Charles Univ. in Prague, 5 X 2015

Nonlocal transport properties due to Andreev scattering

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http://kft.umcs.lublin.pl/doman/lectures

Outline

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⇒ **how can we obtain nano-superconductivity**

/ proximity effect /

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⇒ **how can we obtain nano-superconductivity**

/ proximity effect /

⇒ **how can we observe nano-superconductivity**

/ spectroscopic signatures /

⇒ **where can we use nano-superconductors**

/ practical aspects /

1. Nano-superconductivity:

$\Rightarrow$ **how to obtain it ?**

Superconducting state – of bulk materials

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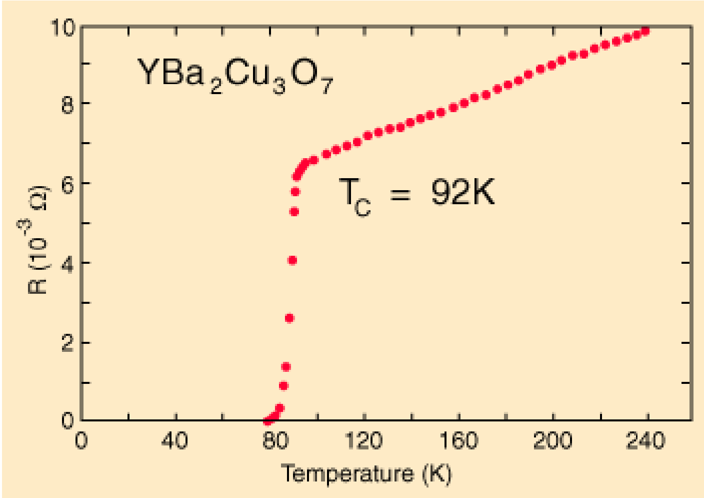
★ **ideal d.c. conductance**



Superconducting state – of bulk materials

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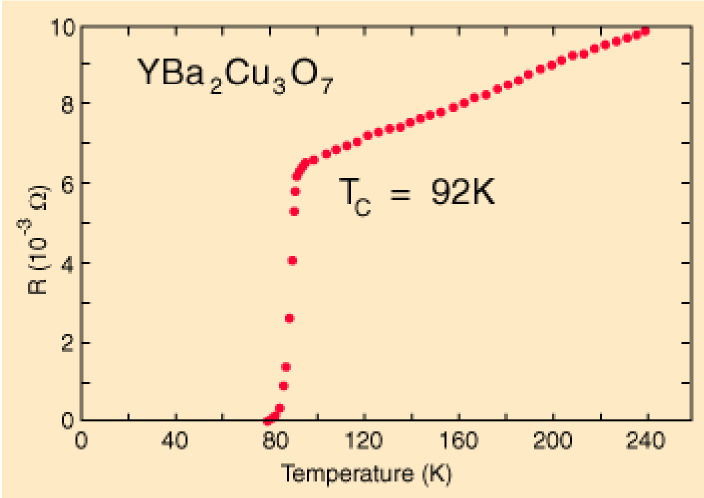
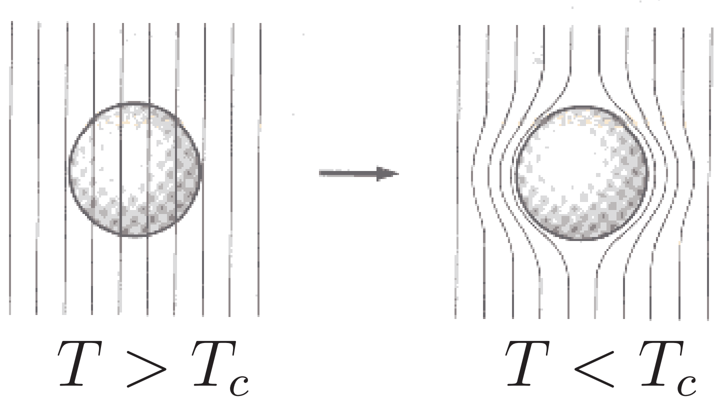


★ **ideal diamagnetism** /perfect screening of the d.c. magnetic field/



Superconducting state – of bulk materials

⟹ ideal d.c. conductance (vanishing resistance)

⟹ ideal diamagnetism (Meissner effect)

are caused by the superfluid electron pairs

$$n_s(T) \;\propto\; 1/\lambda^2$$

that move coherently over macroscopic distances.

Superconducting state – of bulk materials

The pairing mechanisms originate from:

1. **phonon-exchange**

   / classical superconductors, MgB_2, ... /

2. **magnon-exchange**

   / heavy fermion compounds /

3. **strong correlations**

   / spin exchange $\frac{2t_{ij}^2}{U}$ in the high T_c superconductors /

.. **other exotic processes**

   / ultracold atoms, nuclei, gluon-quark plasma /

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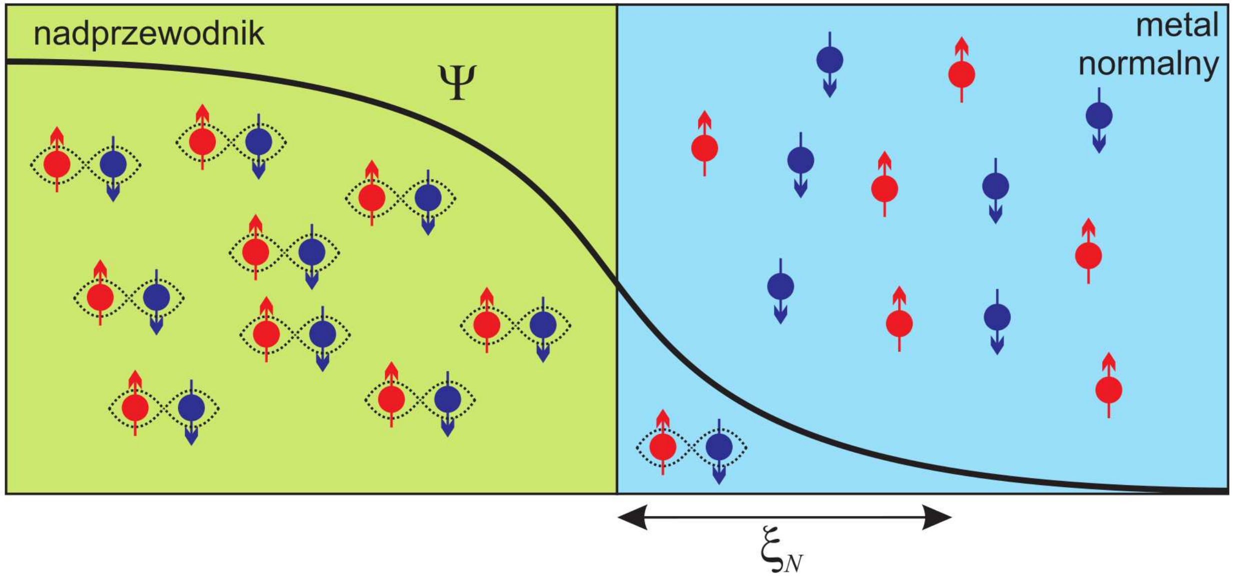
Onset of the fermion pairing often goes hand in hand with appearance of the superconductivity/superfluidity, but it doesn't have to be a rule.

Proximity effect – induced superconductivity

Proximity effect – **induced superconductivity**

★ **Any material brought in contact with superconductor**



Proximity effect – induced superconductivity

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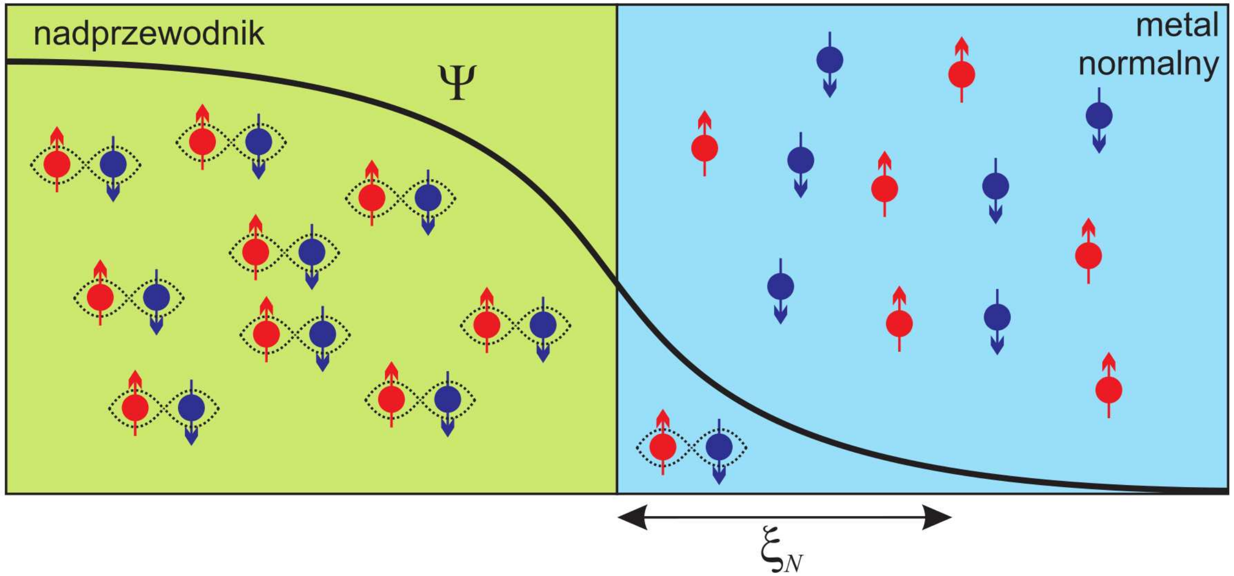

absorbs the paired electrons up to distances $\sim \xi_n$.

Proximity effect – induced superconductivity

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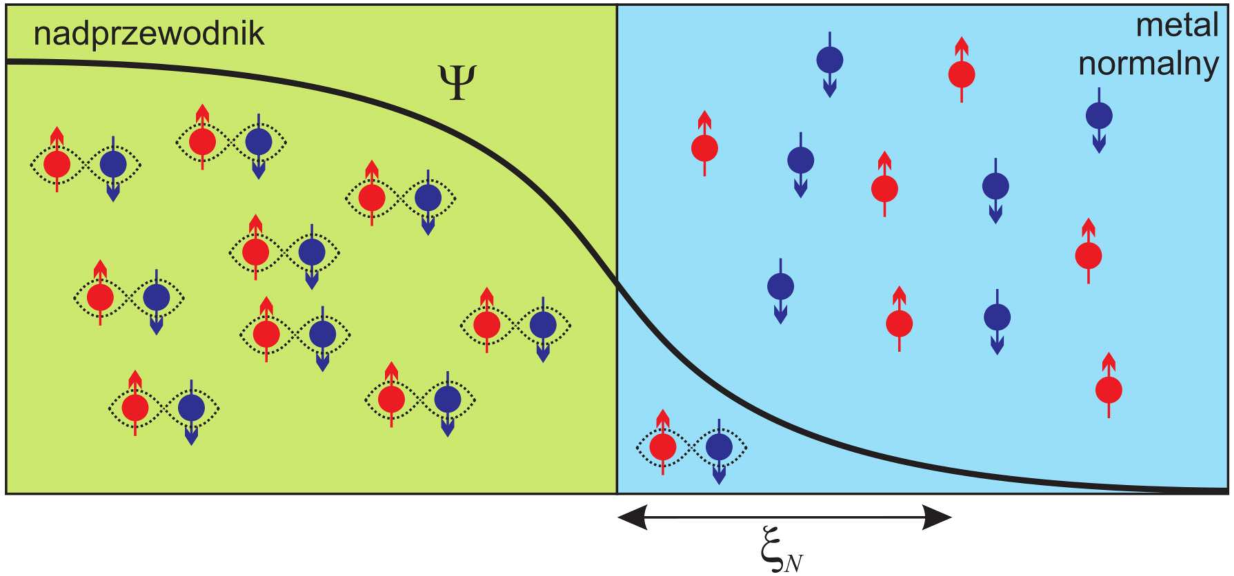

absorbs the paired electrons up to distances $\sim \xi_n$.

★ **Spatial size L of nanoscopic objects is $L \ll \xi_n$!**

2. Nano-superconductivity:

$\Rightarrow$ **how can we observe it ?**

Superconductivity in nanosystems – specific issues

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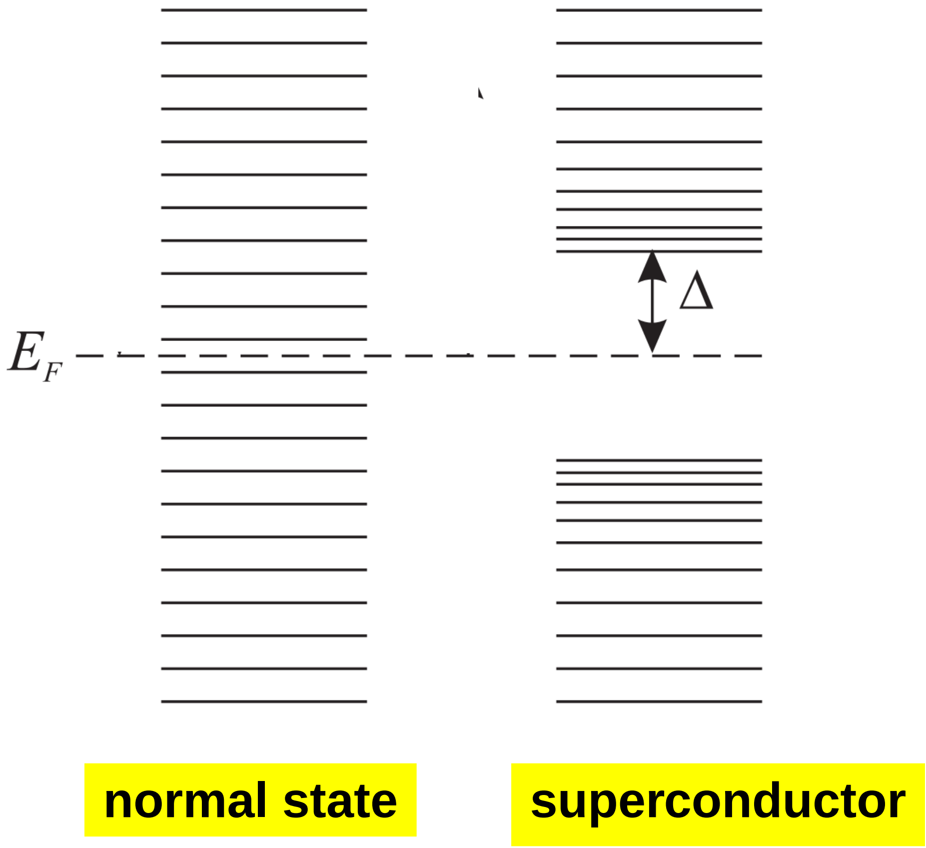
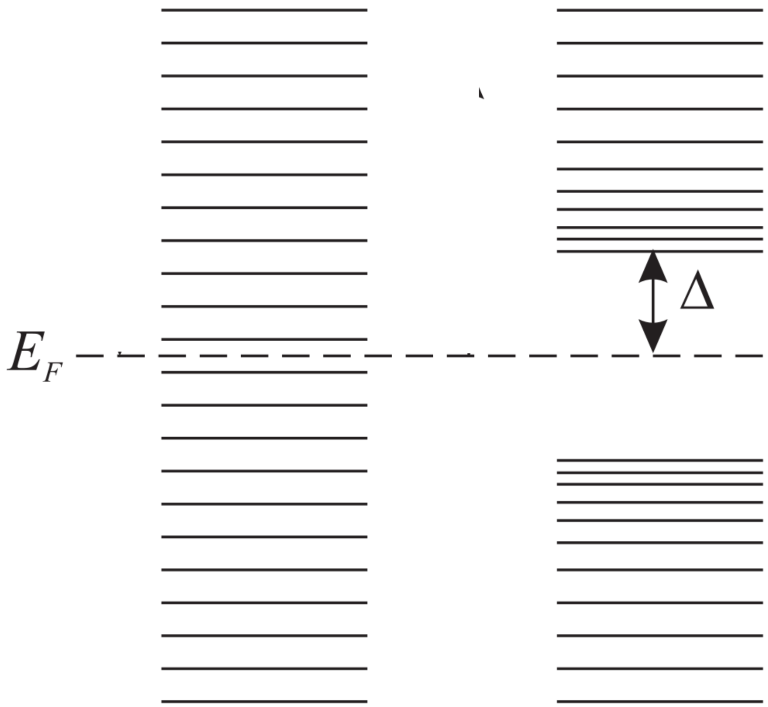
1. Quantum Size Effect ⟶ discrete energy spectrum



Superconductivity in nanosystems – specific issues

1. Quantum Size Effect → discrete energy spectrum



normal state

superconductor

Anderson criterion: superconductivity only for $\Delta > \varepsilon_{i+1} - \varepsilon_i$

Superconductivity in nanosystems – specific issues

2. Coulomb blockade (electron pairing vs repulsion)

The odd / even electron number plays the important and qualitative role !

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Coulomb potential U_C is usually much smaller than Δ, therefore its influence can be in practice observed only indirectly, via :

$$|\uparrow\rangle \quad \Longleftrightarrow \quad u\,|0\rangle - v\,|\uparrow\downarrow\rangle$$

(quantum phase transition)

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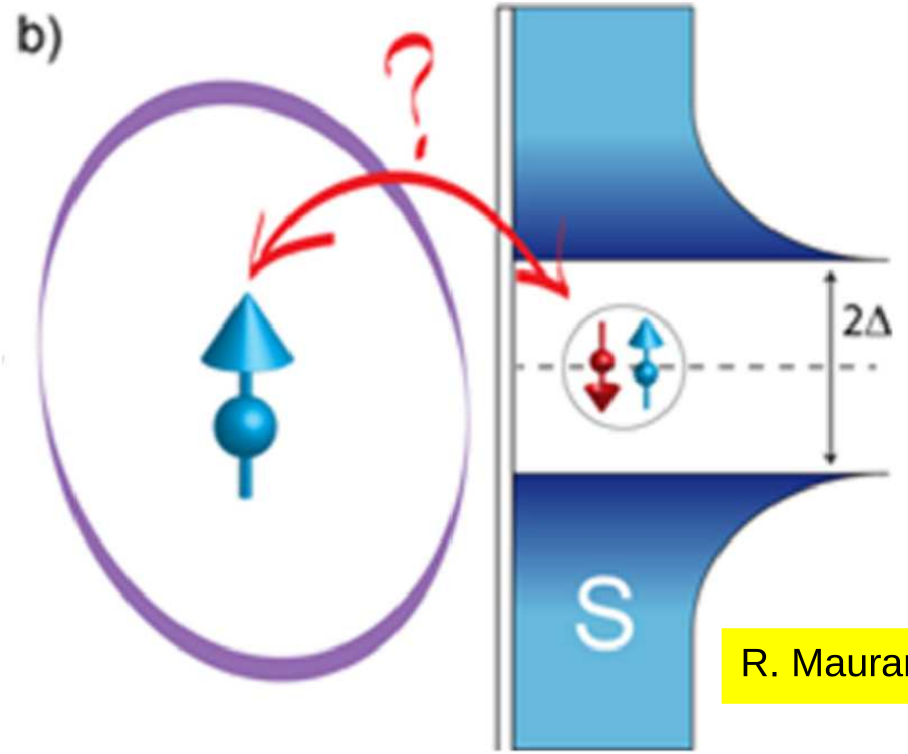
Physical consequences:

$\Rightarrow$ inversion of the Josephson current (in S-QD-S junctions)

$\Rightarrow$ activation/blocking of the Kondo effect (in N-QD-S junctions)

Superconductivity in nanosystems – **specific issues**

3. Pairing vs Kondo state ('to screen or not to screen')



R. Maurand, Ch. Schönenberger, Physics **6**, 75 (2013).

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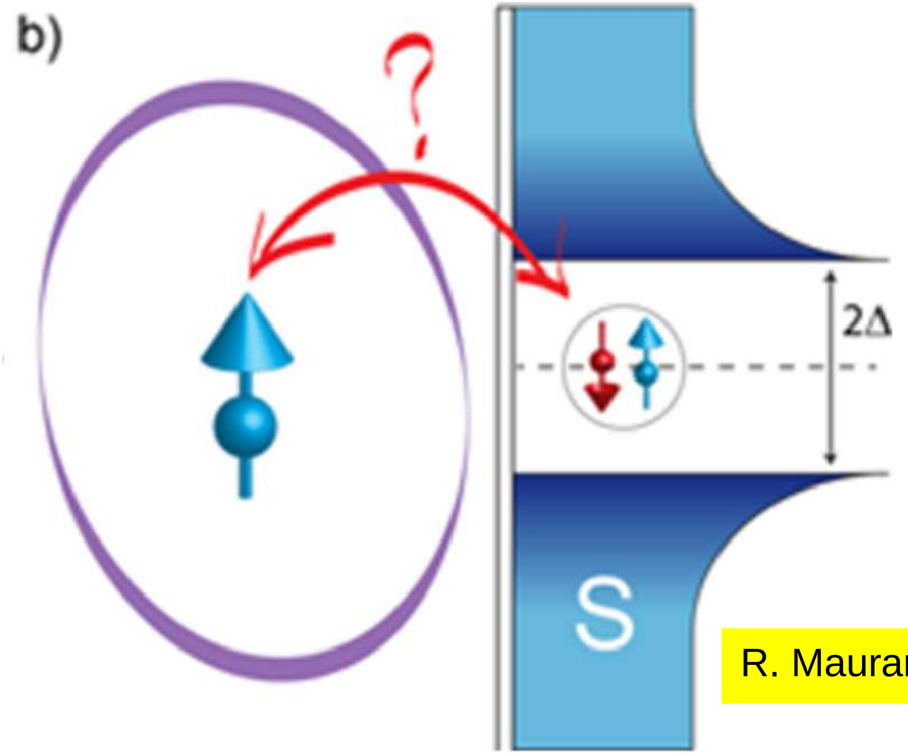


R. Maurand, Ch. Schönenberger, Physics **6**, 75 (2013).

⇒ states near the Fermi level are depleted

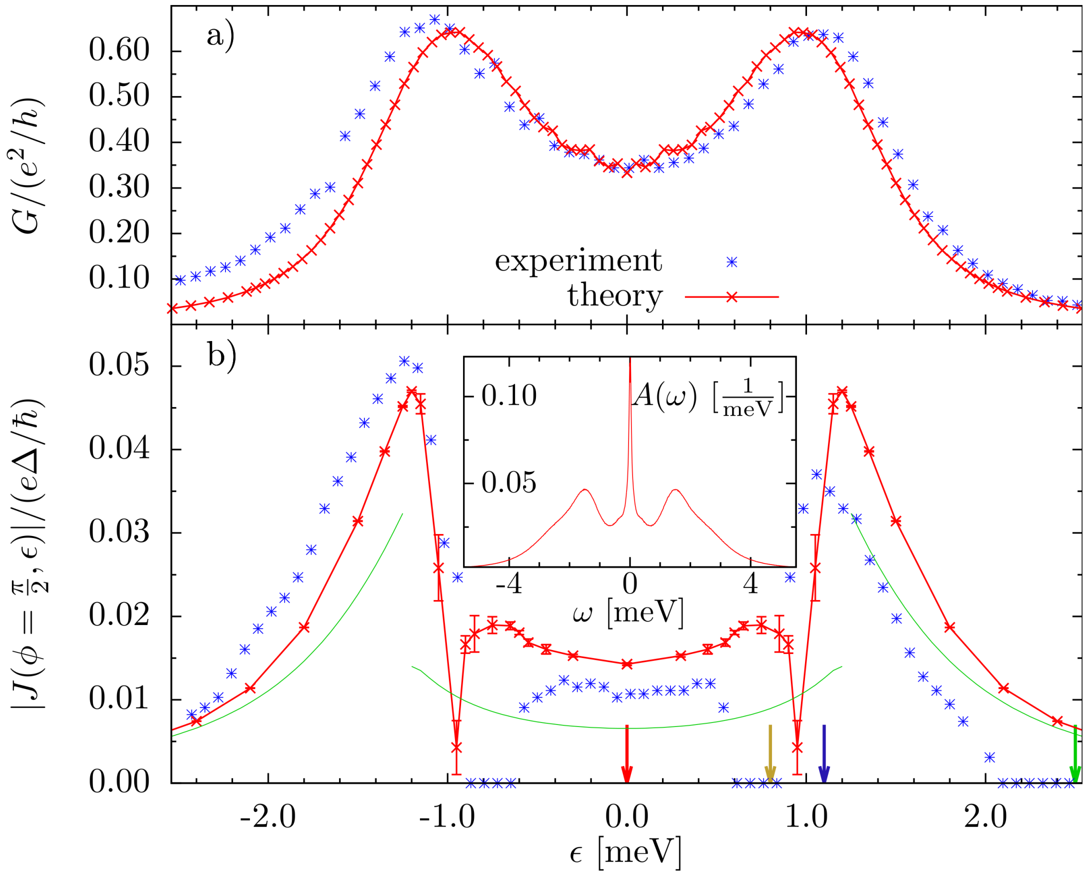
⇒ electron pairing vs the Kondo state (nontrivial relation)

/ $0 - \pi$ transition /

Josephson junctions

/ $0 - \pi$ transition /

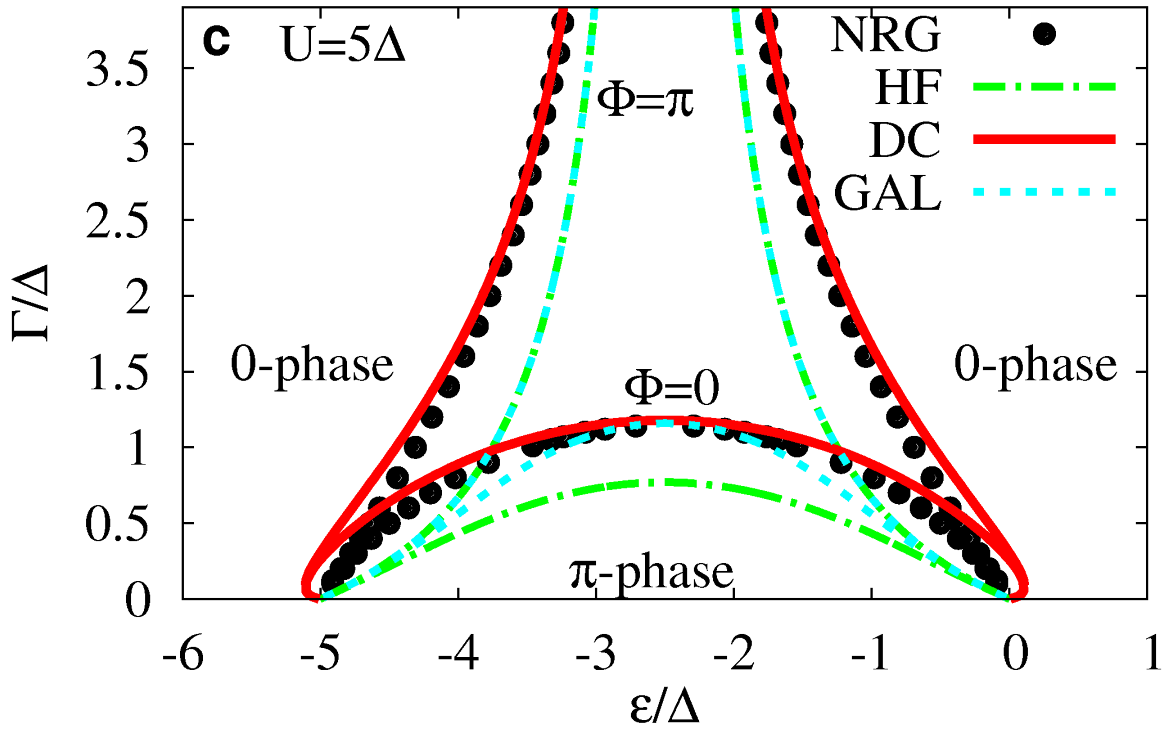
Theory and experiment on $0 - \pi$ transition



D. Luitz, F.F. Assad, T. Novotný, C. Karasch, and V. Meden, Phys. Rev. Lett. **108**, 227001 (2012).

Josephson junctions / $0 - \pi$ transition /

Phase boundaries obtained by several methods



M. Žonda, V. Pokorný, V. Janiš, and T. Novotný, Sci. Rep. **5**, 8821 (2015).

3. Nano-superconductivity:

$\Rightarrow$ **some practical aspects**

Andreev reflections – possible applications

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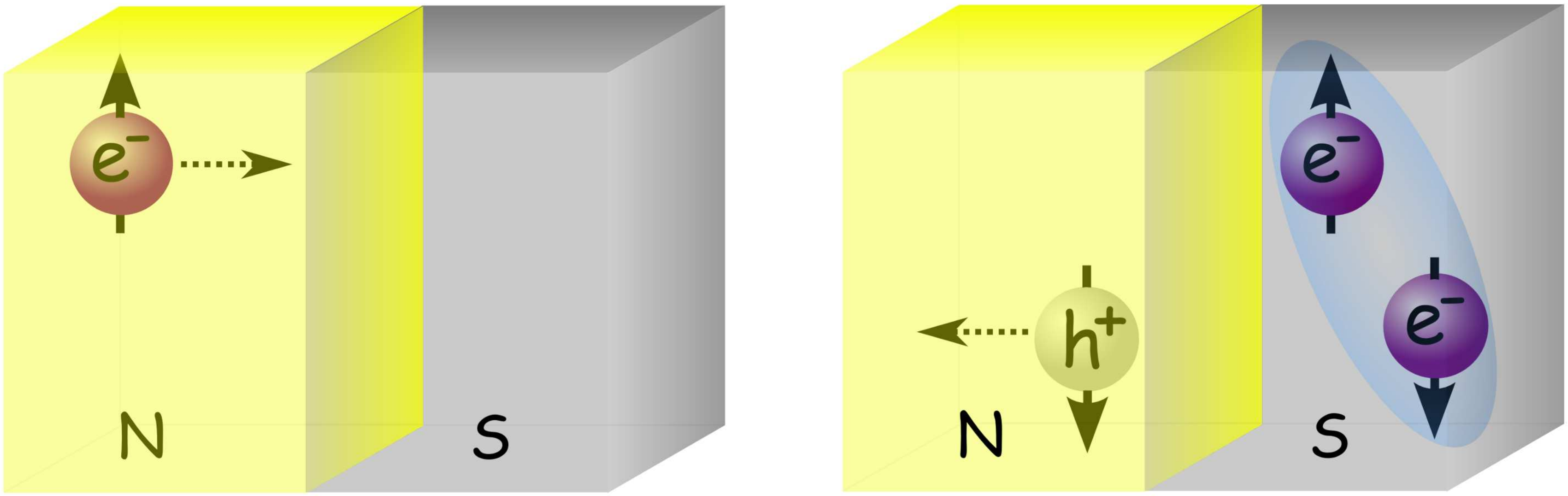
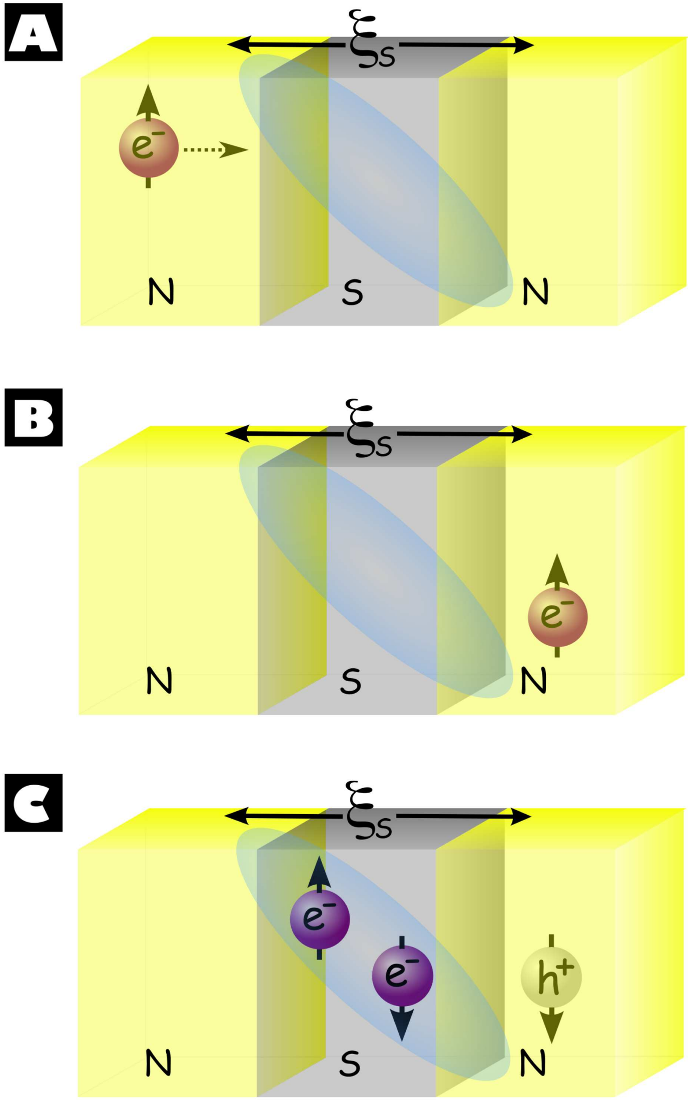


Schematic illustration of the Andreev-type scattering

Andreev reflections – possible applications

Andreev-type scattering can be also considered in more complex junctions



P. Cadden-Zimansky, Ph.D. thesis, Northwestern University (2008).

Andreev reflections – possible applications

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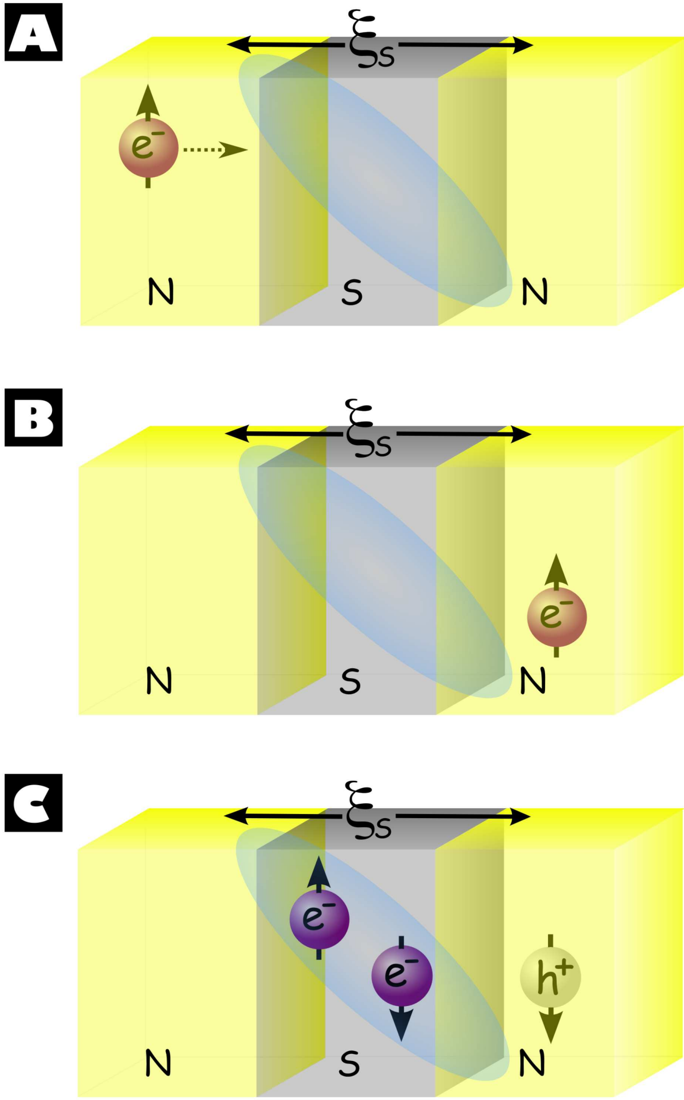
incident electron



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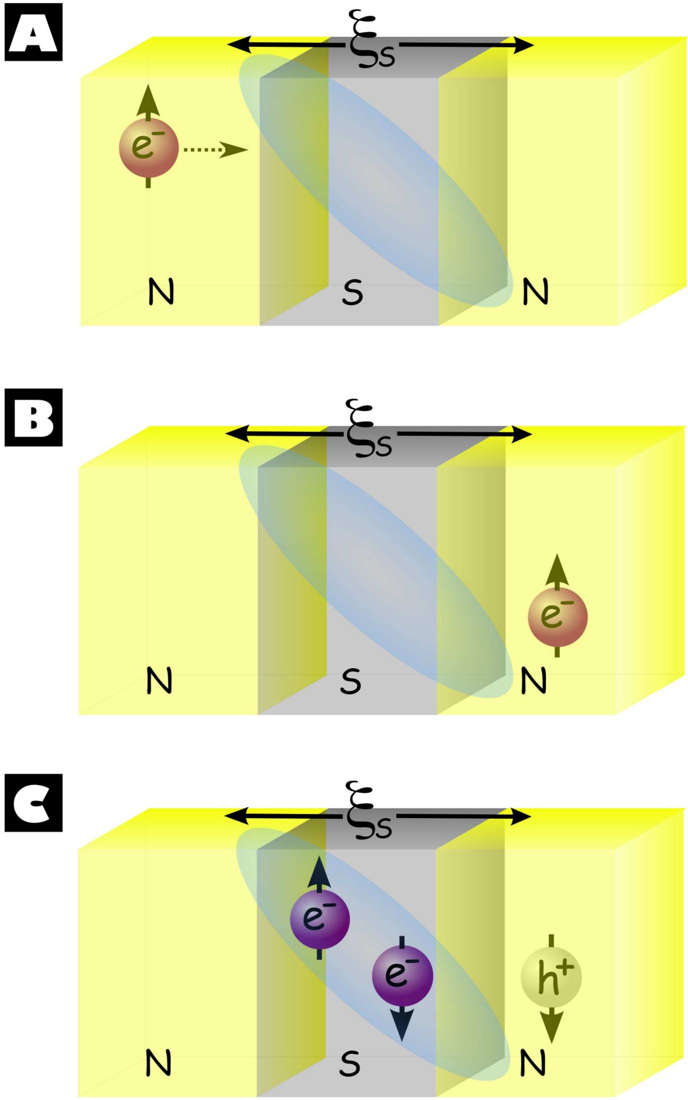

elastic tunelling

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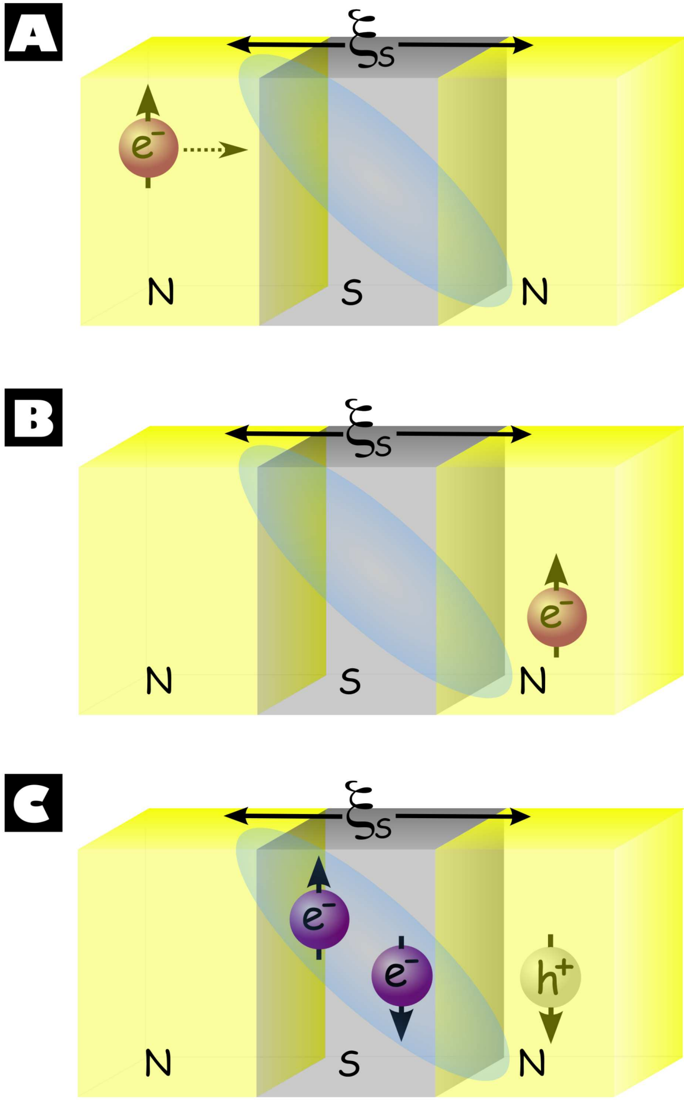

elastic tunelling

crossed Andreev refl.

P. Cadden-Zimansky, Ph.D. thesis, Northwestern University (2008).

Non-local transport – planar junctions

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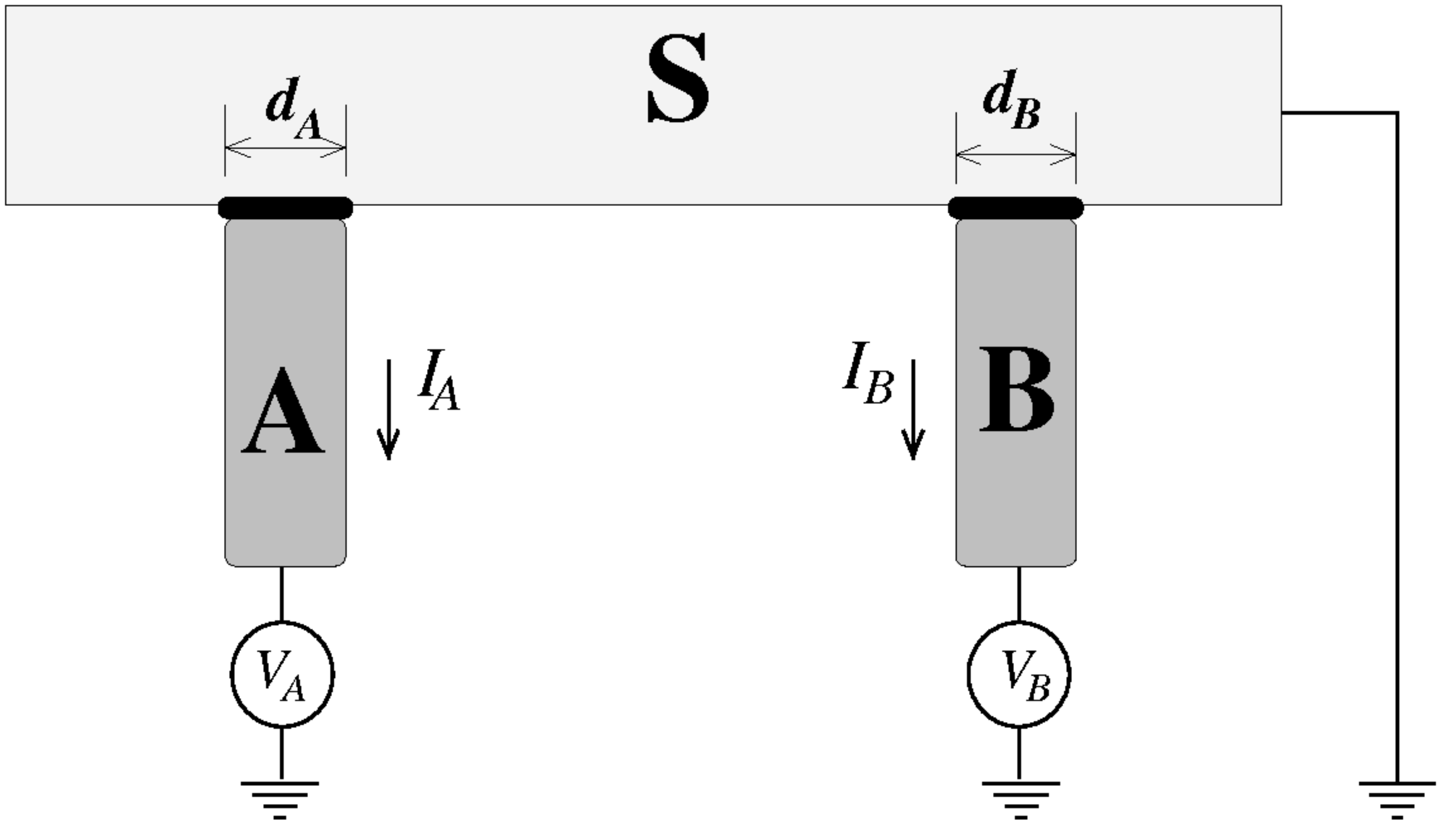
These ET/CAR processes have first considered in the planar junctions

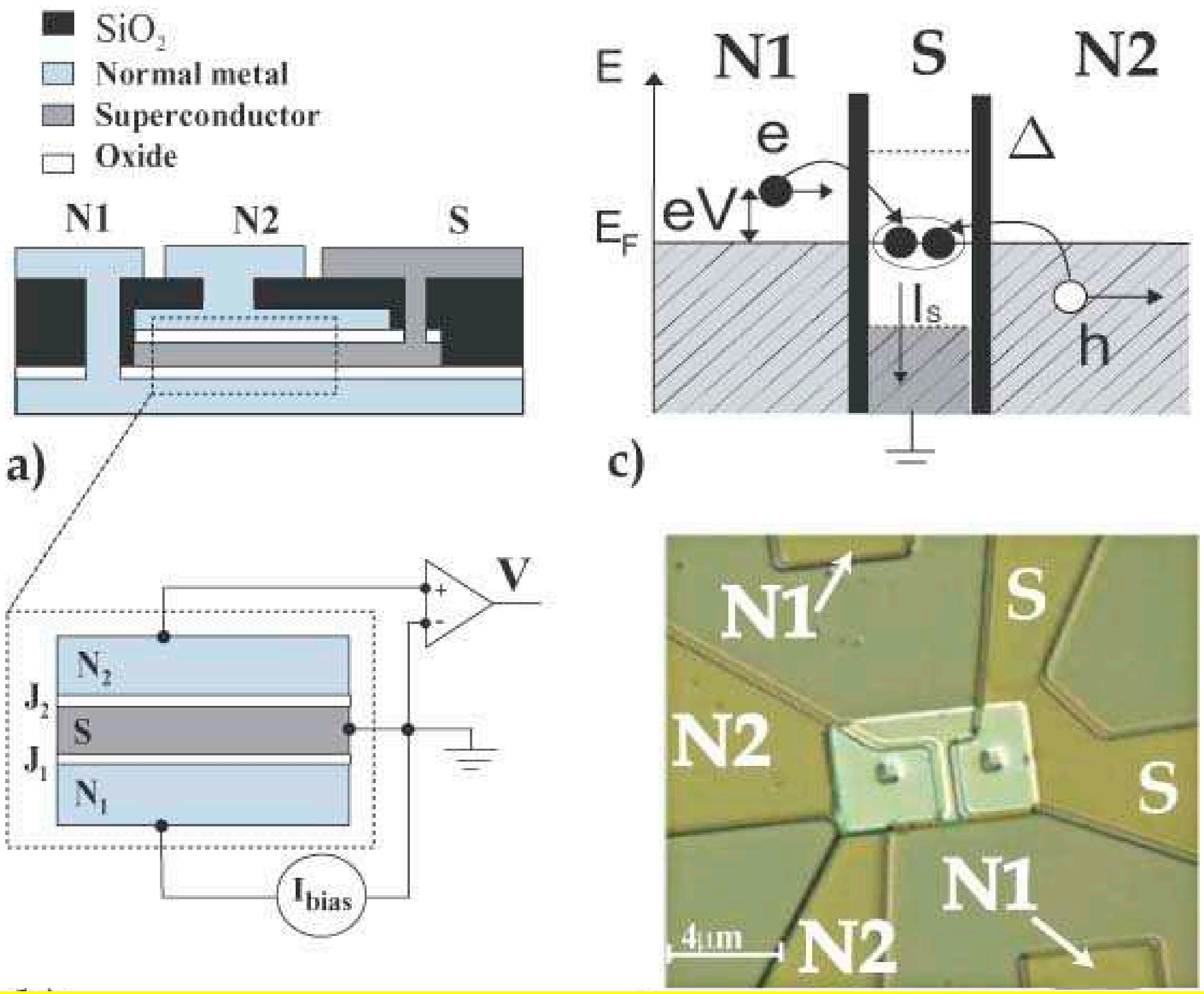


A, B – **normal electrodes,** S – **superconducting material**

G. Falci, D. Feinberg, F. Hekking, Europhys. Lett. **54**, 255 (2001).

Non-local transport – planar junctions

Experimental realization (Delft group)



S. Russo, M. Kroug, T. M. Klapwijk & A.F. Morpurgo, *Phys. Rev. Lett.* **95**, 027002 (2005).

Non-local transport – planar junctions

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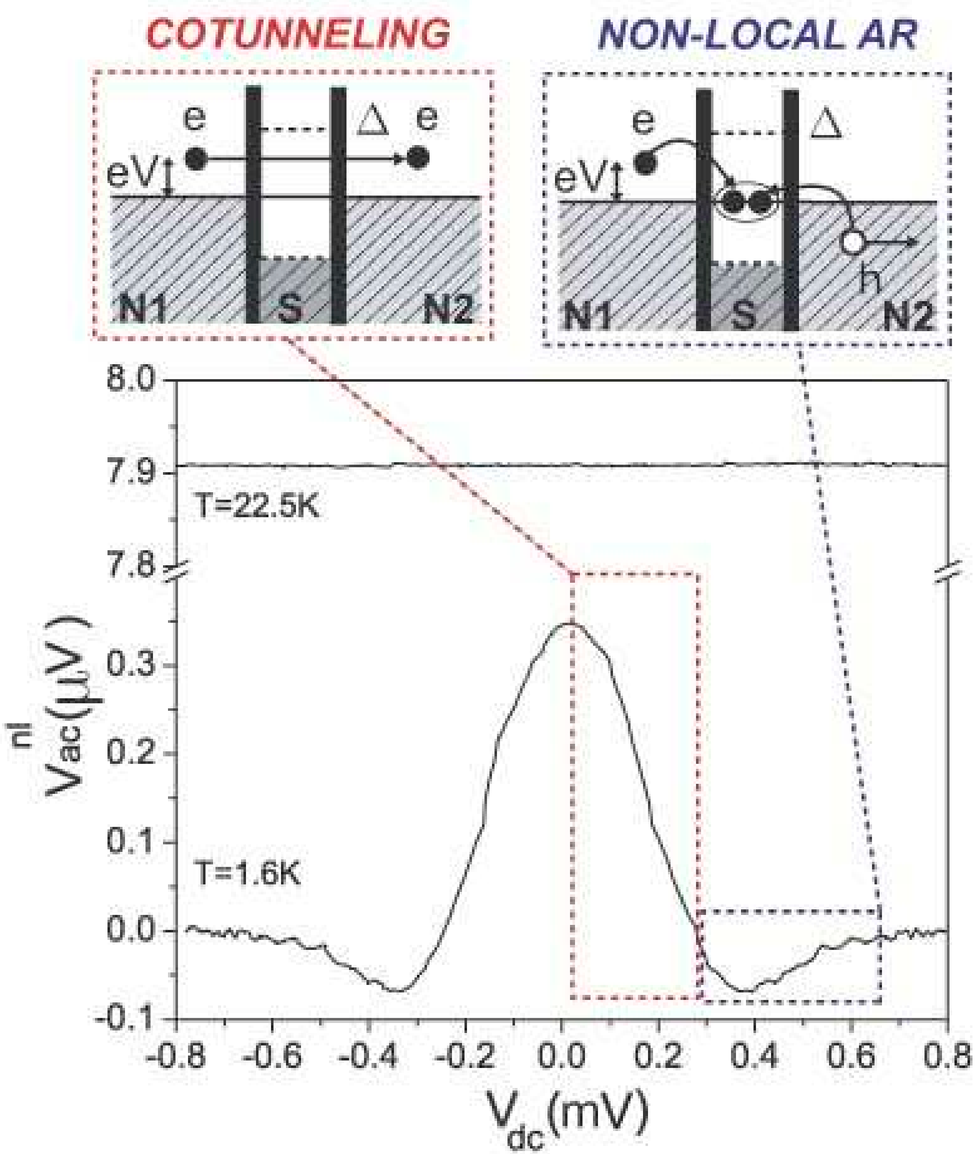

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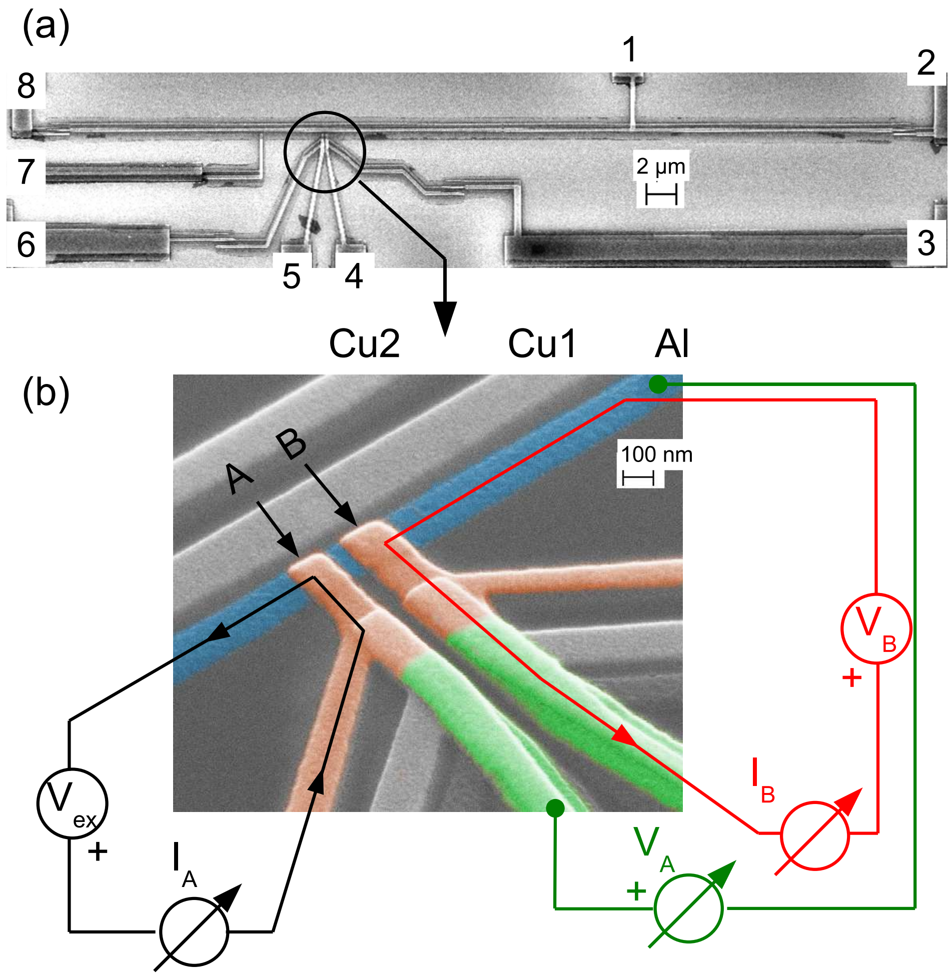
Non-local transport – planar junctions

Experimental realization (Karlsruhe group)



J. Brauer, F. Hübler, M. Smetanin, D. Beckman, D. & H. von Löhneysen, *Phys. Rev. B* **81**, 024515 (2010).

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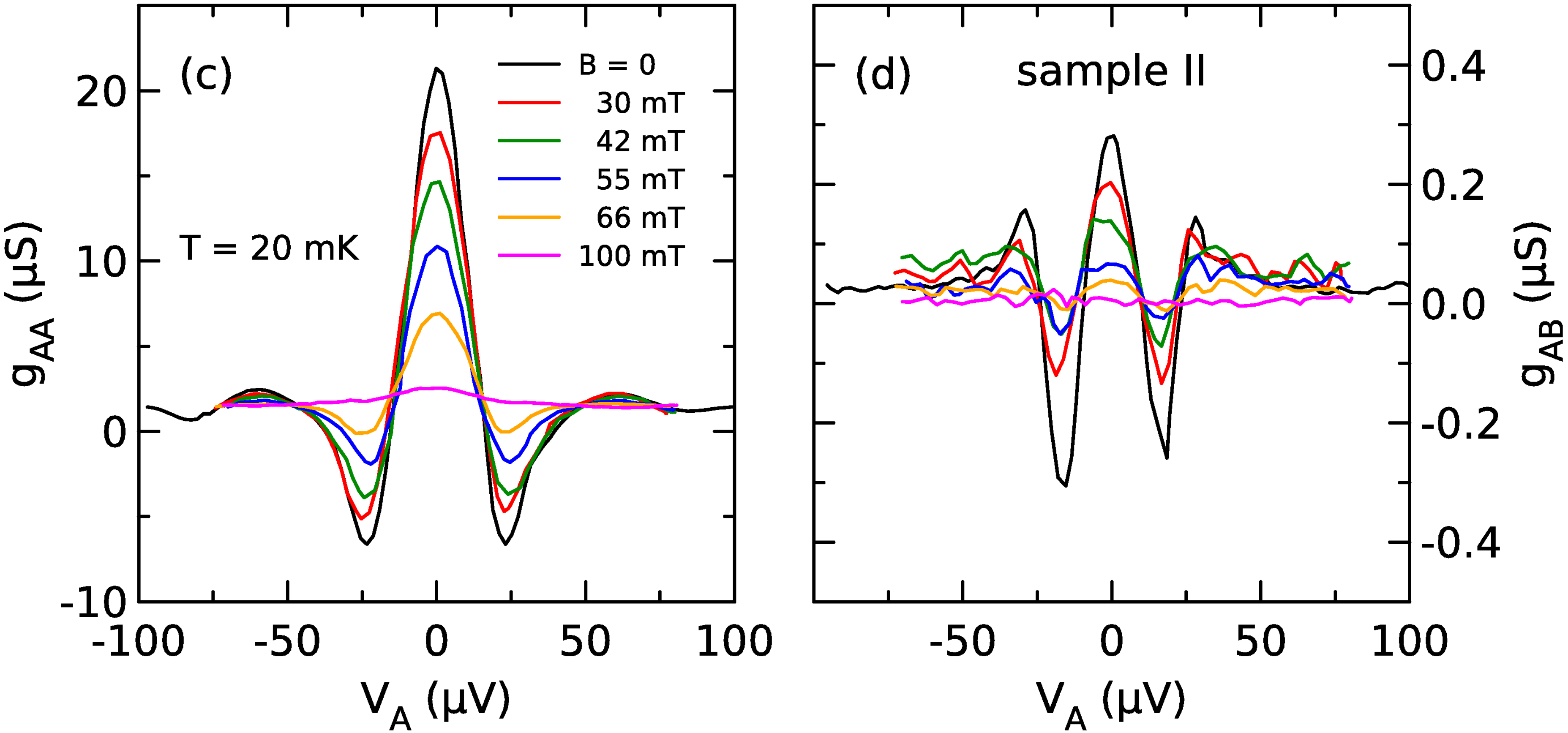

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3-terminal junctions – with quantum dots

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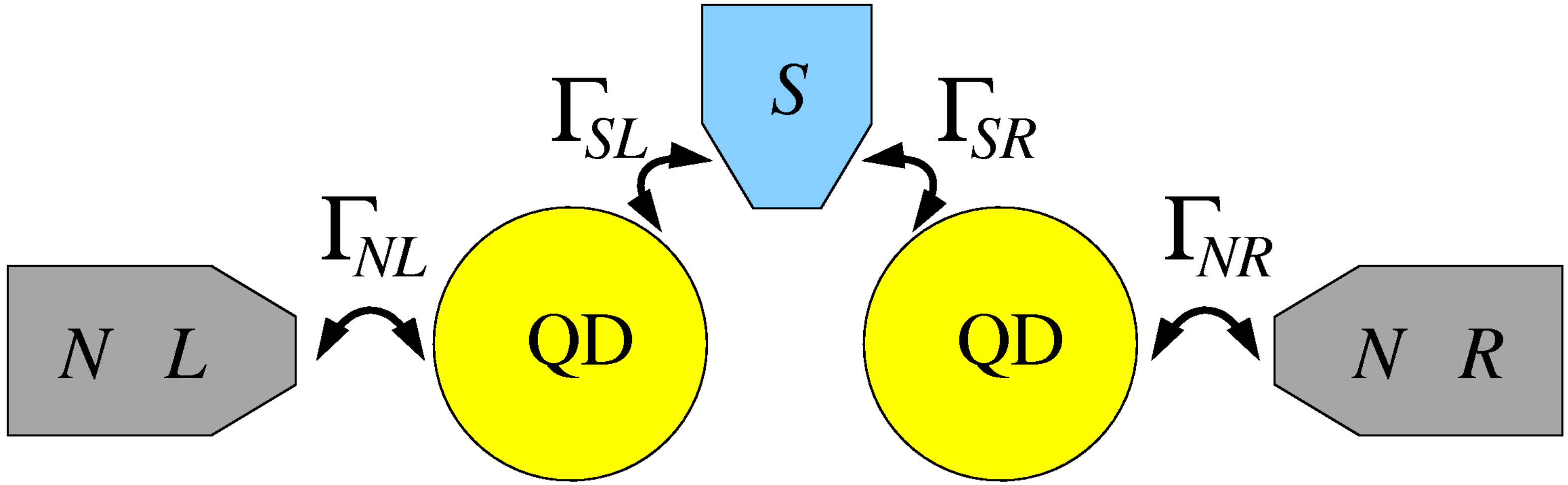


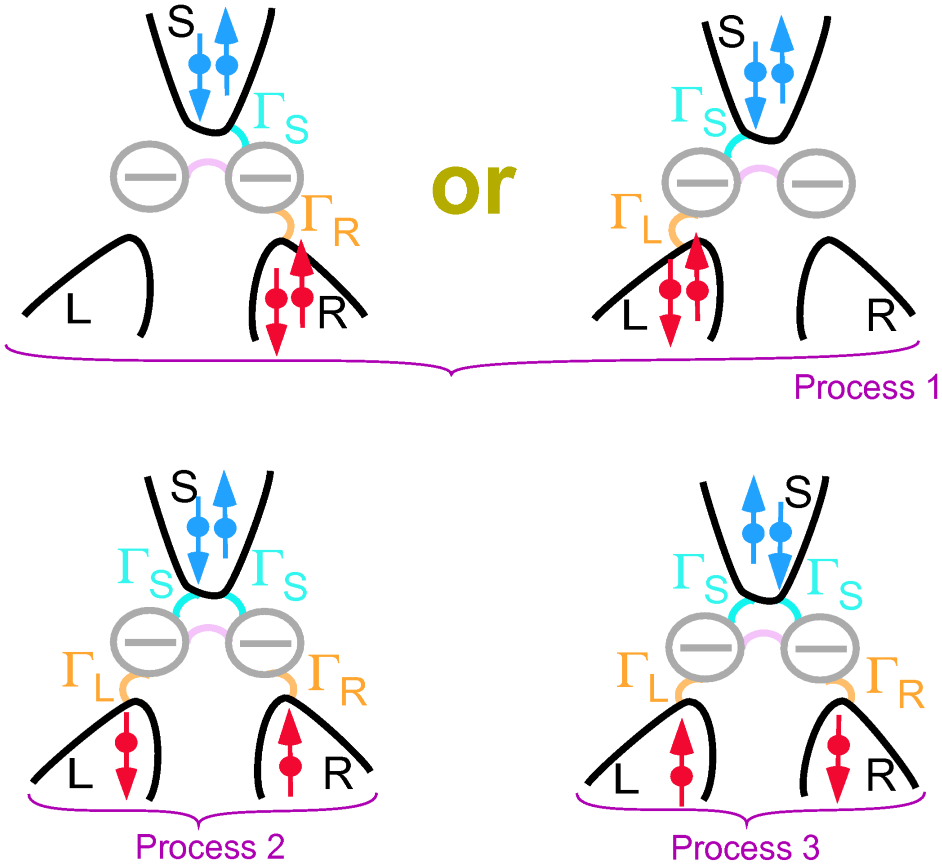
Cooper pairs are split, preserving entanglement of individual electrons.

L. Hofstetter, S. Csonka, J. Nygård, C. Schönenberger, Nature **461***, 960 (2009).*

J. Schindele, A. Baumgartner, C. Schönenberger, Phys. Rev. Lett. **109***, 157002 (2012).*

... and many other groups.

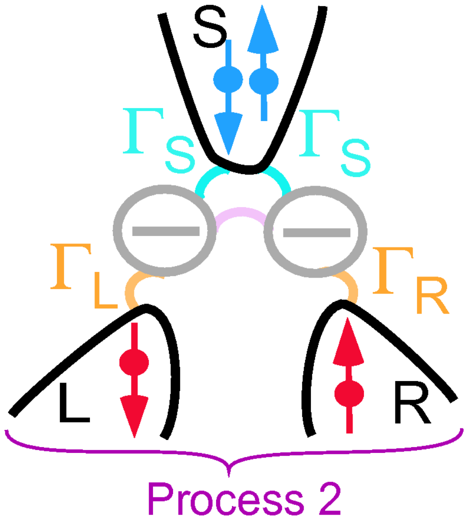
3-terminal junctions – with quantum dots

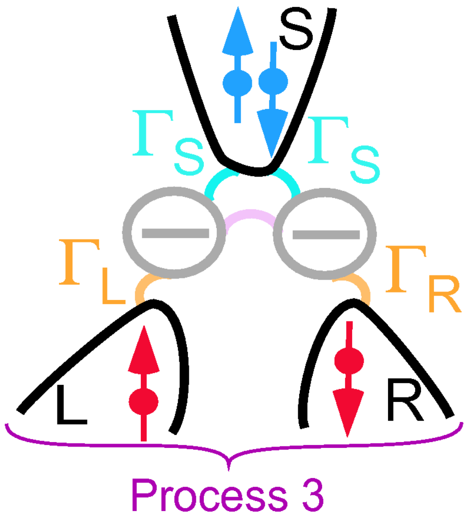


Possible channels of the Cooper pair splitting

L.G. Herrmann et al, *Phys. Rev. Lett.* **104**, *026801 (2010).*

3-terminal junctions – with quantum dots





These processes are similar to the crossed Andreev scattering and cause the strong non-local transport properties.

Non-local transport – crossed Andreev refelections

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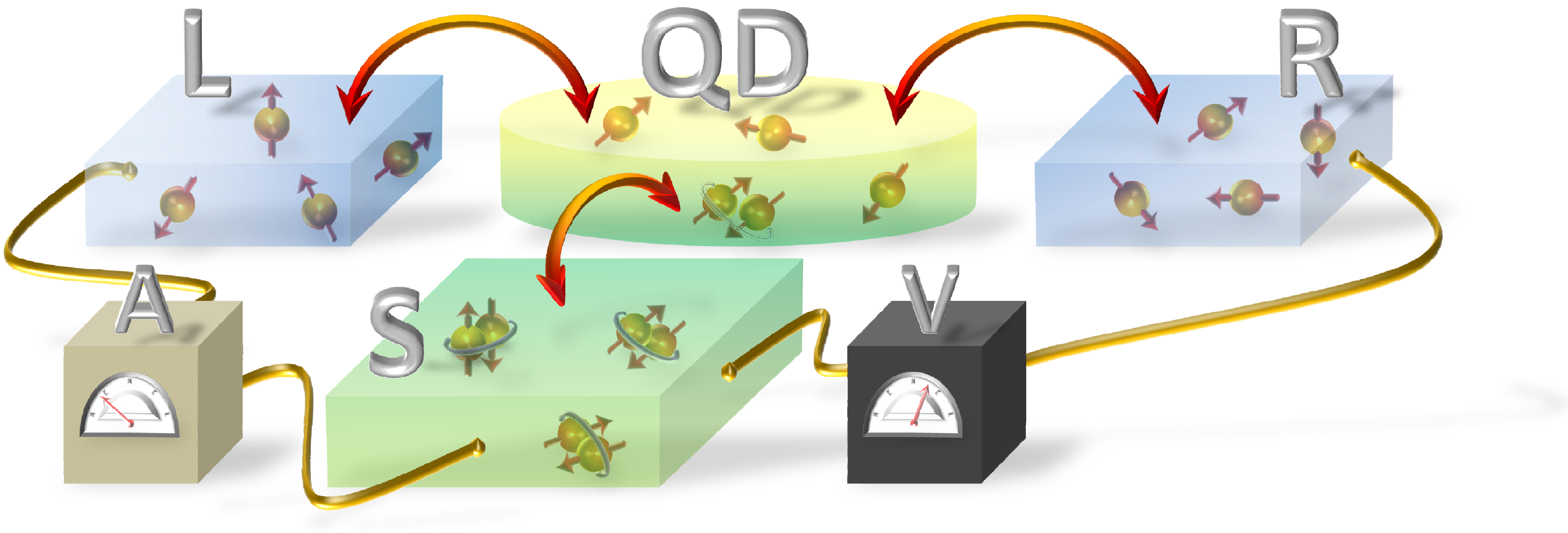
Quantum impurity in the 3-terminal configuration

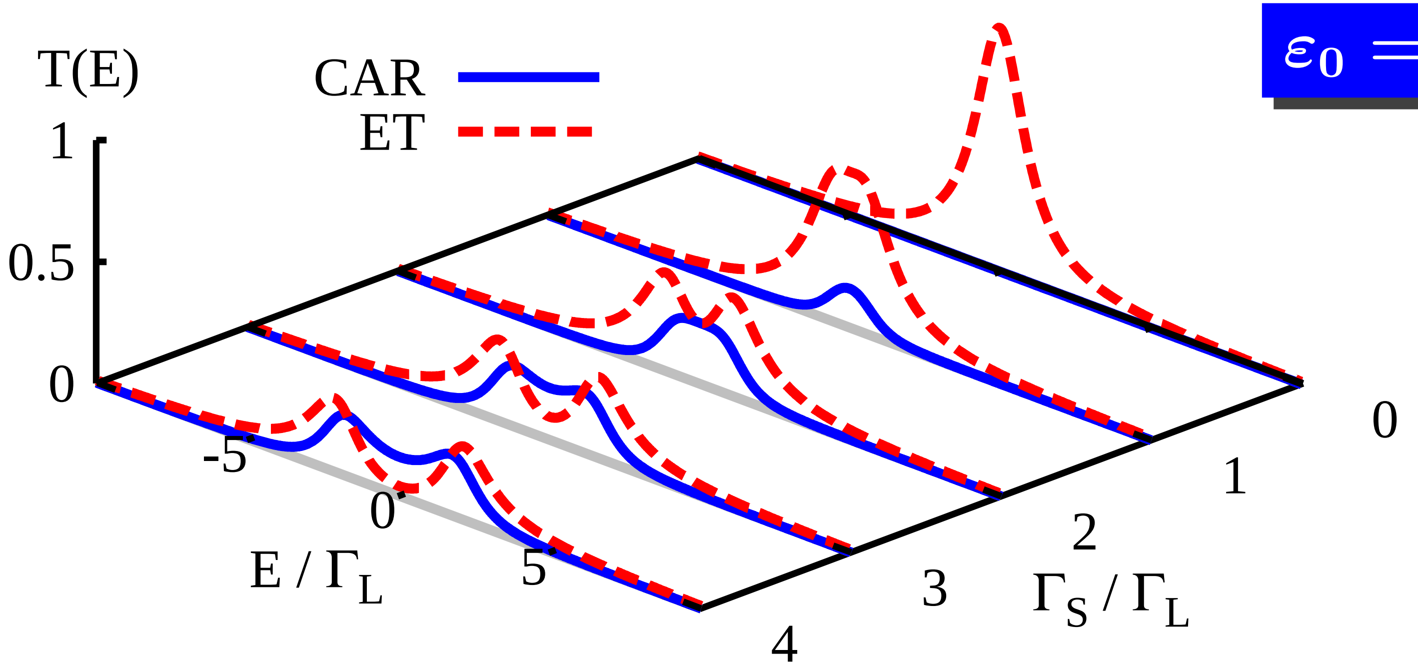


L, R – normal electrodes, S – superconducting reservoir, QD – quantum dot

G. Michałek, T. Domański, B.R. Bułka & K.I. Wysokiński, Scientific Reports **5**, 14572 (2015).

Non-local transport – crossed Andreev refelections

Transmittance of the non-local transport channels

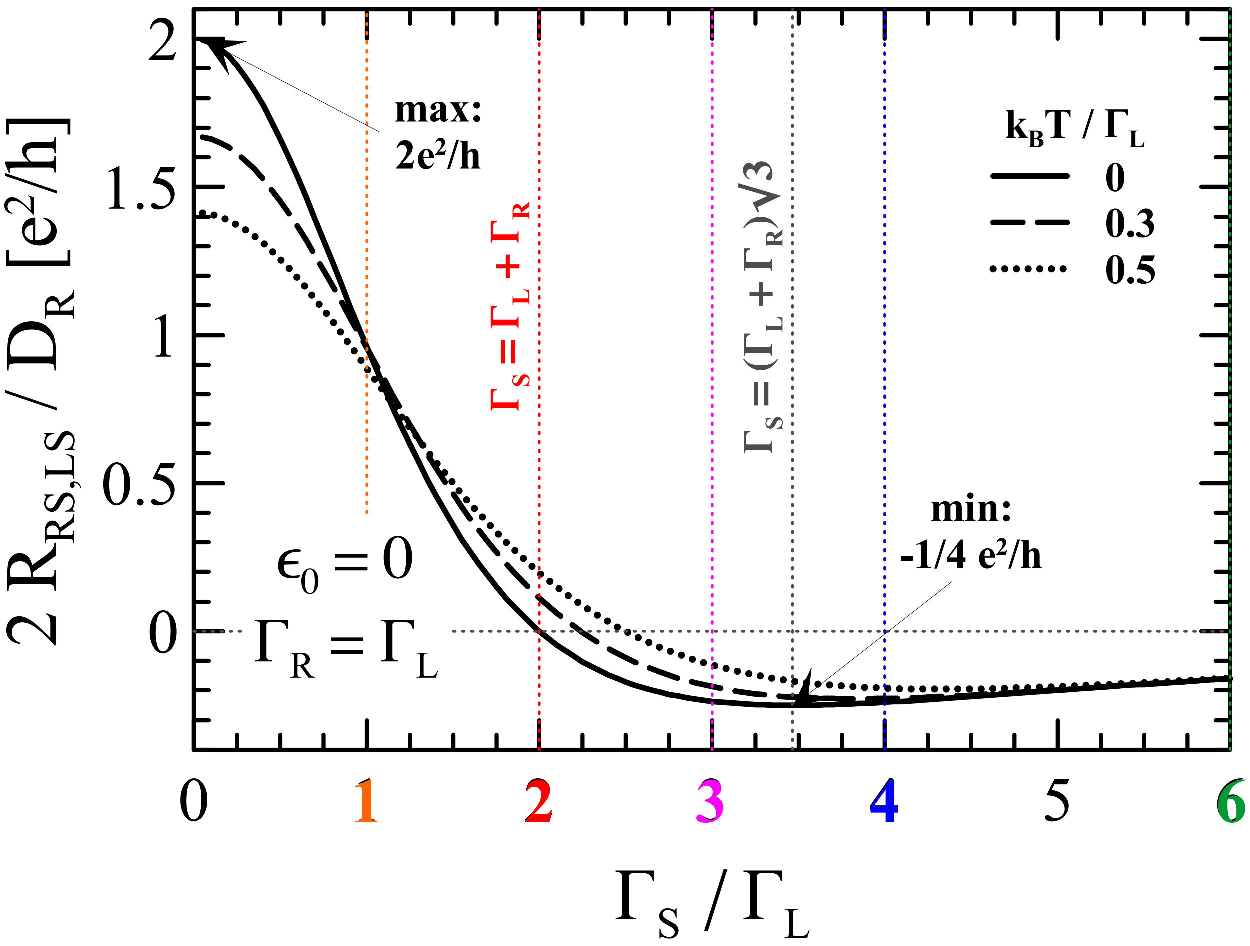


$\varepsilon_0 = 0$

ET – single electron transfer, CAR – crossed Andreev reflection

Non-local transport – crossed Andreev refelections

Non-local resistance in the linear response limit.

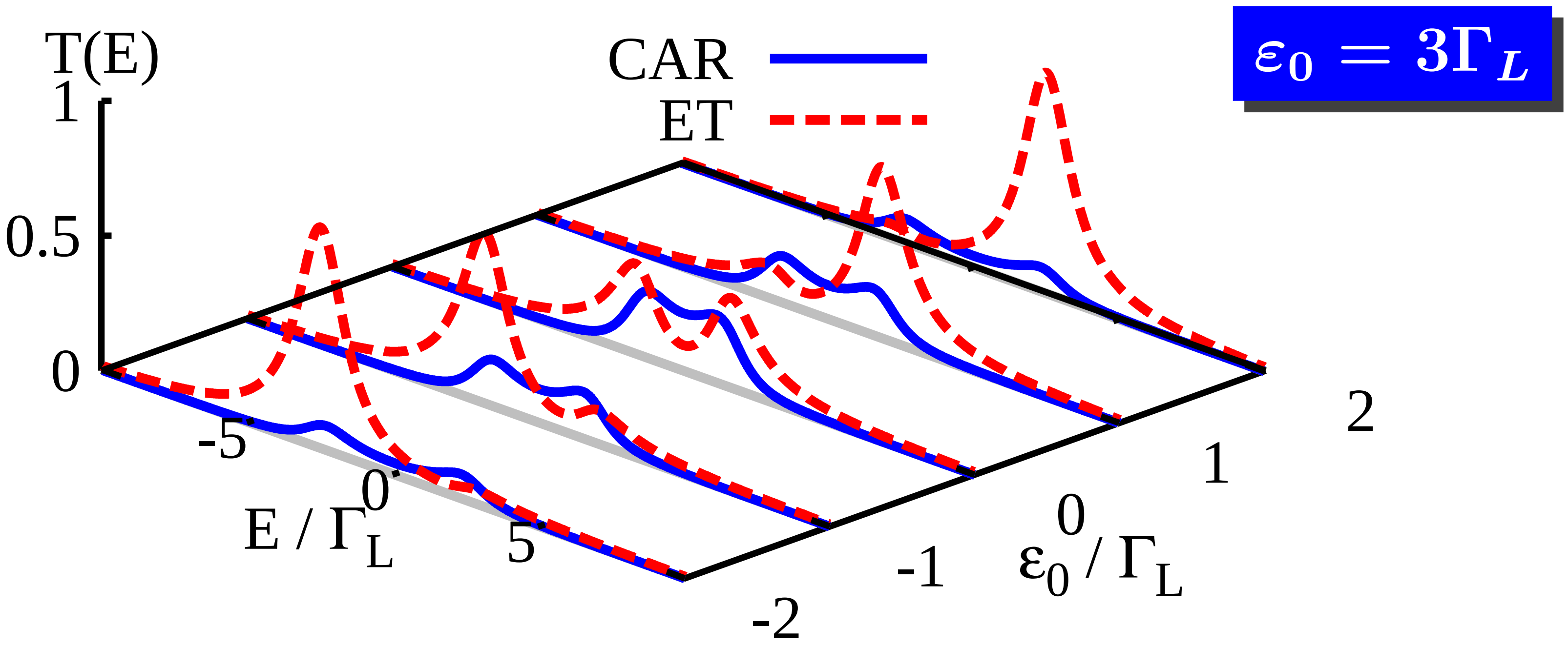


$$R_{RS,LS} \equiv V_{RS}/I_{LS}$$

Negative resistance for strong enough coupling Γ_S !

Non-local transport – crossed Andreev refelections

Transmittance of the non-local transport channels



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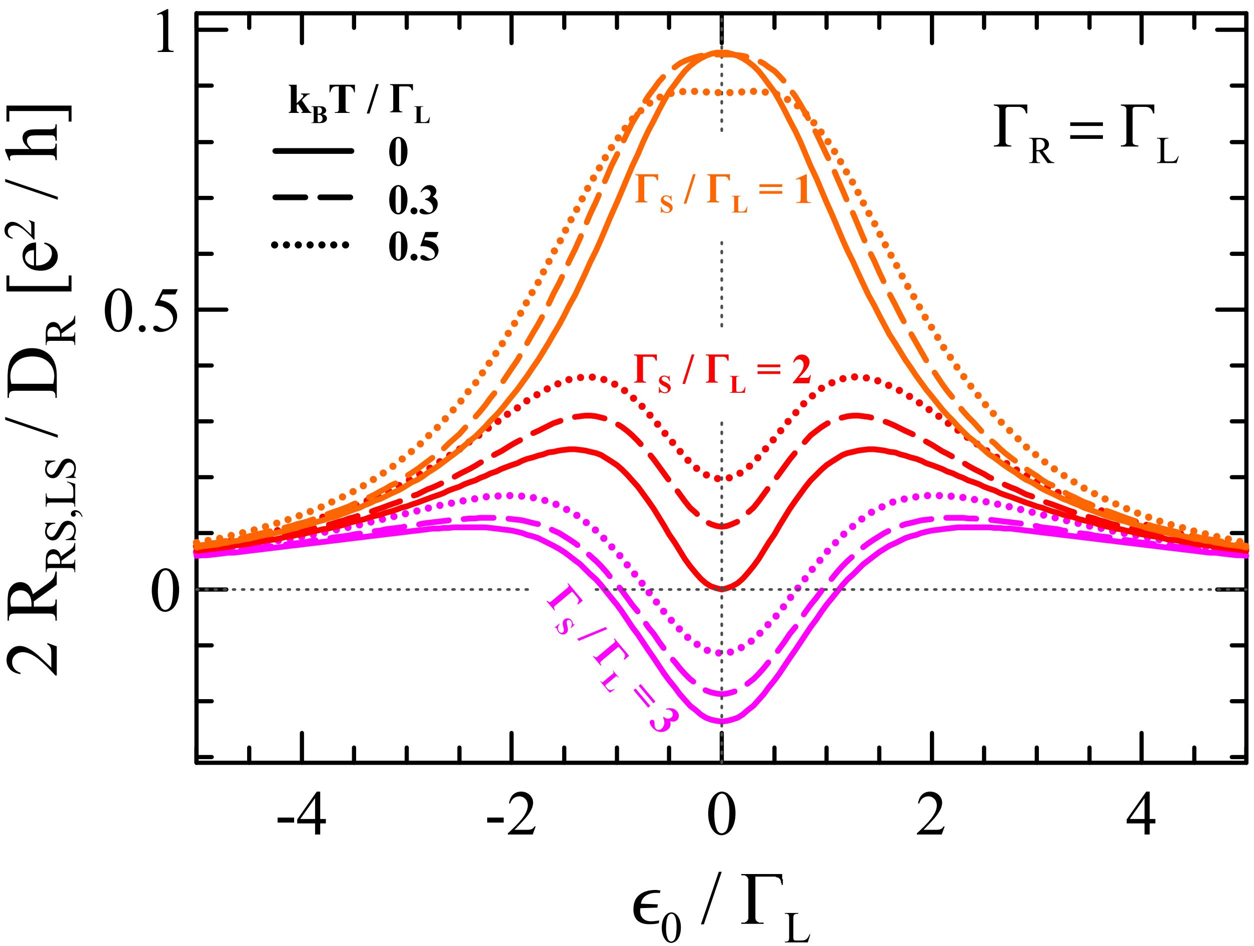

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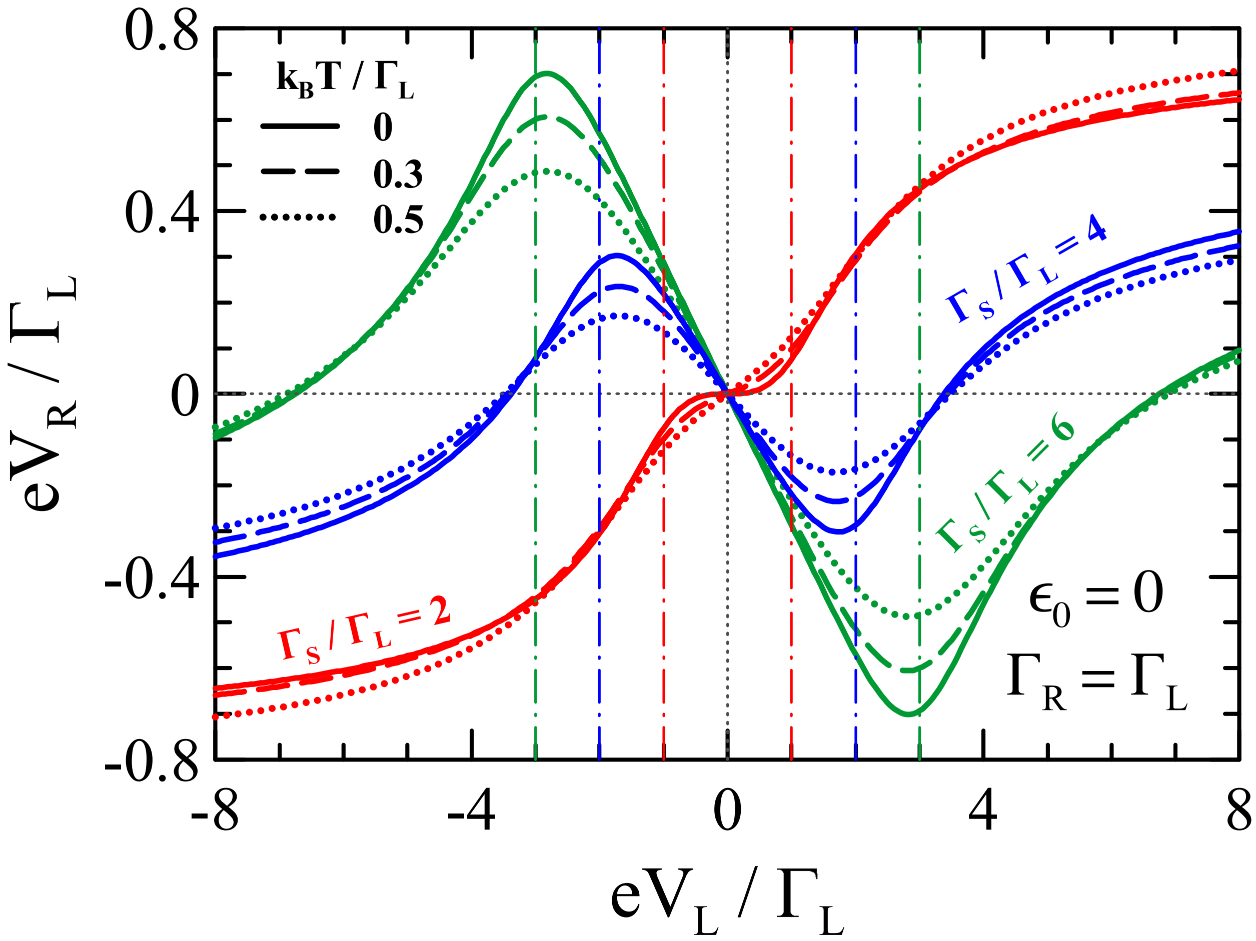
Negative resistance for strong enough coupling Γ_S and $\varepsilon_0 \sim 0$!

Non-local transport – crossed Andreev refelections

Beyond the linear response regime.

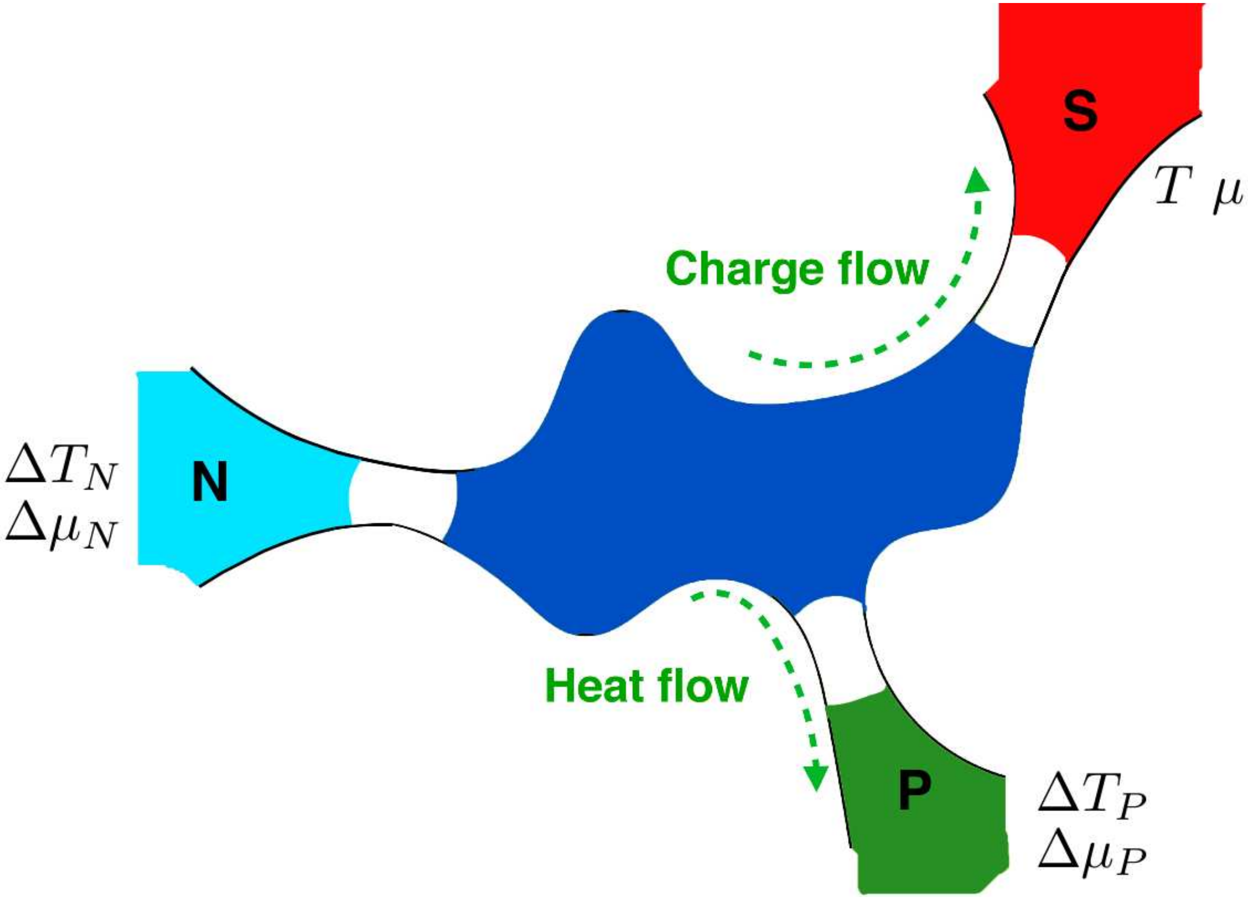


Inverse sign of the non-local voltage for strong enough coupling Γ_S.

Andreev reflections – other perspectives

Andreev reflections – other perspectives

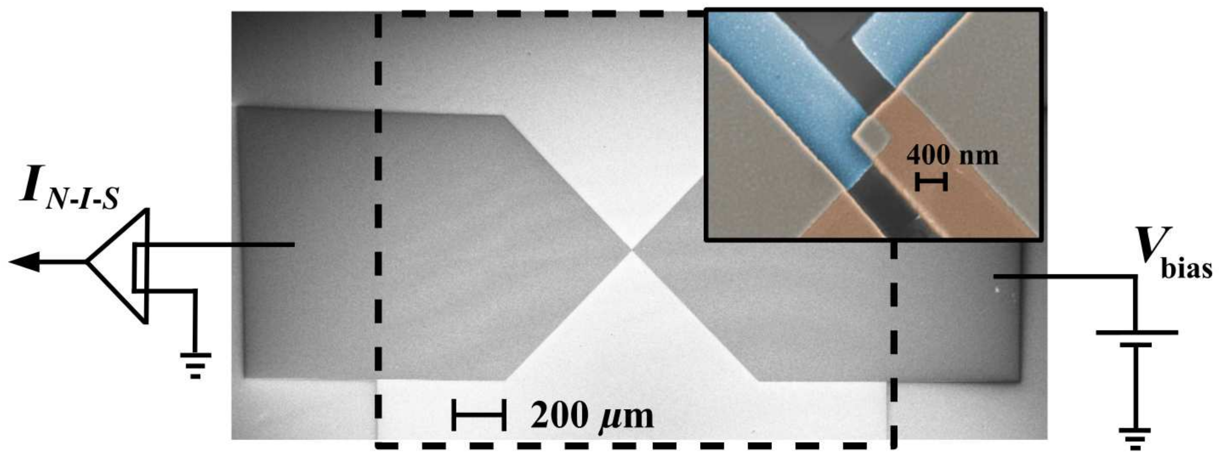
Crossed Andreev reflections enable the separation of charge from heat currents

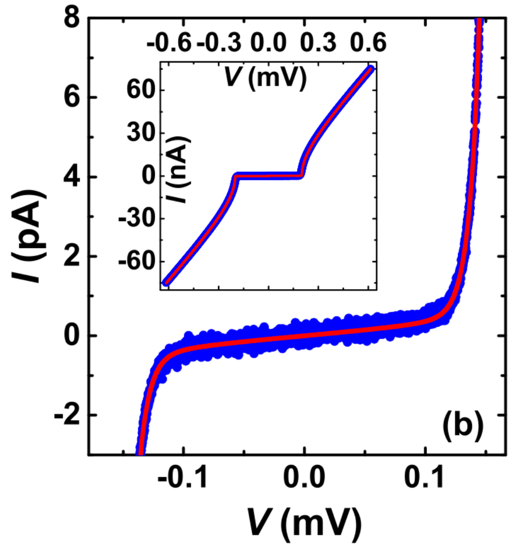


F. Mazza, S. Valentini, R. Bosisio, G. Benenti, V. Giovannetti, R. Fazio and F. Tadddei, Phys. Rev. B **91**, 245435 (2015).

Andreev reflections – other perspectives

On-chip nanoscopic thermometer operating down to 7 mK.





A.V. Feshchenko, L. Casparis, ..., J.P. Pekola & D.M. Zumbühl, Phys. Rev. Appl. **4**, 034001 (2015).

T. Faivre, D.S. Golubev and J.P. Pekola, Appl. Phys. Lett. **106**, 182602 (2015).

Virtues of a device:

⇒ is almost free of any self-heating

⇒ operates at cryogenic temperatures

⇒ can thermally-monitor the qubits

Summary

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⇒ **can be induced by the proximity effect**

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