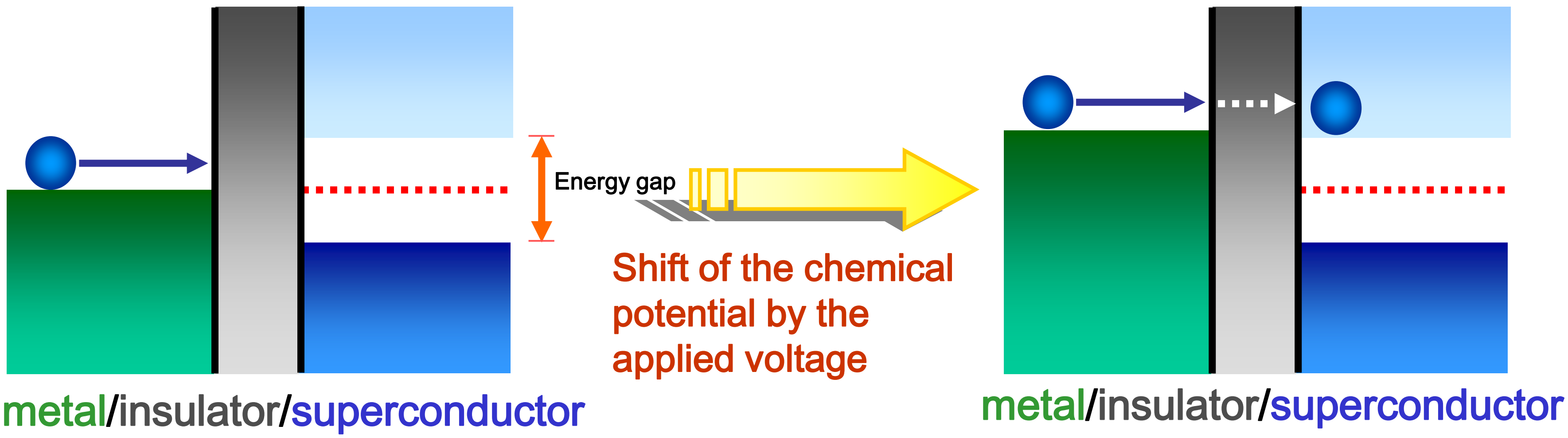
Andrey S. Vasenko

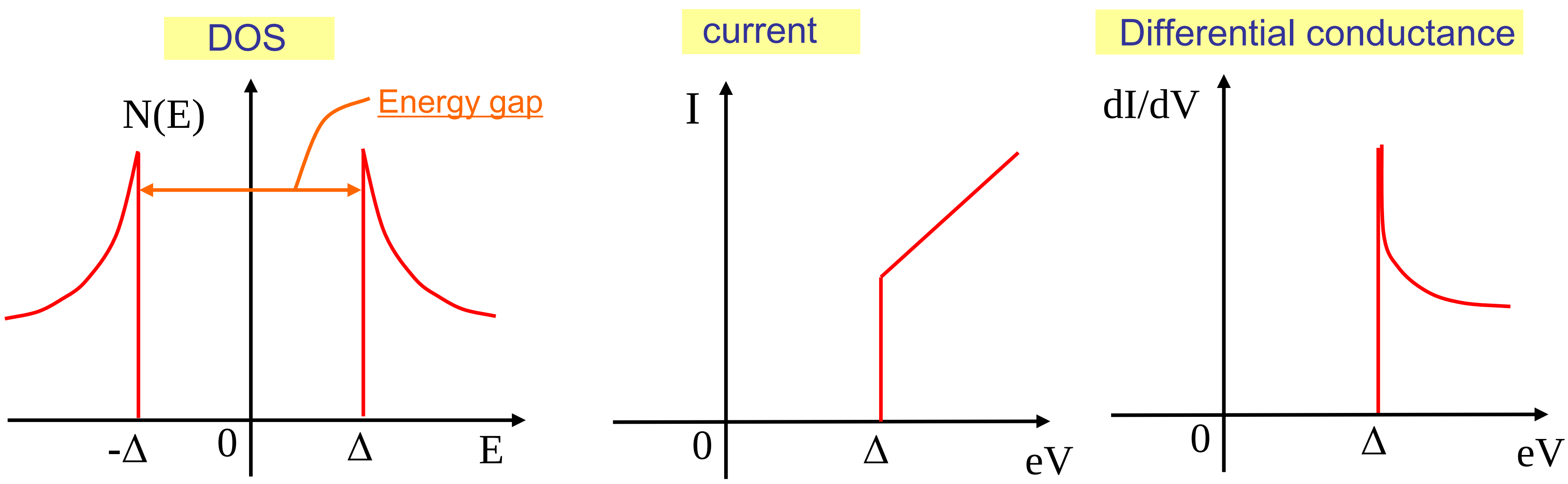
School of Electronic Engineering,
Moscow Institute of Electronics and Mathematics,
Higher School of Economics

Tunneling effect



NIS tunnel junction, T = 0



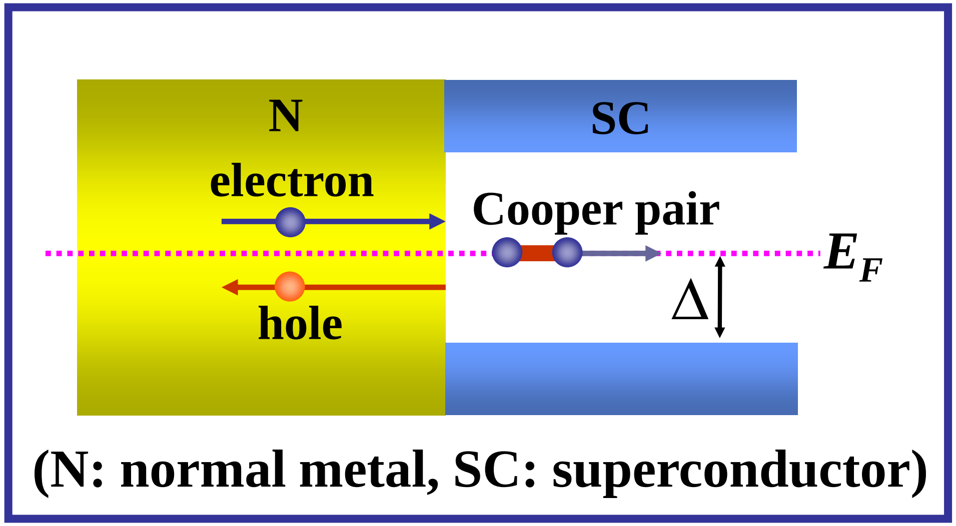


Subgap transport

Andreev reflection, $E < \Delta$

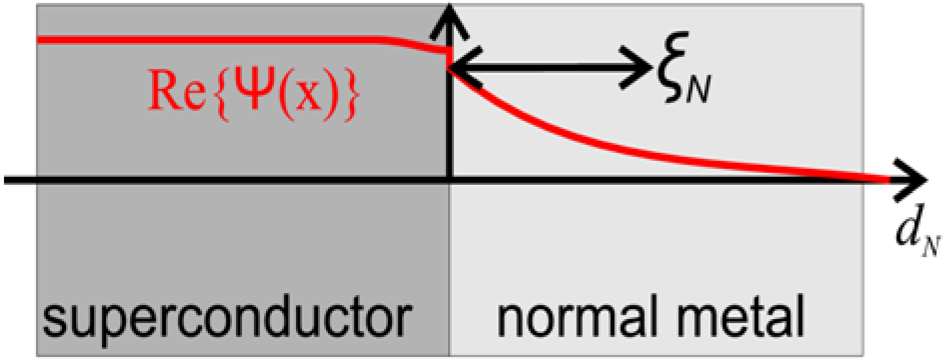
classical (A.F. Andreev, Spain, 2008)

quantum [A.F. Andreev, Sov. Phys. JETP, **19**, 1228, (1964)]



S/N proximity effect

$$\Psi = \Psi_0 e^{-d_N/\xi_N}$$



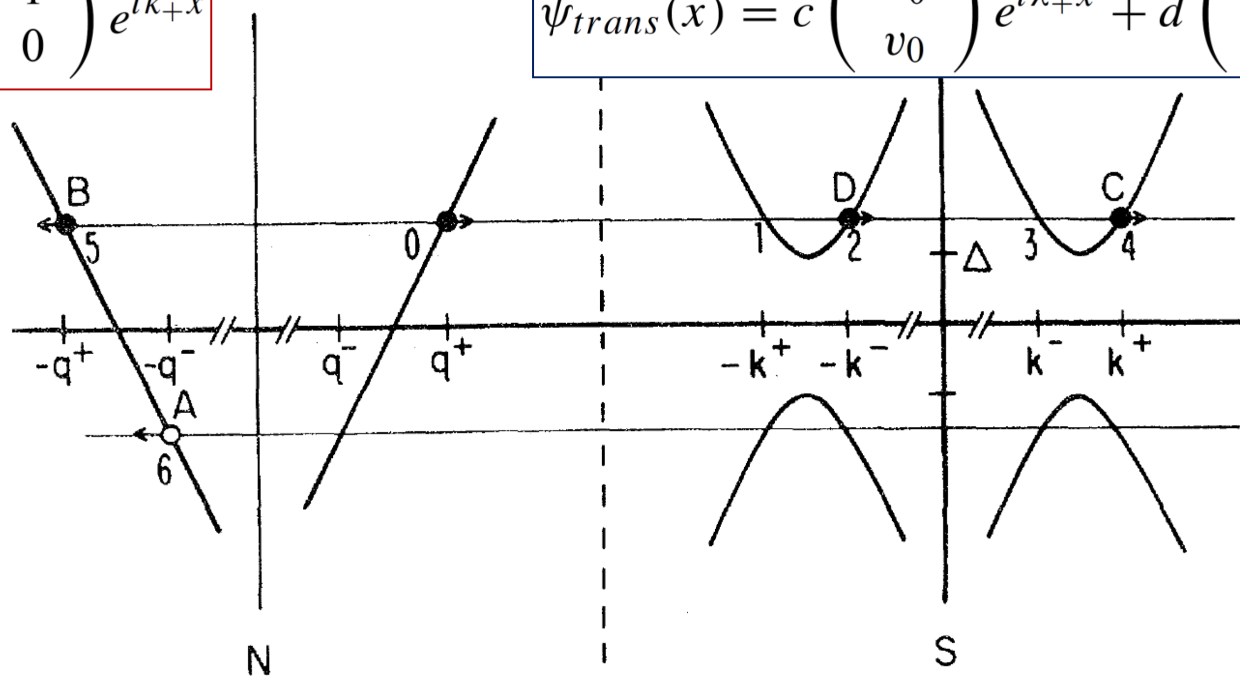
PHYSICAL REVIEW B VOLUME 25, NUMBER 7 1 APRIL 1982

Transition from metallic to tunneling regimes in superconducting microconstrictions: Excess current, charge imbalance, and supercurrent conversion

G. E. Blonder, M. Tinkham, and T. M. Klapwijk*

$$\psi_{inc}(x) = \begin{pmatrix} 1 \\ 0 \end{pmatrix} e^{ik_+x}$$

$$\psi_{trans}(x) = c \begin{pmatrix} u_0 \\ v_0 \end{pmatrix} e^{i\lambda_+x} + d \begin{pmatrix} v_0 \\ u_0 \end{pmatrix} e^{-i\lambda_-x}$$

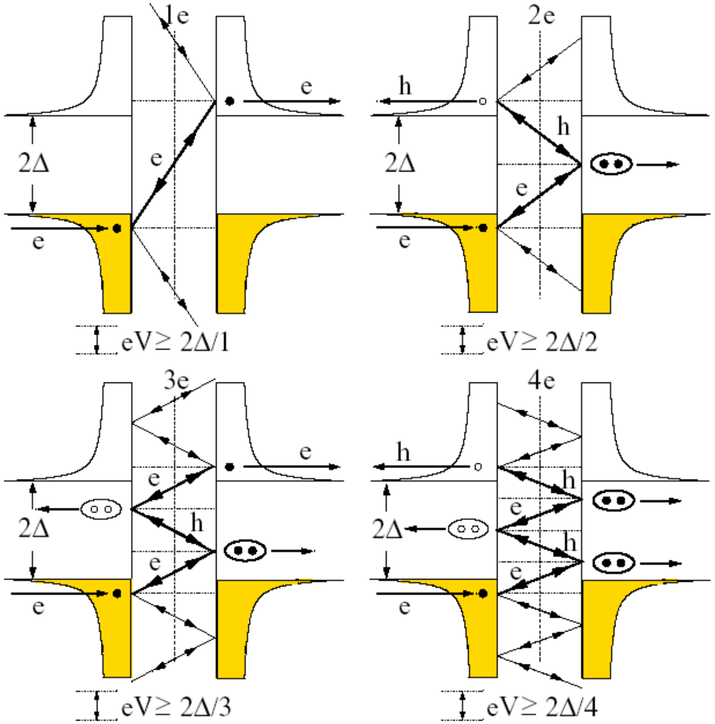


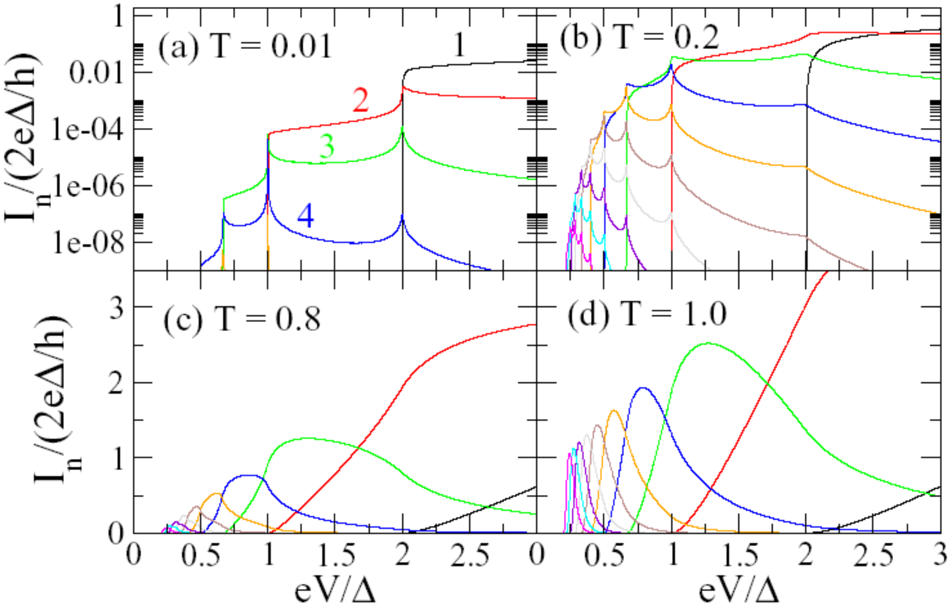
$$\psi_{refl}(x) = a \begin{pmatrix} 0 \\ 1 \end{pmatrix} e^{ik_-x} + b \begin{pmatrix} 1 \\ 0 \end{pmatrix} e^{-ik_+x}$$

Physica 109 & 110B (1982) 1657–1664
North-Holland Publishing Company

EXPLANATION OF SUBHARMONIC ENERGY GAP STRUCTURE IN SUPERCONDUCTING CONTACTS

T.M. KLAPWIJK*, G.E. BLONDER and M. TINKHAM



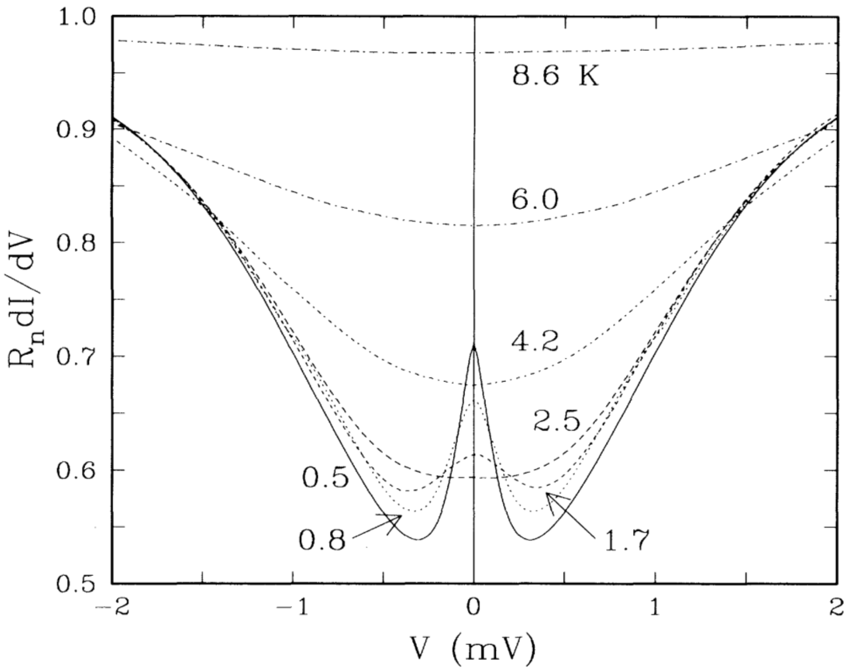


A natural extension of the S:c:S problem would be to include a barrier at the interface, but this task has proven to be quite difficult.

VOLUME 67, NUMBER 21 PHYSICAL REVIEW LETTERS 18 NOVEMBER 1991

Observation of Pair Currents in Superconductor-Semiconductor Contacts

A. Kastalsky,[(1),(a)] A. W. Kleinsasser,[(2)] L. H. Greene,[(1)] R. Bhat,[(1)] F. P. Milliken,[(2)]
and J. P. Harbison[(1)]

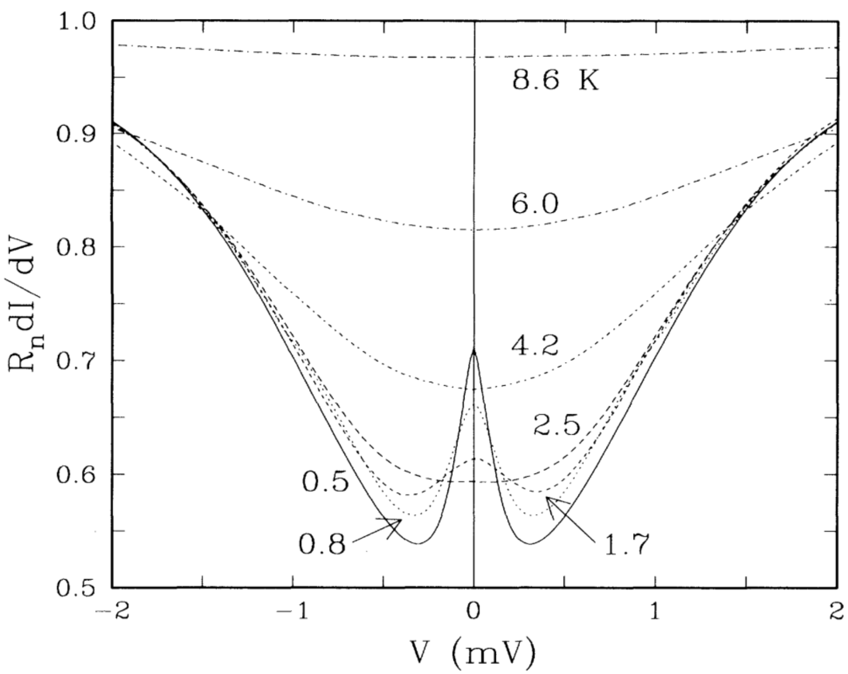


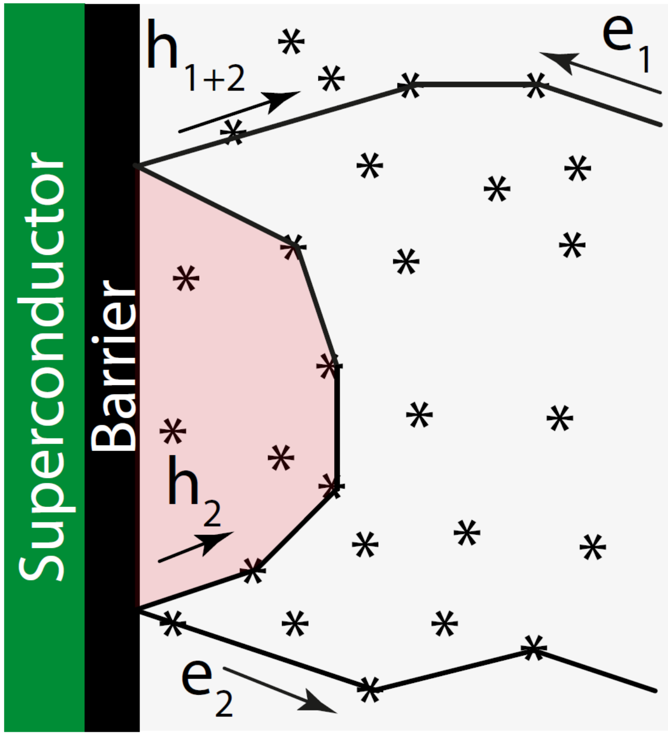
Zero bias anomaly

VOLUME 69, NUMBER 3 PHYSICAL REVIEW LETTERS 20 JULY 1992

Excess Conductance of Superconductor-Semiconductor Interfaces Due to Phase Conjugation between Electrons and Holes

B. J. van Wees,[(1)] P. de Vries,[(2)] P. Magnée,[(1)] and T. M. Klapwijk[(1)]





Zero bias anomaly

the incident electron $(E_F + \epsilon, k_F + \delta k/2)$

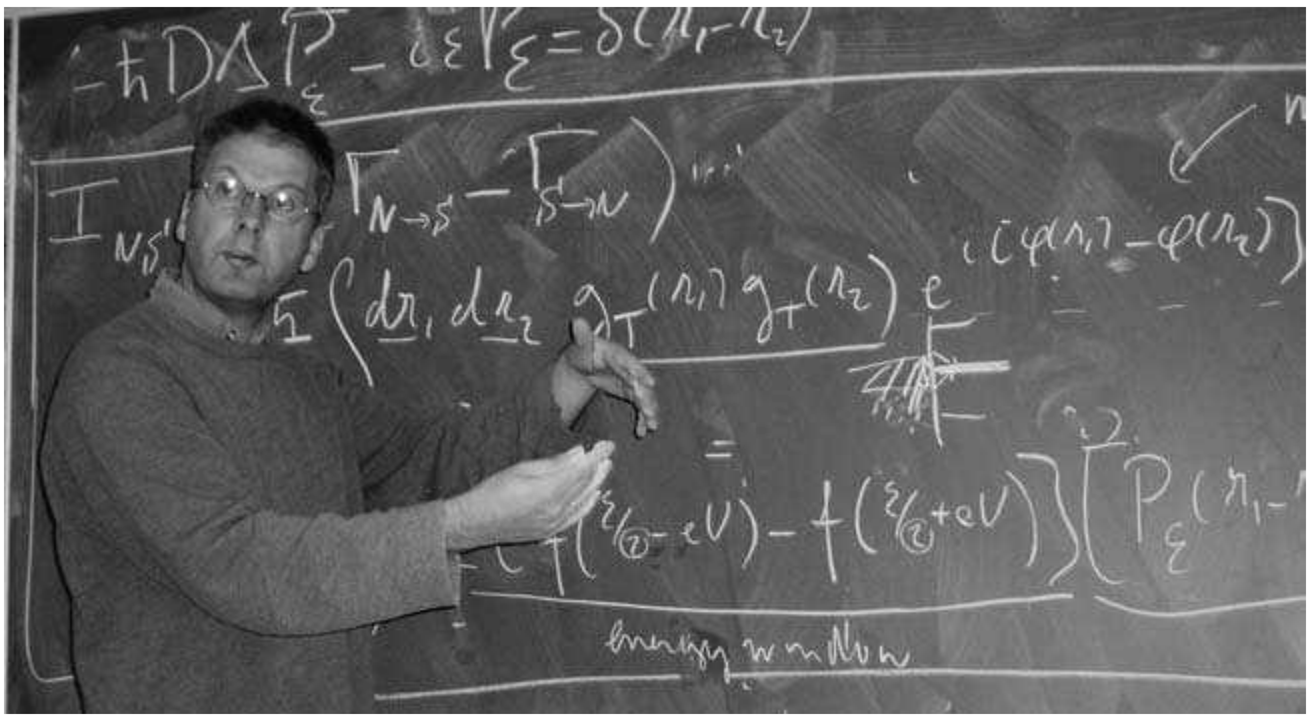
the reflected hole $(E_F - \epsilon, -k_F + \delta k/2)$

VOLUME 71, NUMBER 10 PHYSICAL REVIEW LETTERS 6 SEPTEMBER 1993

Interference of Two Electrons Entering a Superconductor

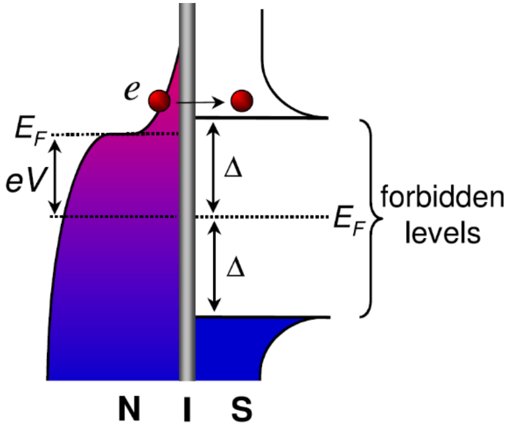
F. W. J. Hekking and Yu. V. Nazarov*

The subgap conductivity of a normal-superconductor (NS) tunnel junction is thought to be due to tunneling of two electrons. There is a strong interference between these two electrons, originating from the spatial phase coherence in the normal metal at a mesoscopic length scale and the intrinsic coherence of the superconductor. We evaluated the interference effect on the transport through an NS tunnel junction.

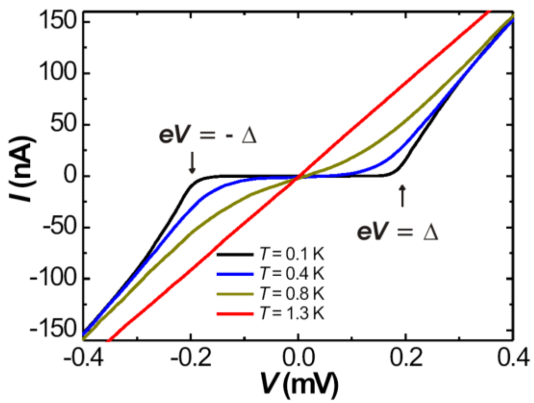


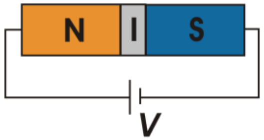
Electron cooling by NIS: milestones

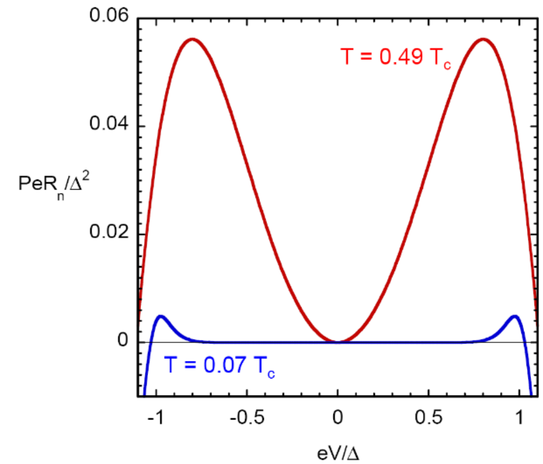
- M. Nahum, T.M. Eiles, J.M. Martinis, APL 65, 3123 (1994)



NIS thermometer (electron T)







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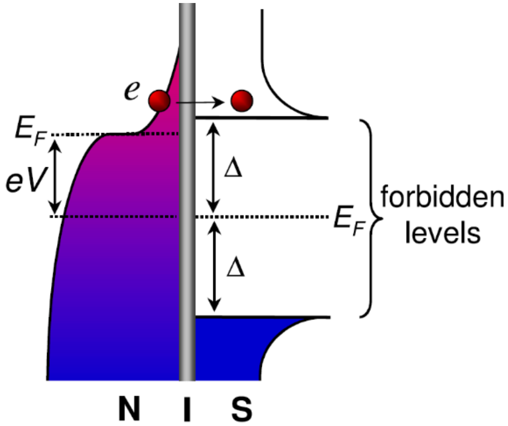

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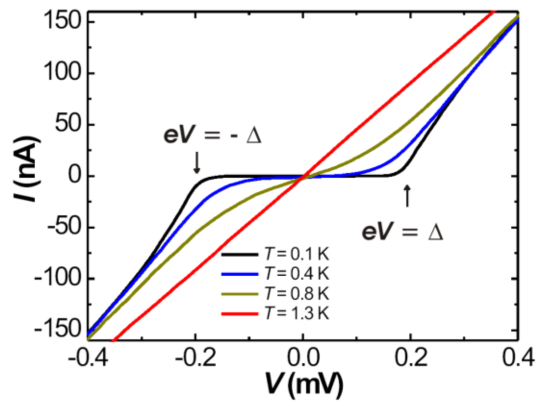
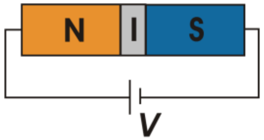
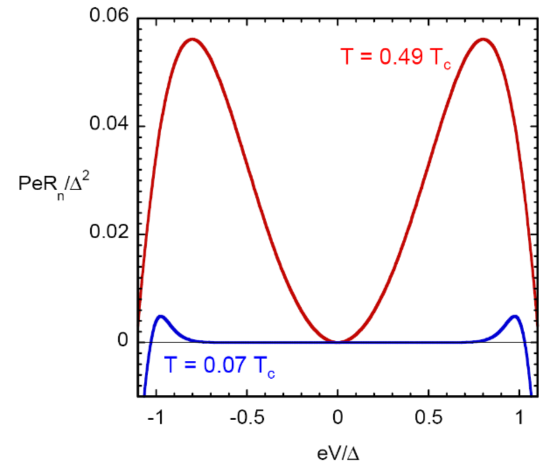
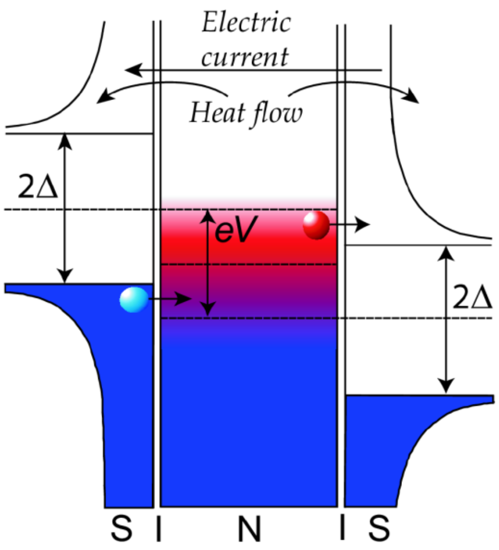






- M.M. Leivo, J. P. Pekola, D.V. Averin, APL 68, 1996 (1996)



$$P(V) = \frac{1}{e^2 R}\int_{-\infty}^{+\infty} N(E)(E - eV)\{n_S(E - eV) - n_N(E)\}dE$$

Energy current

Joule dissipation(=I×V)

COOLING

HEATING

Electron cooling by NIS: applications

- A.M. Clark et al, APL 86, 173508 (2005)

On-chip cooling of micro and nano-sized systems:
-Sensors (bolometers)
-Quantum devices (qubits, etc.)

Reduction of electronic temperature from 300 mK to about 100 mK;
Reduction of phonon temperature (320 mK to 240 mK – A.M. Clark);

Only the small electronic sensor is cooled

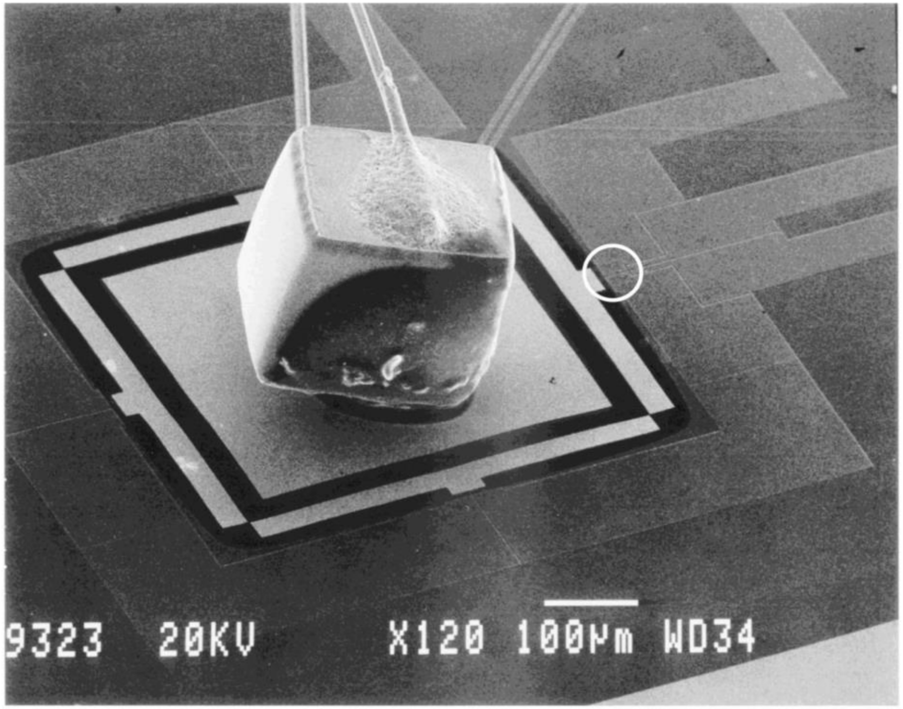
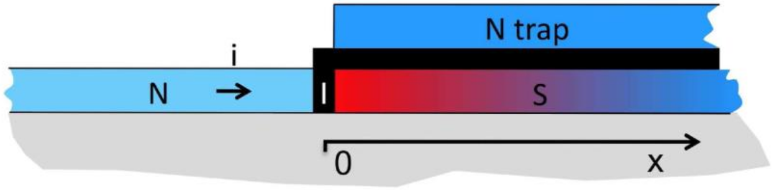


FIG. 2. Scanning electron microscope image of NIS refrigerator with attached neutron transmutation doped (NTD) germanium resistance thermometer. One of the four pairs of refrigerator junctions is circled. Additional junctions for thermometry are located beneath the NTD. The ratio of the volumes of the NTD and the refrigerating junctions is comparable to the ratio of the volumes of the Statue of Liberty and an ordinary person (about 11 000).

Electron cooling by NIS: limitations

- J.P. Pekola, D.V. Anghel, T.I. Suppula, J.K. Suoknuuti, A.J. Manninen, and M. Manninen, APL 76, 2782 (2000)



Nonequilibrium quasiparticles (qp) injected into S electrode accumulate near the tunnel interface.

- overheating of the S electrode
- backtunneling of hot qp to the N
- qp recombination into the Cooper pairs

This problem can be solved by imposing a local thermal equilibrium in the S electrode.

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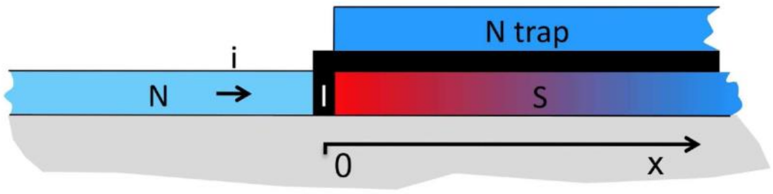

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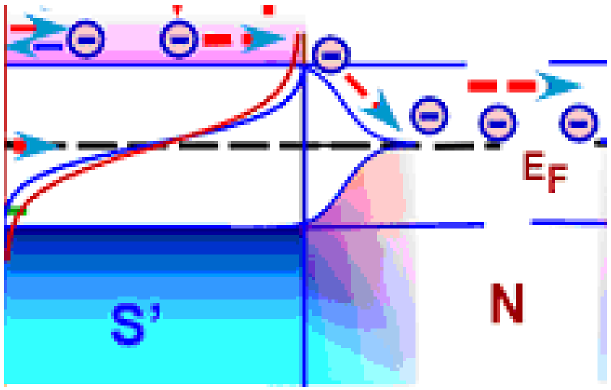
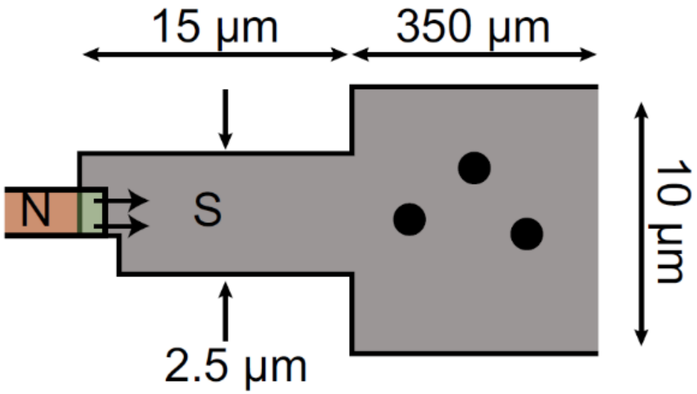
This problem can be solved by imposing a local thermal equilibrium in the S electrode.

- QP (proximity) trap



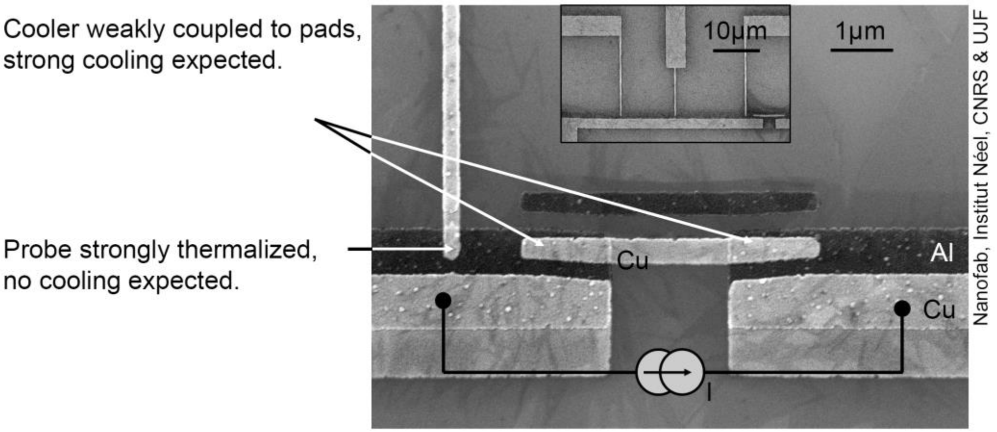
- Magnetic field

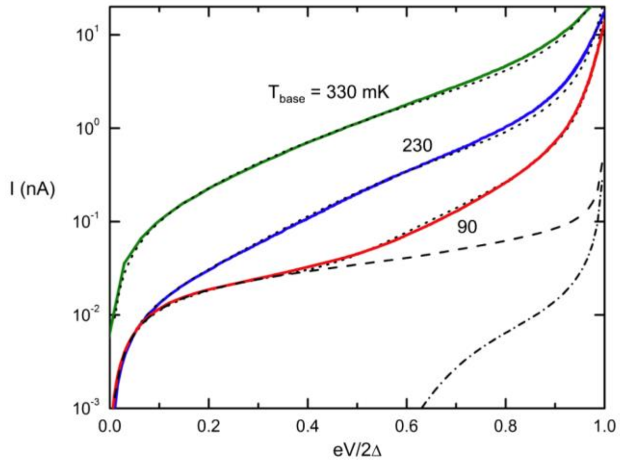


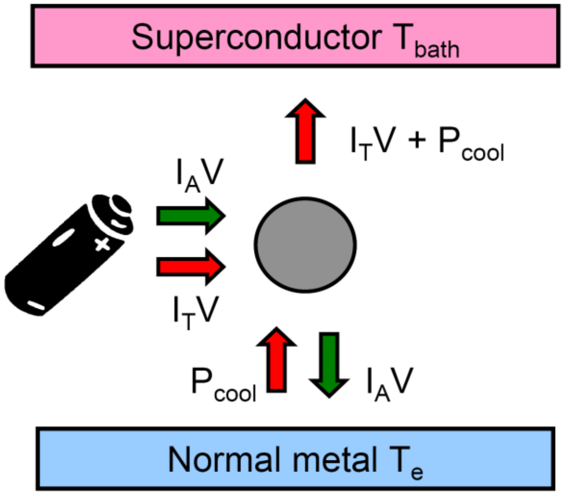
J.T. Peltonen, J.T. Muhonen, M. Meschke, N.B. Kopnin, and J.P. Pekola, PRB 84, 220502 (2011)

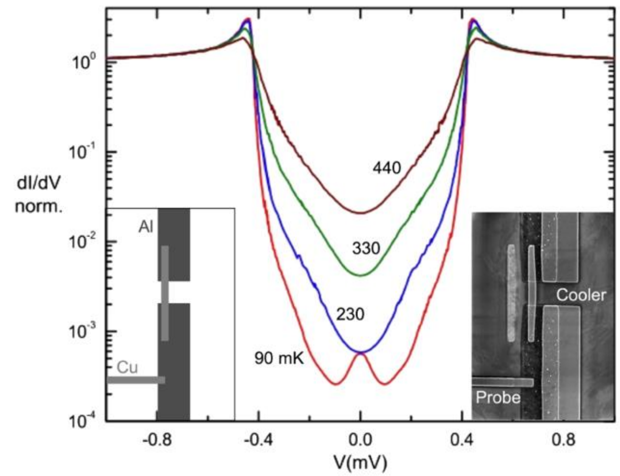
Electron cooling by NIS: Andreev Joule heating

- S. Rajauria, P. Gandit, T. Fournier, F.W.J. Hekking, B. Pannetier, H. Courtois, PRL **100**, 207002 (2008)

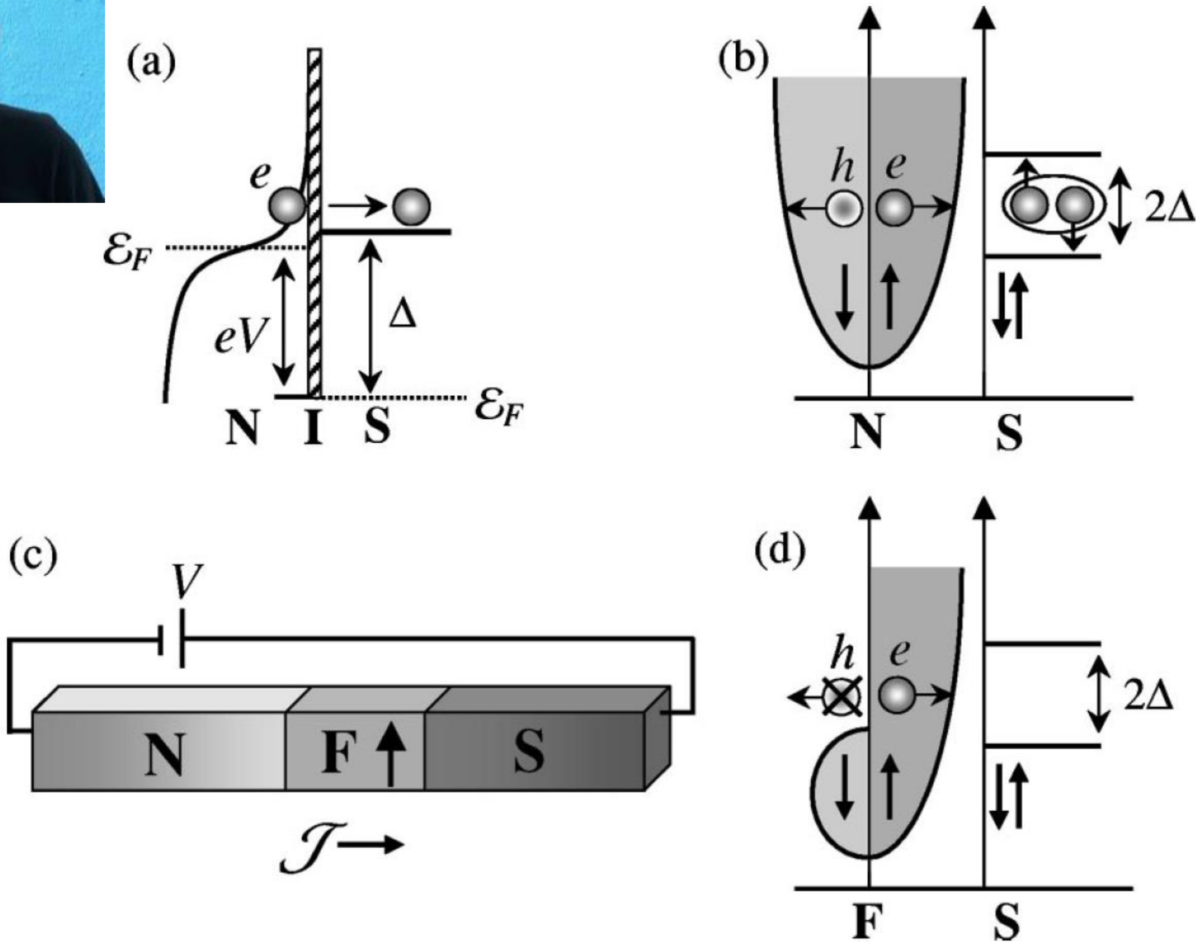






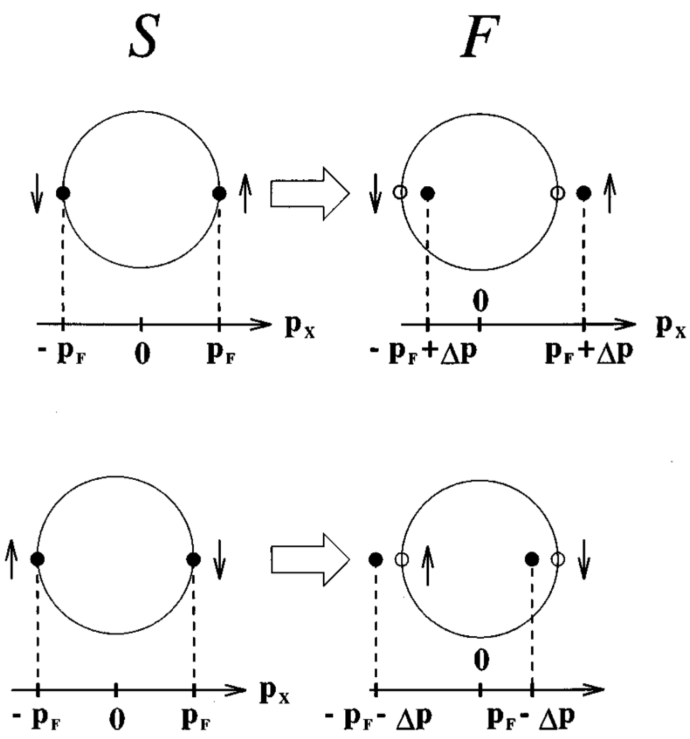


How to reduce the Andreev current?

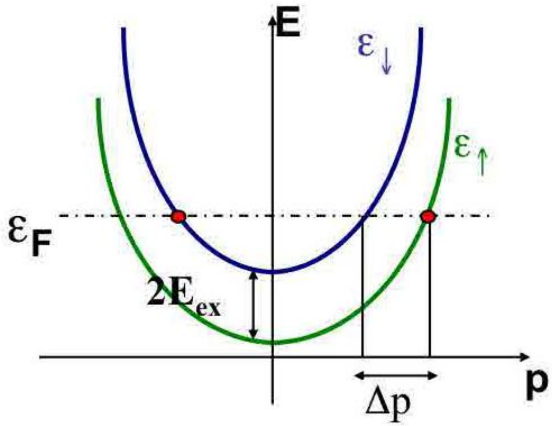


F. Giazotto, F. Taddei, R. Fazio, and F. Beltram, APL 80, 3784 (2002)

S/F proximity effect



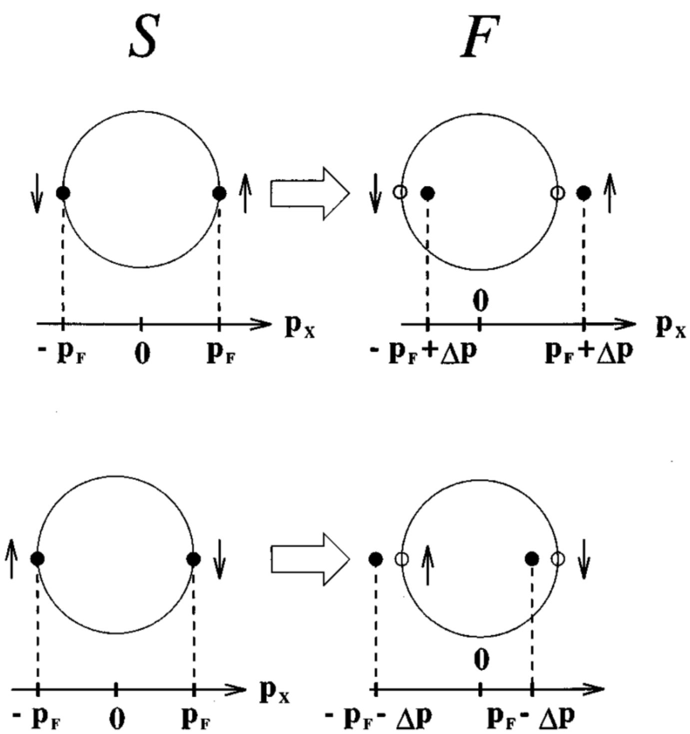
Buzdin & Kupriyanov, JETP **53**, 321 (1991)
Demler *et al.*, PRB **55**, 15174 (1997)



$$|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle$$ **S**

$$e^{ix\Delta p}|\uparrow\downarrow\rangle - e^{-ix\Delta p}|\downarrow\uparrow\rangle$$ **F**

S/F proximity effect



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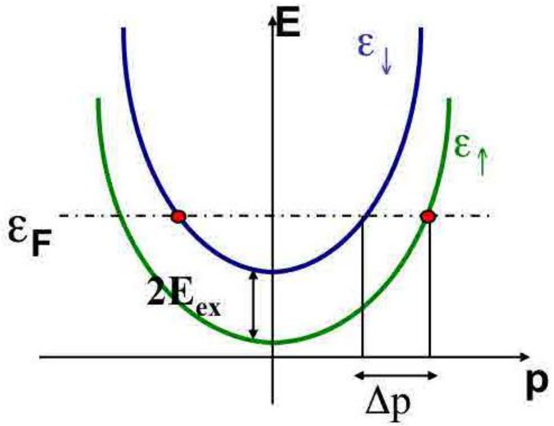

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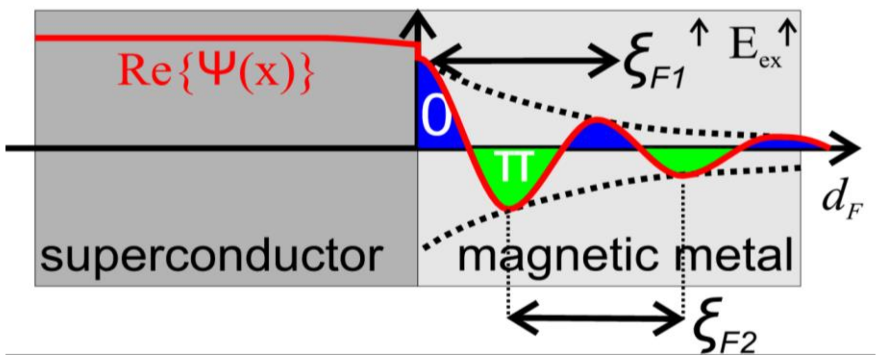
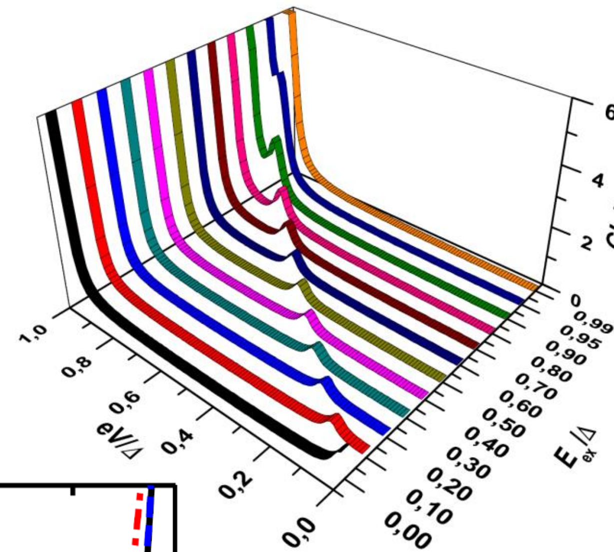
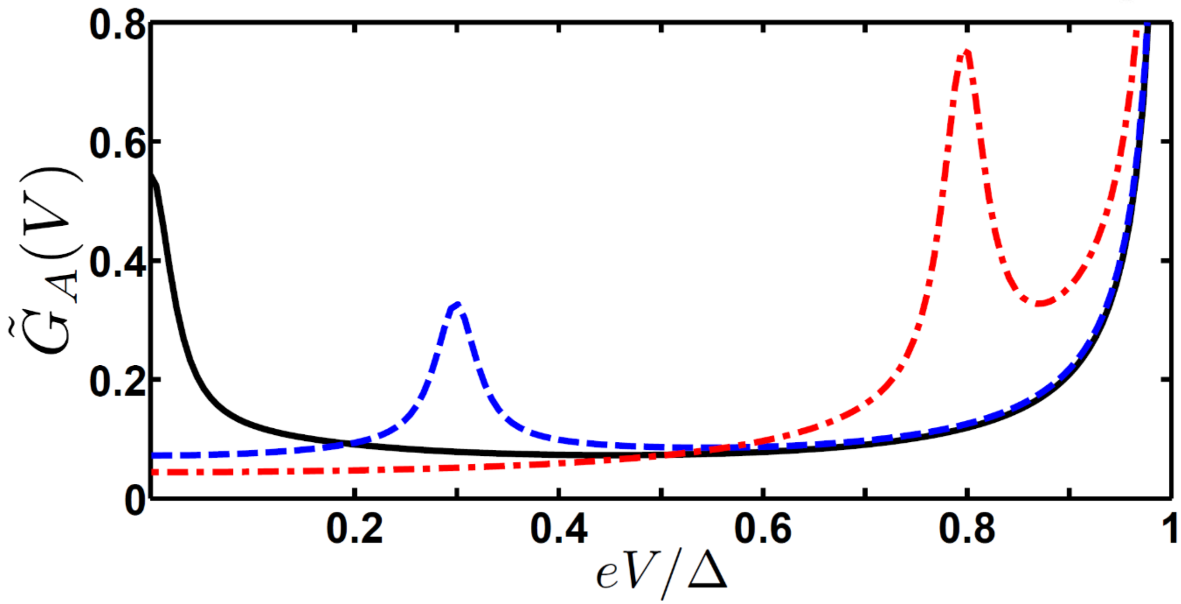


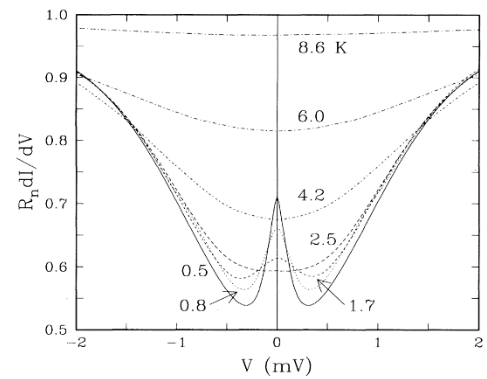
$$\Psi = \Psi_0 e^{-d_F/\xi_{F1}} \cos\left(\frac{d_F}{\xi_{F2}}\right)$$

$$\xi_F = \sqrt{\frac{D}{E_{ex}}}$$

Subgap conductance in FIS junctions





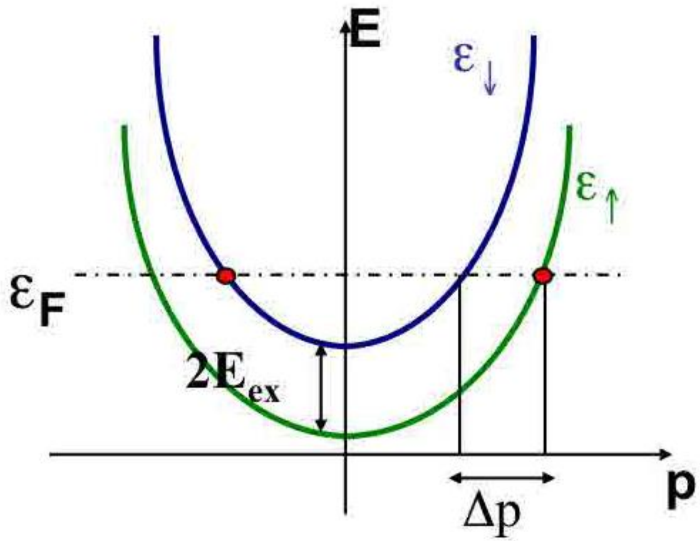


Ozaeta, Vasenko, Hekking, Bergeret, PRB ***85****, 174518 (2012); PRB* ***86****, 060509(R) (2012)*

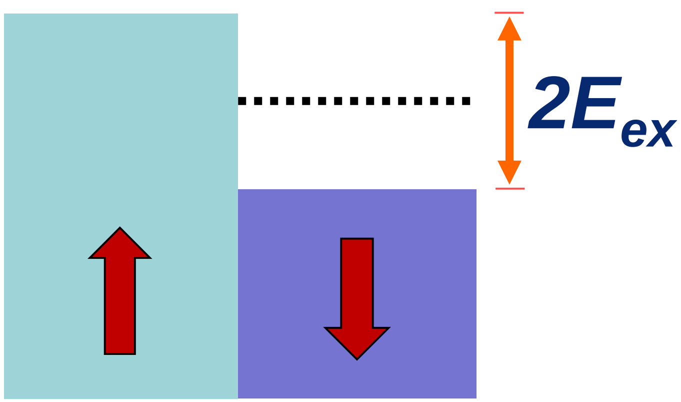
Shift of the ZBA peak

Spin-up electron lowers its E_{pot} by E_{ex}, increases E_{kin}

Spin-down electron raises its E_{pot} by E_{ex}, decreases E_{kin}



Kinetic energy:



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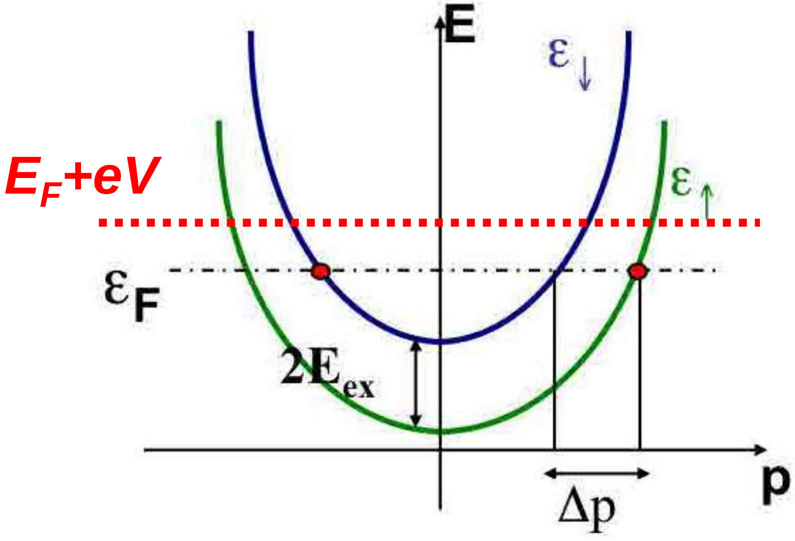
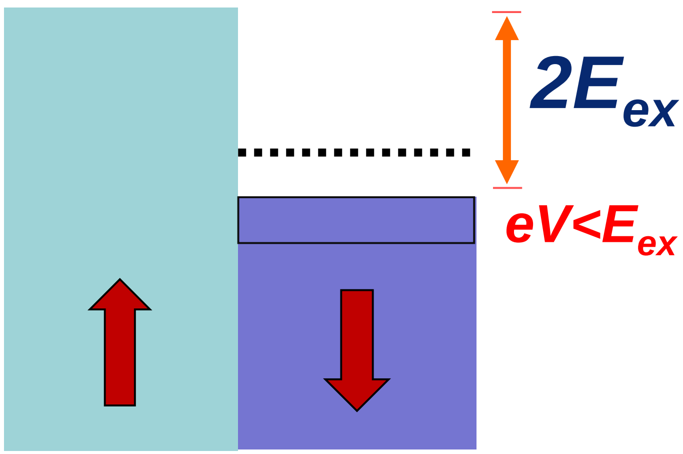


Kinetic energy:



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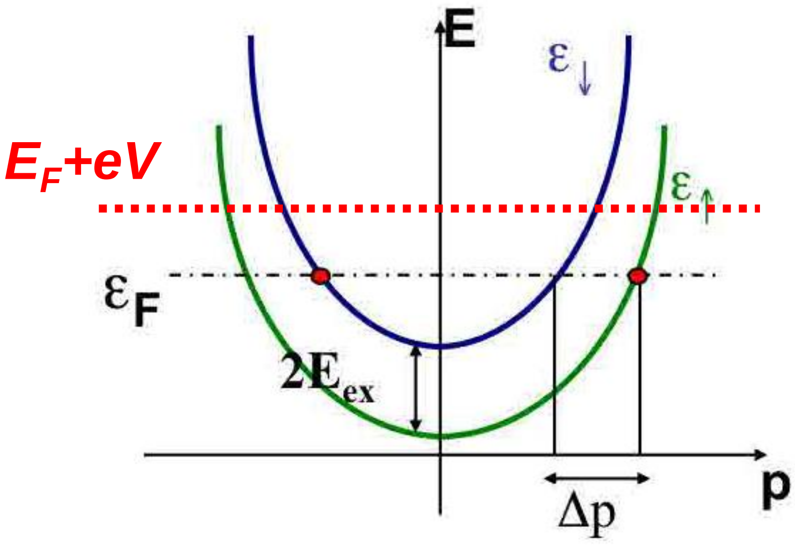

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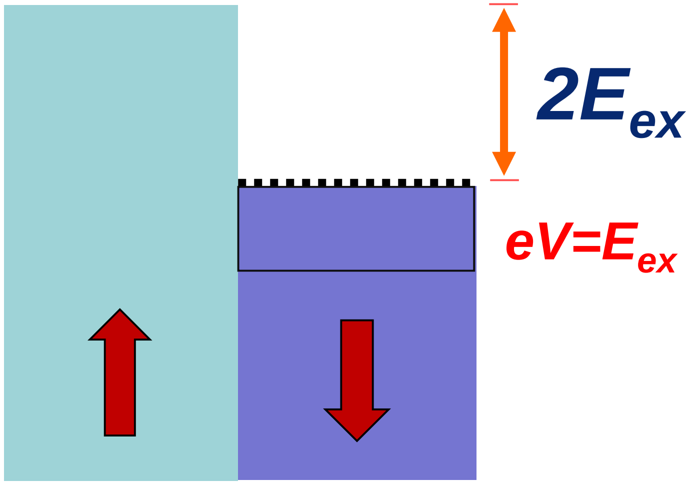
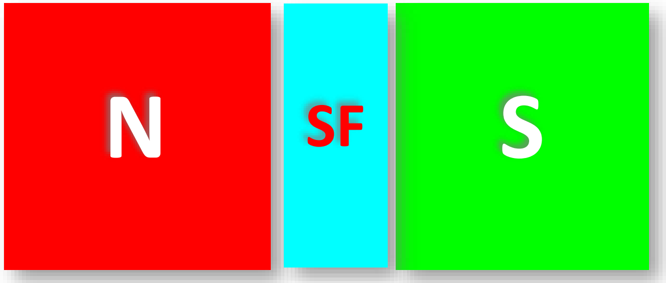


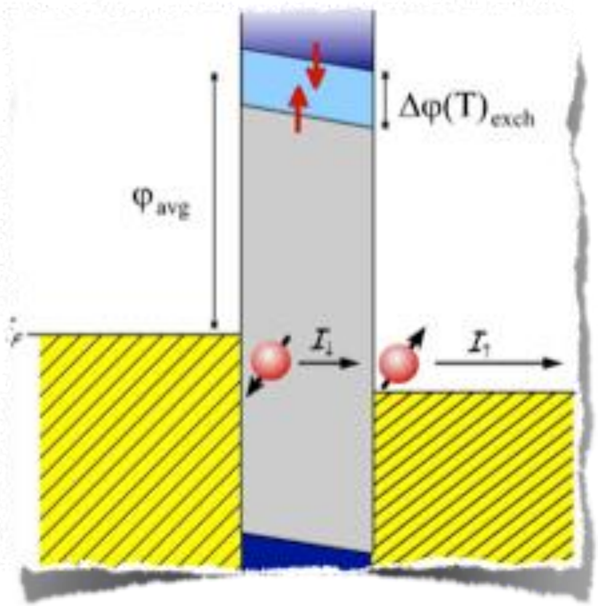
Spin-filter based cooler

Spin filter



N-SF-S cooler

$$t_\uparrow \gg t_\downarrow$$



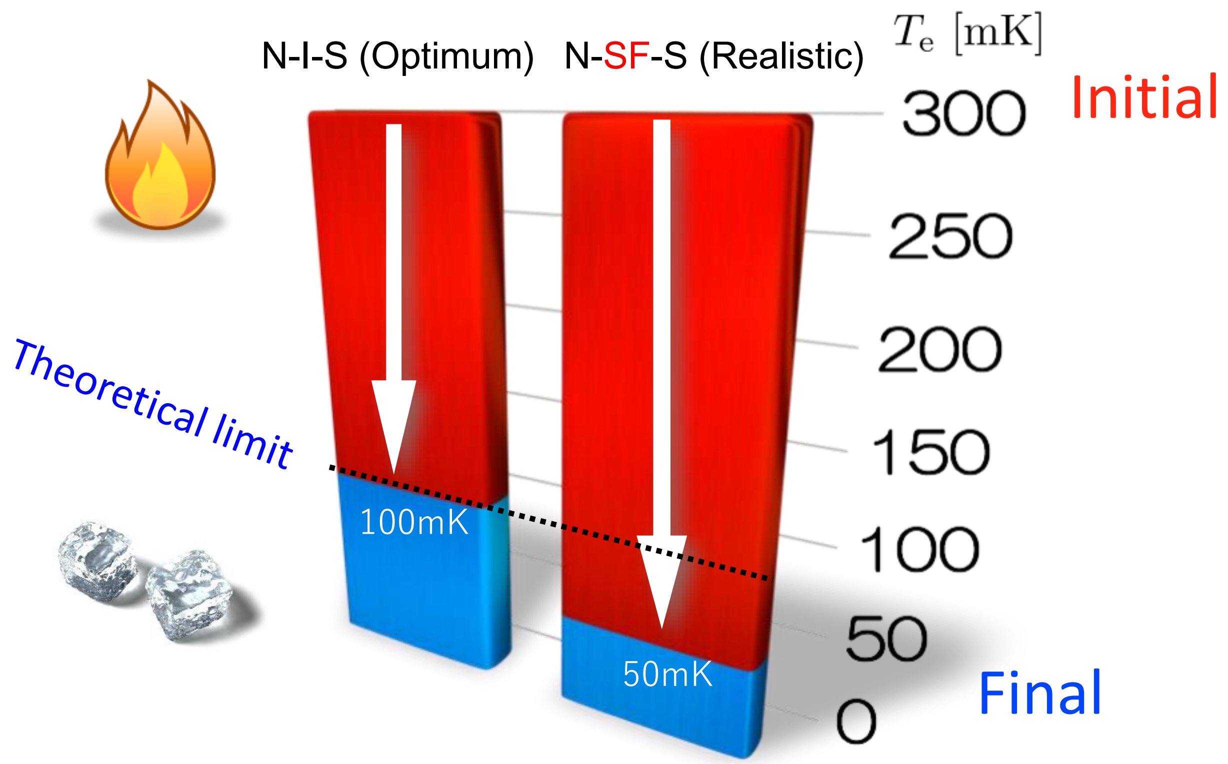
Spin filtering efficiency $$P = \frac{t_\uparrow - t_\downarrow}{t_\uparrow + t_\downarrow}$$

0(Insulator) < P < 1(perfect SF)

Kawabata, Ozaeta, Vasenko, Hekking, Bergeret, APL ***103****, 032602 (2013)*

Spin-filter based cooler

Example: Dirty Cu-EuSe-Al cooler



Cooling from 300mK to 50mK is possible!