Vol 439 |23 February 2006 |doi:10.1038/nature04550 nature

LETTERS

Quantum supercurrent transistors in carbon nanotubes

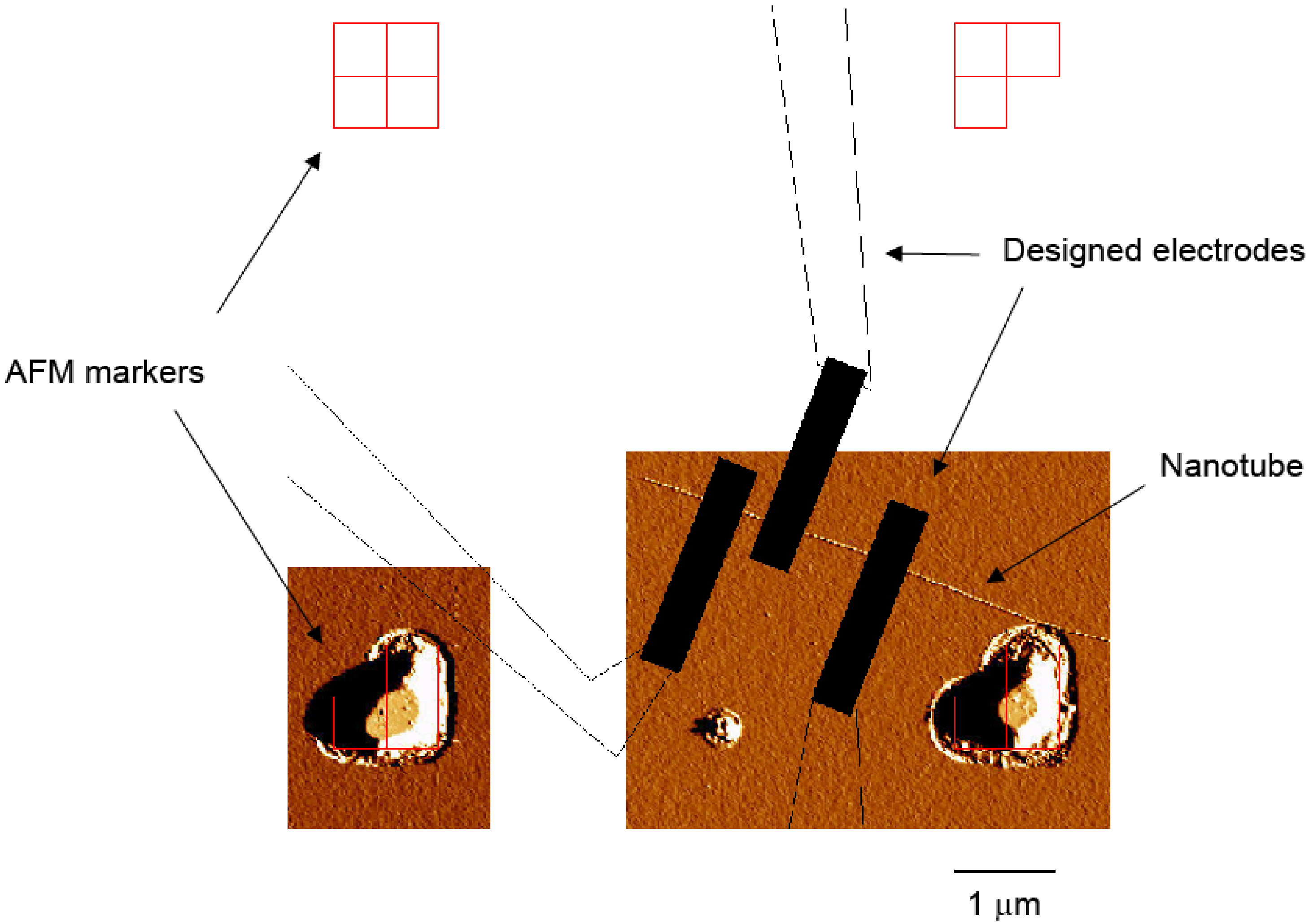
Pablo Jarillo-Herrero [1], Jorden A. van Dam [1] & Leo P. Kouwenhoven [1]

Abstract

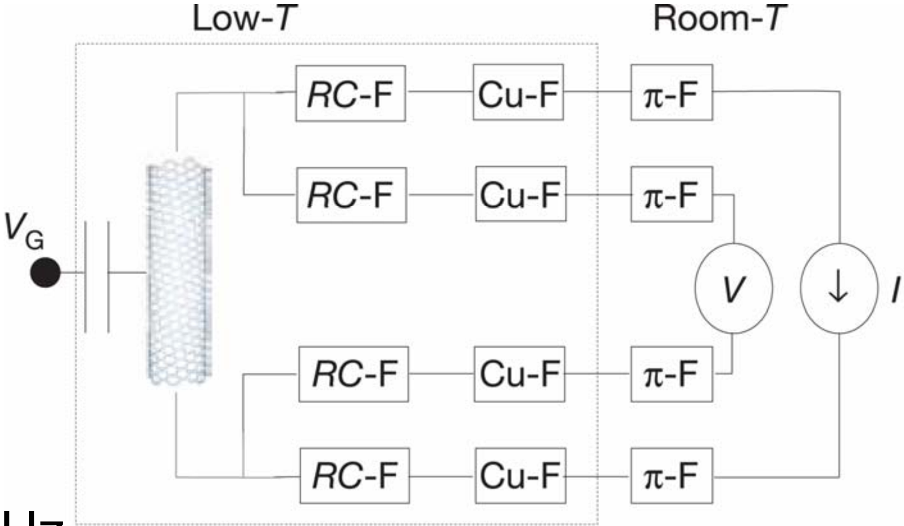
- Electronic transport through nanostructures with superconducting leads has been studied for various systems (SNS, SFS, ScS, etc.) all of which have a continuous density of states
- Interesting to study the behavior of a nanostructure coupled to superconducting leads when there is only a discrete number of electronic states like in a quantum dot or „artifical atom“ (→ carbon nanotube)

Sample Setup

- CNTs CVD grown with catalysts consisting of
  - 40 mg $Fe(NO_3)_3 * 9H_2O$
  - 40 mg $MoO_2(acac)_2$ (Sigma Aldrich)
  - 30 mg Alumina nanoparticles (Degussa Aluminum Oxide C)
- CVD at 900°C with 700 sccm H_2 and 520 sccm CH_4 for 10 min
- metal electrodes: 10 nm Ti and 60 nm Al
- only metallic nanotubes with RT-resistance of $<50 k\Omega$


Designed electrodes
AFM markers
Nanotube
1 µm

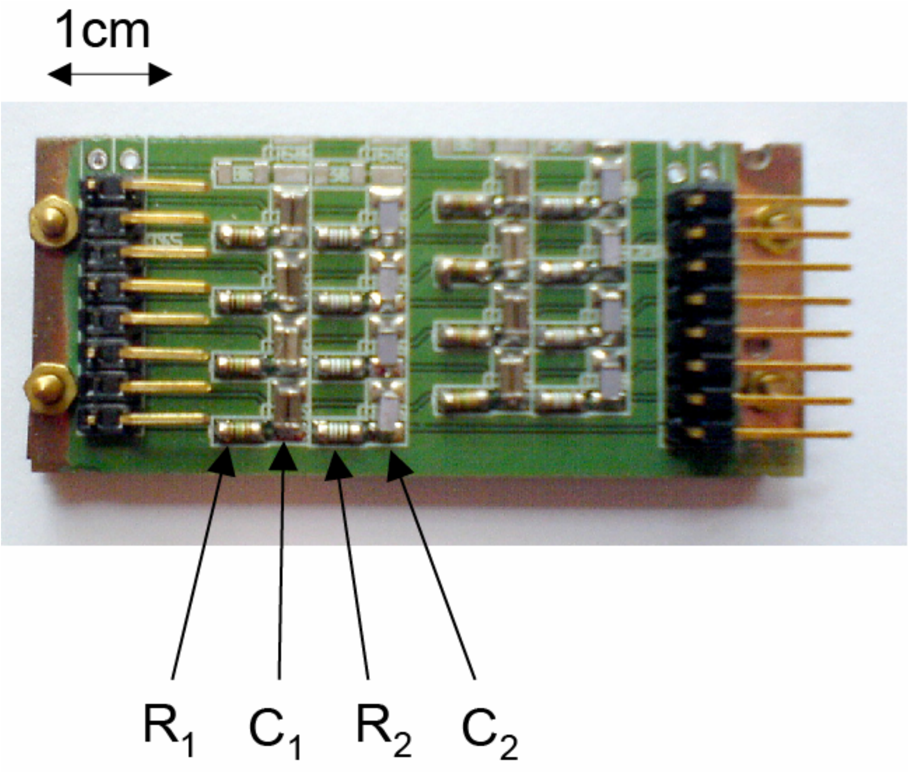
Measurement Setup



most important ingredient:
3 filters in series

- copper-powder filter $f \geq 1GHz$
- π-filter $f \sim 10MHz-2GHz$
- 2-stage RC-filter $f \sim$ few kHz-100MHz

for the 2-stage RC-filter they claim to see a damping of 40 dB per decade instead of the 20 dB for usual systems

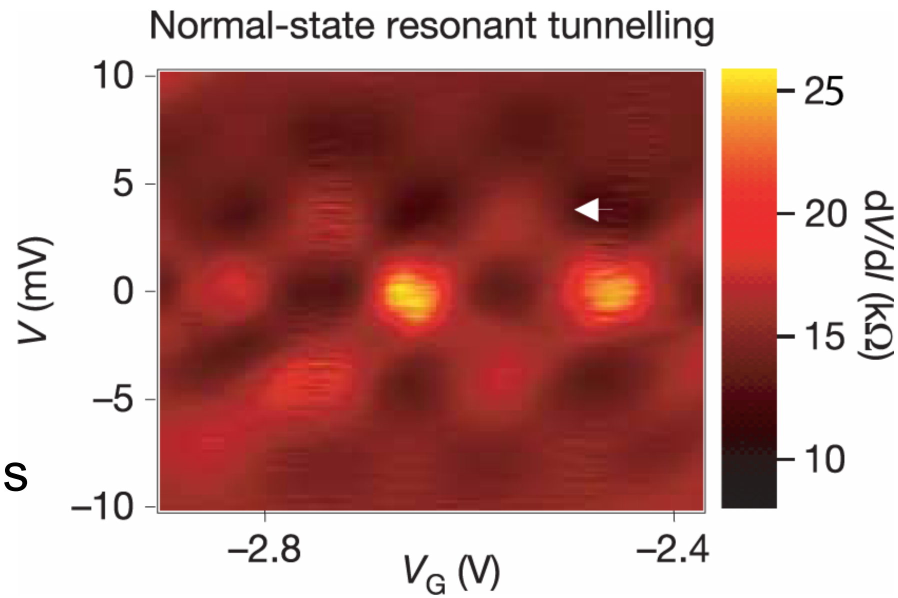

1cm
R1
C1
R2
C2

Results 1: characterization above T_C

dV/dI versus measured voltage, V, and gate voltage, V_G, at T=4,2 K

typical picture of electron interference and Fabry-Perot like transmission

► strong coupling Γ to the leads



i) $h\Gamma >> U$ (open QD regime) → quantum interference of non-interacting electrons

ii) $h\Gamma \leq U$ (intermediate transparency regime) → charging effects important, but higher-order tunneling processes significant too (cotunneling and Kondo effect)

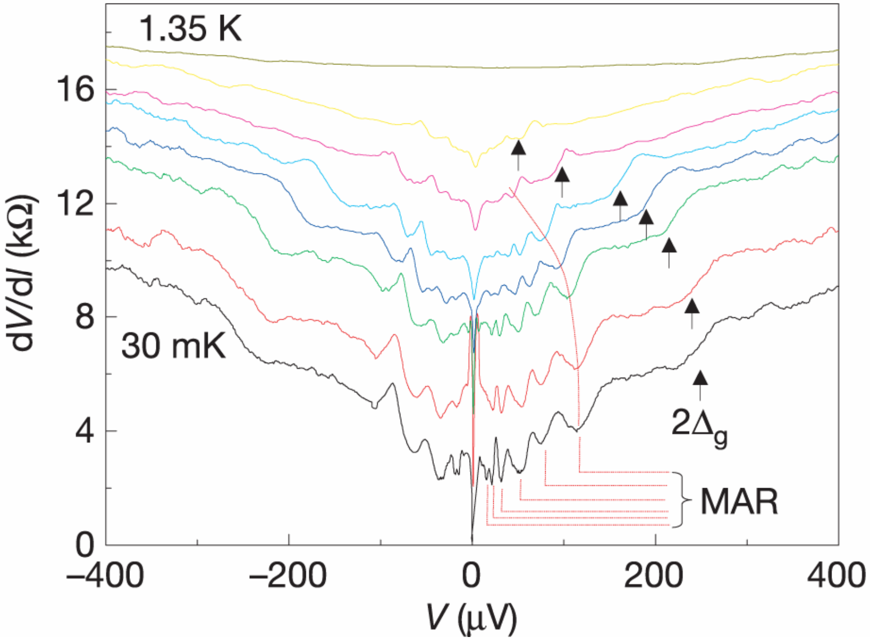
iii) $h\Gamma << U$ (closed QD regime) → charging effects dominate transport (Coulomb blockade)

Results 2: behavior below T_C

rich subgap structure appears

proximity effect is evident from the multiple Andreev reflections (MARs)

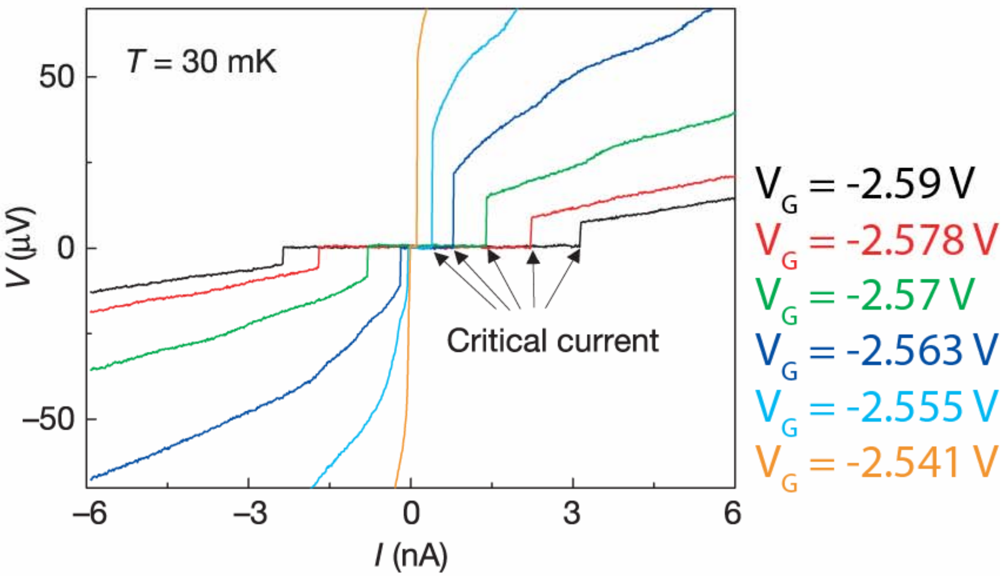
large dip in the center of the curves indicates a supercurrent flowing through the nanotube



Results 3: I-V characteristic

Typical I-V characteristics of Josephson-junction:

- ►dispationless current flows up to a critical value I_C
- ►above I_C the system is in the resistive normal conducting state
- ►the I-V dependence above I_C becomes linear ($\rightarrow R_N$)



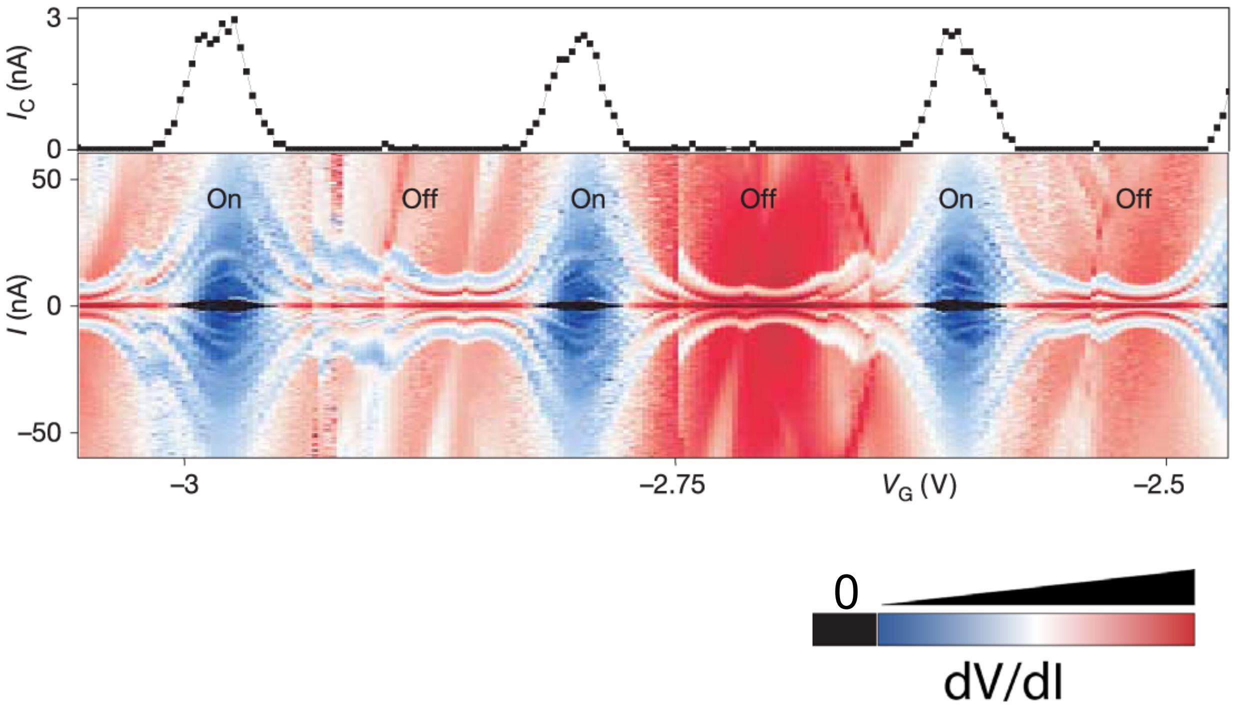
The critical current I_C shows a strong variation within gate voltages of 50 mV!

Results 4a: $dV/dI(V_G,I)$ and $I_C(V_G)$

► periodic series of areas with high and low differential resistance

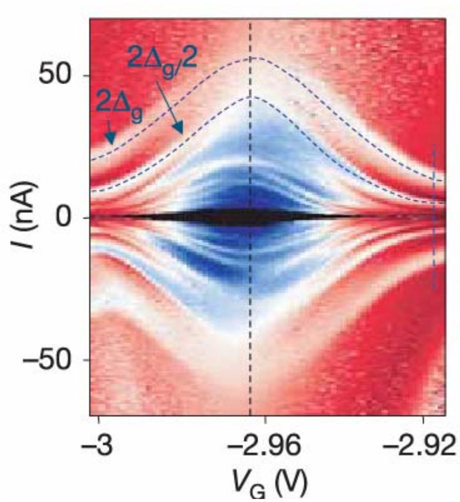
► same period for high and low critical current

► energy levels in the CNT are tuned on and off resonance



Results 4b: high resolution

higher resolution image shows again the MARs as subgap structure and the dependence of the critical current on the gate voltage

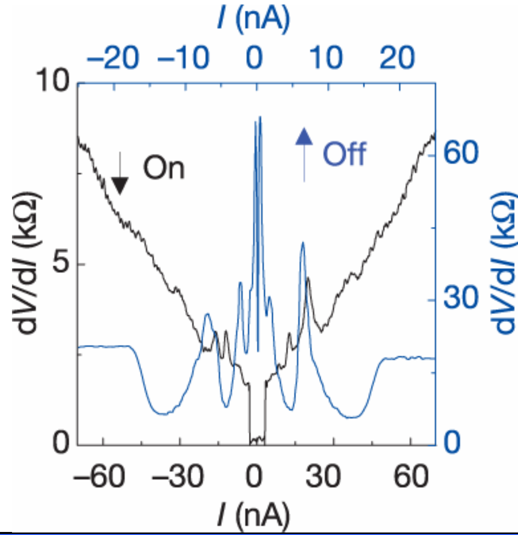


blue and black dotted lines show linescans at fixed values of the gate voltage

Within ~ 50 mV of gate voltage range the behavior of the critical current changes drastically:

on resonance -> dV/dI decreases with decreasing current I

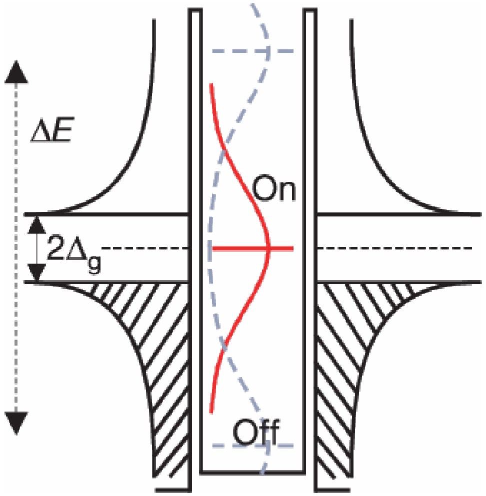
off resonance -> dV/dI increases with decreasing current I

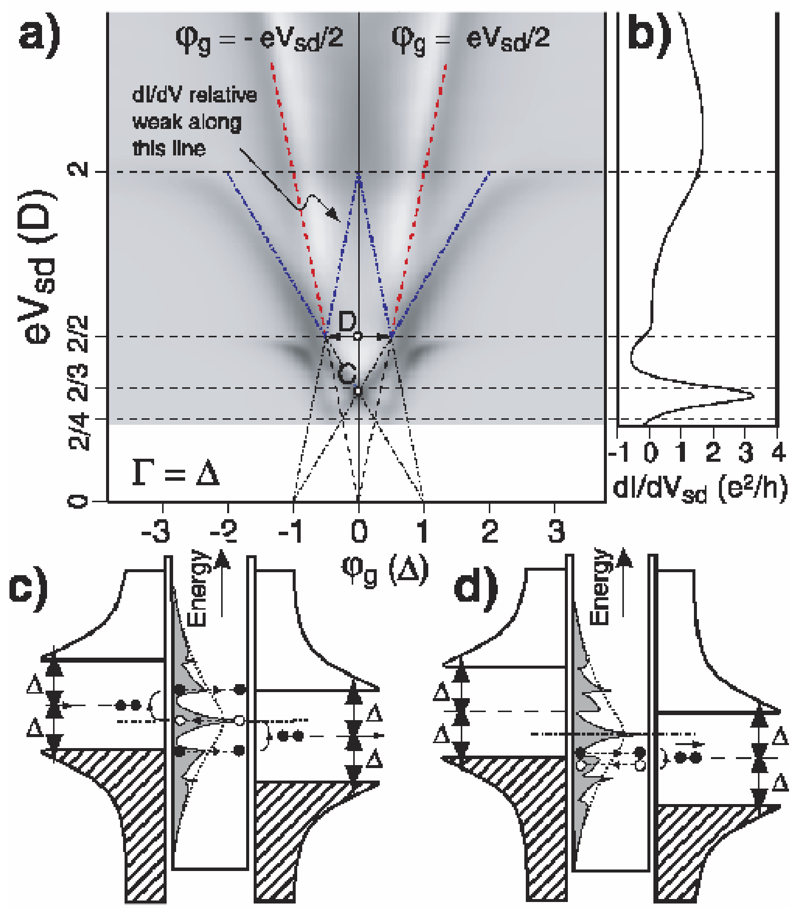


Schematics and reminder

current transfer via resonant levels

full resonance when Fermi levels in the leads are aligned with the discrete energy level of the quantum dot





for unaligned levels there are still special cases when current transfer is possible:

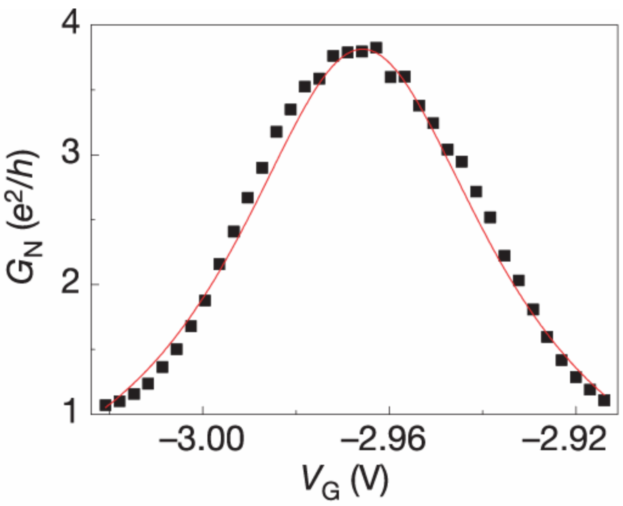
Multiple Andreev Reflexion

(at voltages $V = 2\Delta_g/en$)

Compared to theory 1

correlation between normal state resistance R_N and critical current I_C is well studied for SNS-structures and is in the case of short junctions in diffusive systems: $I_C R_N \sim \Delta_g/e$ (constant)

situation changes for a single discrete energy level



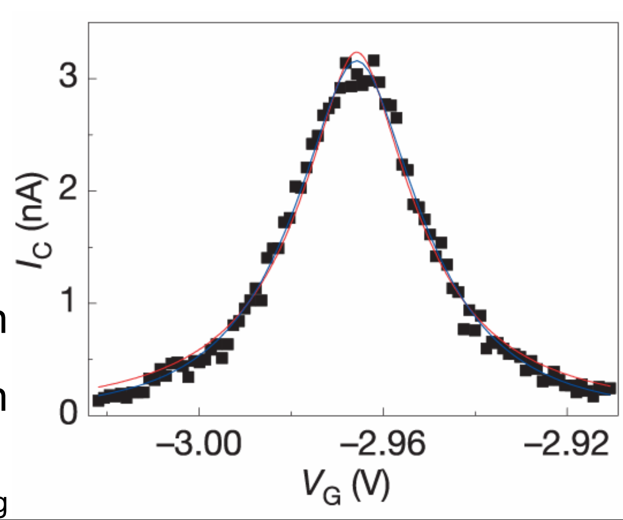
$G_N = (4e^2/h)\, T_{BW}$, with

$T_{BW} = \Gamma_1\Gamma_2/((\varepsilon_R/h)^2 + 0.25\Gamma^2)$

$I_C = I_0[1-(1-T_{BW})^{1/2}]$, with

$I_0 = 4\pi e\Delta_g/h$

for $h\Gamma >> \Delta_g$



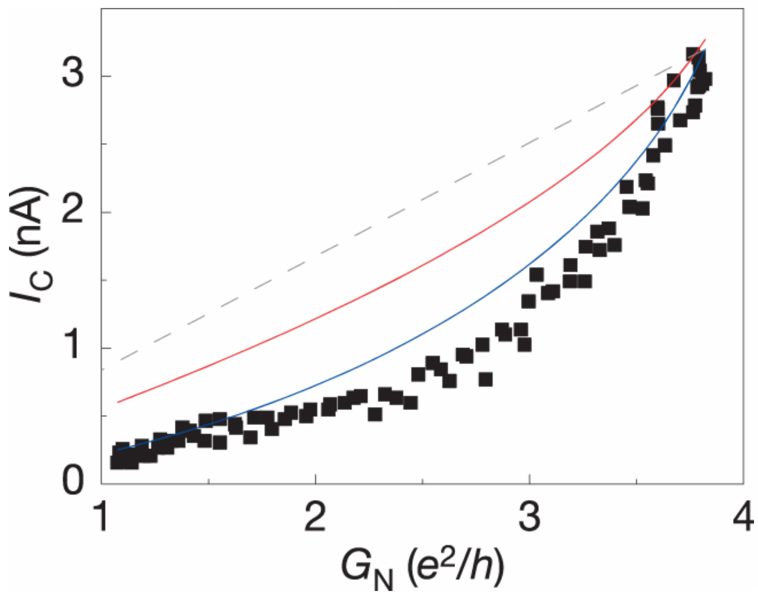
Compared to theory 2

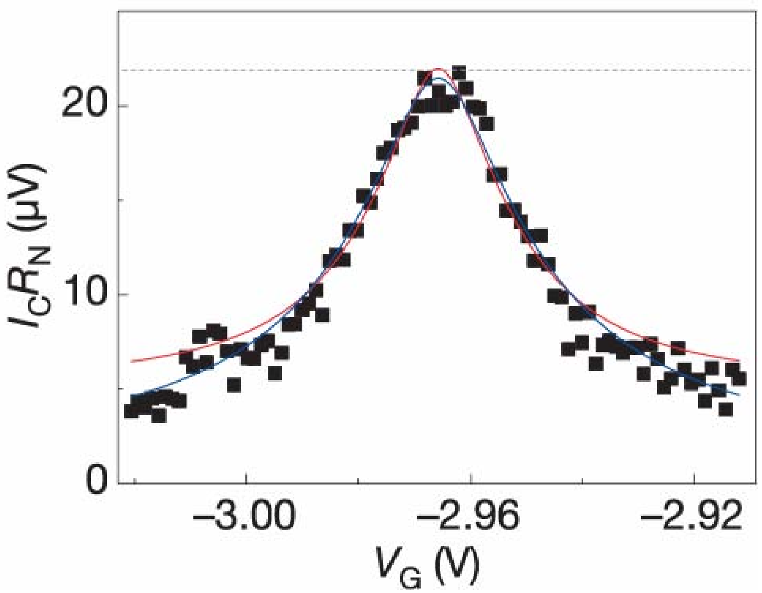
possible explanation for the deviation of I_C from the theoretically expected value might be the electromagnetic coupling to the environment

the influence of the environment can be seen best in the correlation between G_N and I_C

the lineshape of the critical current gets modified:

$$I_{CM} = I_{0M}[1-(1-T_{BW}(V_G,\Gamma)^{1/2}]^{3/2}$$





Concluding Remarks

first observation of a Josephson transistor mechanism, purely due to the discrete nature of the energy levels in a nanostructure

although both superconductivity and the Kondo effect are collective many body phenomena, their effect on resonant tunneling is very different:

- Kondo enhancement occurs off resonance
- superconducting zero-resistance state is most pronounced on-resonance
- for CNT devices with intermediate transmission (larger Coulomb interaction) they expect Kondo-enhanced supercurrents in the off-resonant case

FINE

Grazie per la tua attenzione!