Positive Electronic Cross-Correlations in a Highly Transparent Normal-Superconducting Beam Splitter

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Introduction

- Condensed matter theory

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- Proposal and interpretation of experiments

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- All considered systems are solvable:
  - Two types of methods:
    - Scattering calculations (wave-function approach)
    - Non equilibrium microscopic Green's functions
  - Two types of solutions
    - Exact analytical expressions
    - Numerical calculations = very small error-bars

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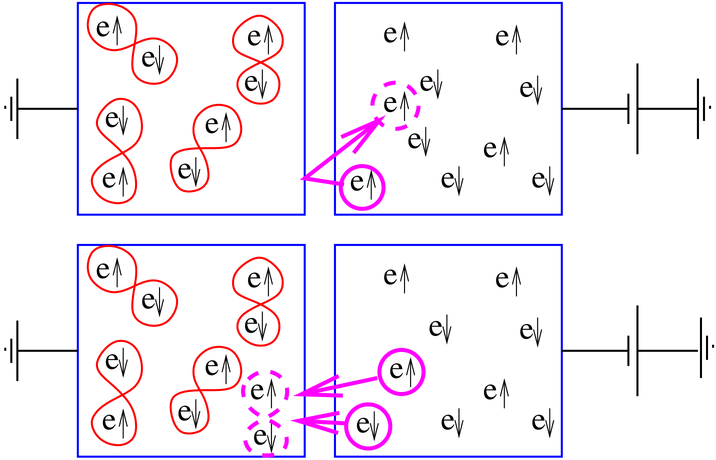
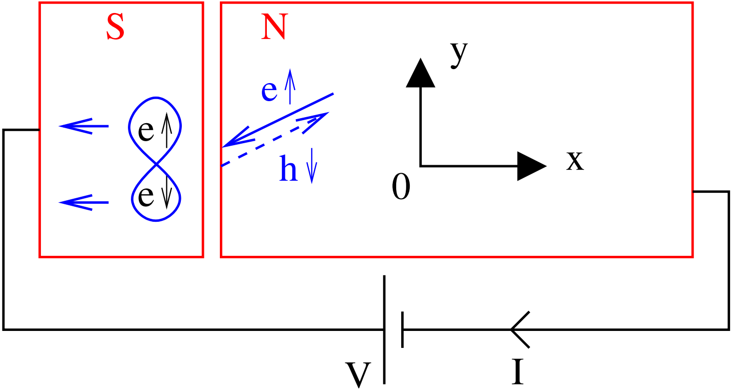
    - Numerical calculations = very small error-bars
- Physical difficulty: Often, interpretation comes at the end, as for experiments → sometimes, surprises and nontrivial effects

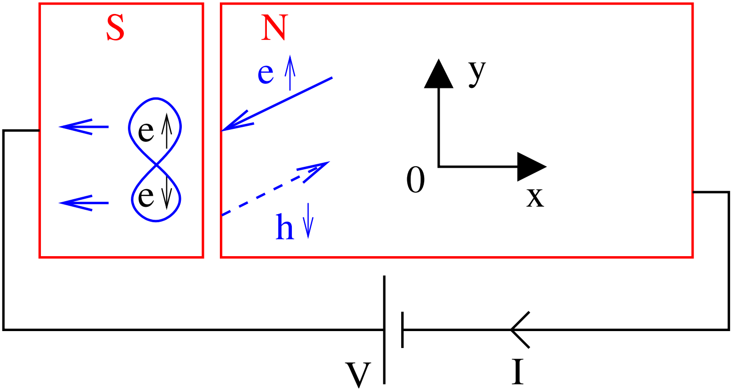
SN Junction: Andreev Reflection (1/2)



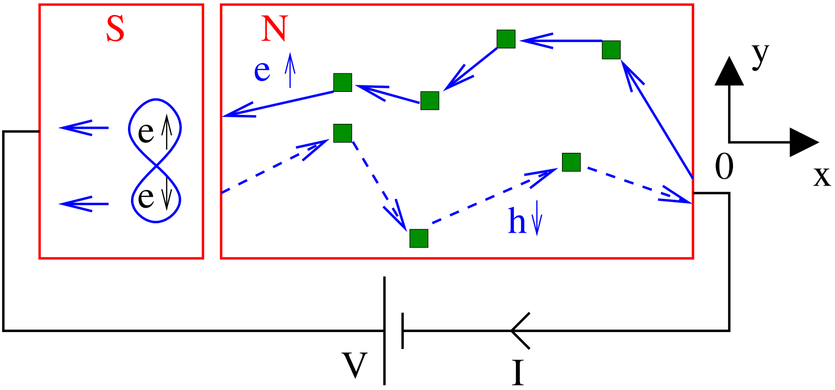
SN Junction: Andreev Reflection (2/2)



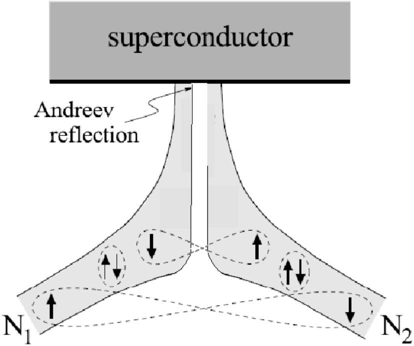
SN Junction: Nonlocal Andreev Reflection (1/3)



Nonlocal Andreev Reflection (2/3)



Nonlocal Andreev Reflection ≡ Cooper Pair Splitting (3/3)

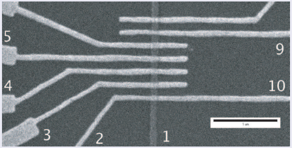


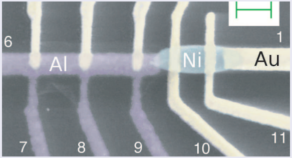
Three-terminal set-up required in experiments

Quest: Manipulation of spatially separated spin-entangled pairs of electron

First theoretical contributions: Byers-Flatté, Martin, Anatram-Datta, Deutscher-Feinberg, Falci-Hekking, Choi-Bruder-Loss, Mélin

Highly Transparent Contacts
(Chandrasekhar group, North-Western University, PRL '06)





High values of interface transparency

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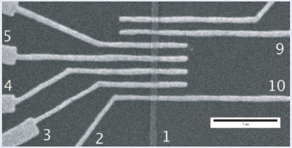

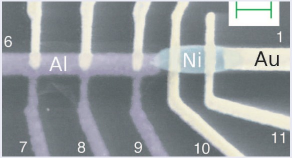

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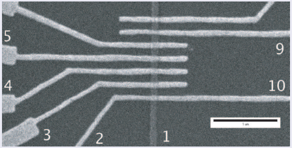
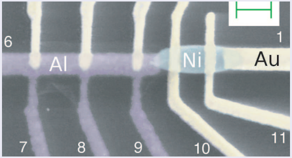
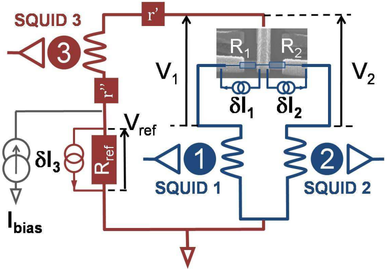




- Yes or no is it a way to obtain a massive signal for separated pairs ?
- <u>Answer is no:</u> Experimental signal not controlled by Cooper pair splitting



- Lefloch / Courtois experiment, PRL 2011
- Incoherent SNSNS
- SQUID-based amplifiers
- CEA-Grenoble / NEEL

Current noise $S_{a,a}$ and current noise cross-correlations $S_{a,b}$

$$S_{a,a}(t') = \langle \delta\hat{I}_a(t+t')\delta\hat{I}_a(t)\rangle \text{ and } S_{a,b}(t') = \langle \delta\hat{I}_a(t+t')\delta\hat{I}_b(t)\rangle$$

Race to Positive Current-Current Cross-Correlations: Example of Exact Analytical Solution

Collaboration with

Martina Flöser

Axel Freyn

Small transparency

Cooper pair splitting $\Rightarrow$ Positive current-current cross-correlations

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Common wisdom for all transparency

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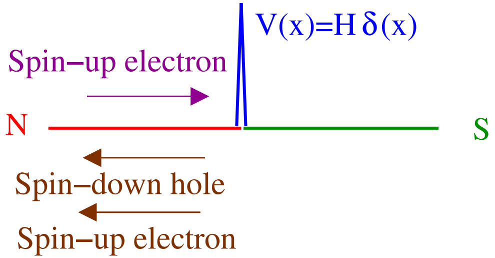
What we have shown at high transparency

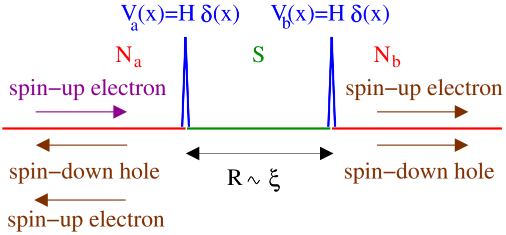
Positive current-current cross-correlations $\not\Rightarrow$ Cooper pair splitting

The method (Blonder, Tinkham, Klapwijk PRB 1982)



- One-dimensional geometry
- Two-component wave-functions for electrons and holes
- Matching of $\psi(x)$ and $\partial\psi(x)/\partial x$ at the interfaces
- Below the gap:
  - Evanescent wave-functions in S + response linear in voltage
  - Current is conserved: quasi-particles converted as pairs

Wave-function matching for a NSN structure



- Calculation of the *s*-matrix
- Asumption: applied voltages small compared to the gap

$\Rightarrow$ Evanescent wave-functions in S

- Mimicking a multichannel 3D junction with a 1D systems
  $\Rightarrow$ averaging over λ_F oscillations in 1D model
- Analytic expression for the average
  $S_{a,b} = \langle \delta\hat{I}_a \delta\hat{I}_b \rangle$ at arbitrary transparency

$\Rightarrow$ $S_{a,b} > 0$ at high transparency without Cooper pair splitting

- Unusual sign due to exchange of two fermions

Conclusion (1/2): Present-time status of entanglement in NSN

What is the value of interface transparency
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- Probing entanglement for tunnel contacts ?
- Simple theoretical anwser is YES (Cooper pair splitting) ... But simple perturbation theory contradicted by experiments (Delft, Karlsruhe, Northwestern University)

Conclusion (2/2)

- NSN structures should be abandoned in order to produce entangled pairs of electrons
- Three promising directions:
  - N-dot-S-dot-N (production of split pairs)
  - S-N-S-N-S (production of nonlocal pairs of pairs)
  - S-dot-S-dot-S (production of nonlocal pairs of pairs)