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SMR. 628 - 6

Research Workshop in Condensed Matter, Atomic and Molecular Physics
(22 June - 11 September 1992)

Working Party on
"NOISES IN MESOSCOPIC SYSTEMS"
(27 July - 7 August 1992)

"Co-tunneling and noises in the systems of tunnel junctions"

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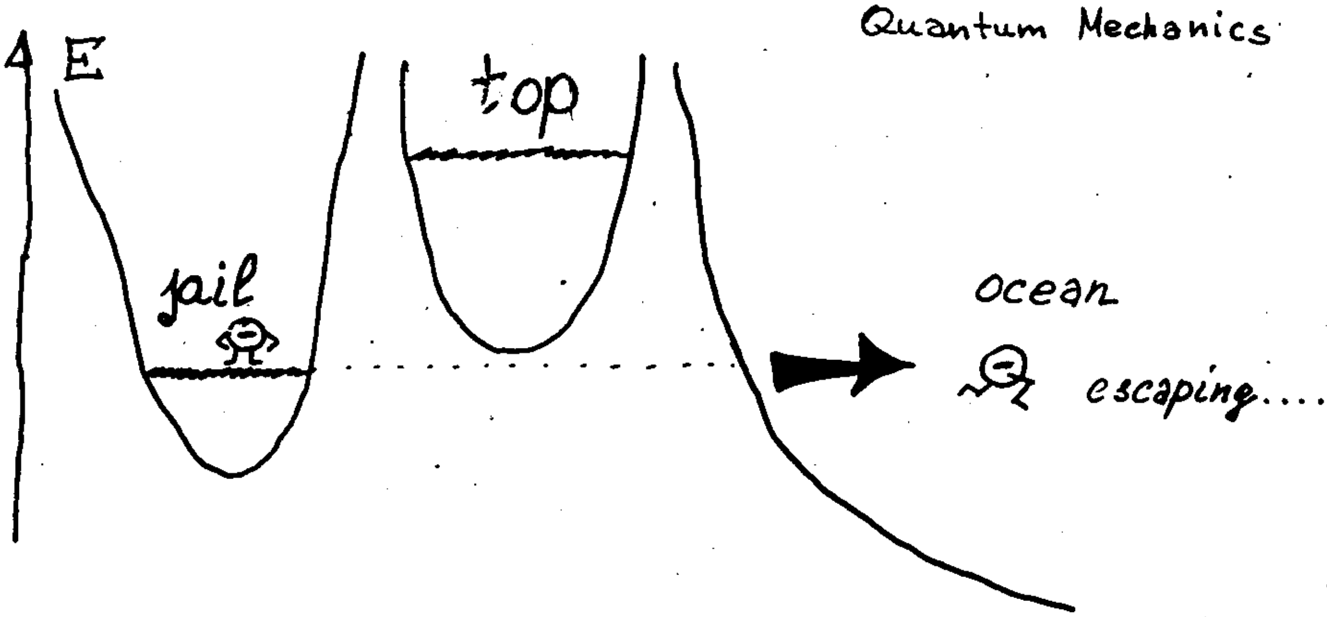
Co-tunneling and noises in the systems of tunnel junctions

(presented by Yu. V. Nazarov)

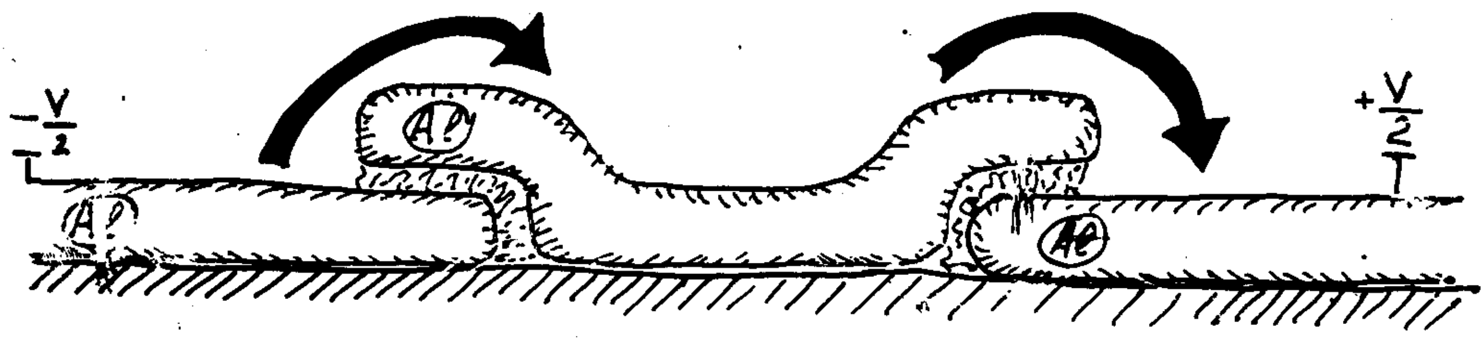
1. General principle of freedom: essence of Quantum Mechanics



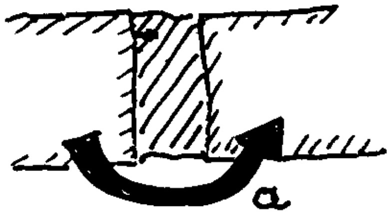
$$\Gamma = 2\pi \sum_{\text{ocean}} |Am|^2 \delta(E_{jail} - E_{ocean})$$

$$Am = \langle jail | \hat{H} | top \rangle \frac{1}{E_{jail} - E_{top}} \langle top | \hat{H} | ocean \rangle$$

2. Systems of tunnel junctions ⟶ poor man's manybody effects



3. Types of co-tunneling:



a

$$\Gamma_{single} = \frac{GV}{e^2} \simeq \frac{G}{C} \quad \left(V \simeq E_c \simeq \frac{e^2}{C} \right)$$

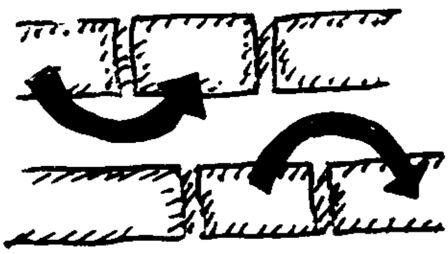
b

$$\Gamma_{double} = \Gamma^{(1)} \Gamma^{(2)} \frac{\hbar}{\Delta E}$$

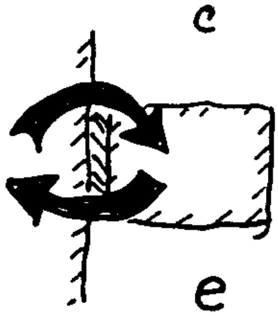
← time uncertainty

$$\simeq \Gamma_{single} \cdot (R_K G)$$

$$R_K = \frac{2\pi\hbar}{e^2} \simeq 6.5 \cdot 10^3 \text{ Ohm}$$

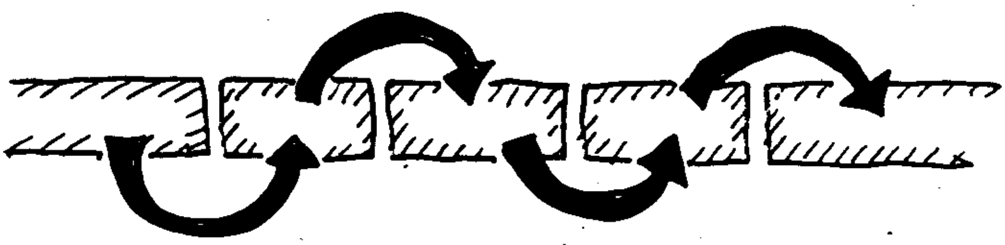


c



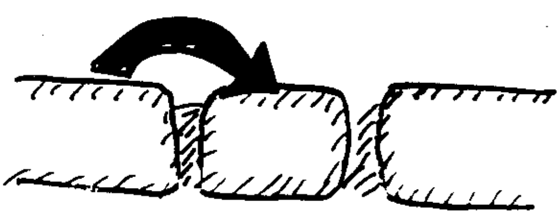
e

$$Re[G(\omega)] = (R_K G) \left(\hbar\omega / E_c \right)^6$$

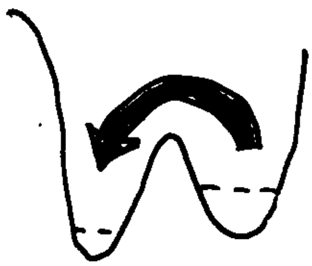


$$\Gamma_N = \Gamma_{single} (R_K G)^{N-1}$$

f



$$\Gamma \simeq \Gamma_{fluct} (R_K G)$$



fluctuator

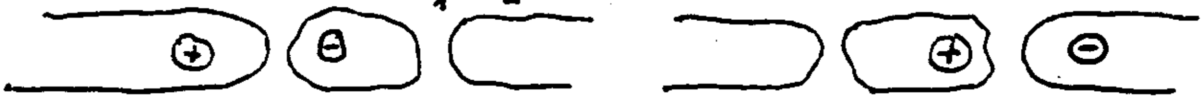
1. = co-tunneling of two electrons

Averin Odintsov 1989

initial state

two intermediate states

$E^- + \varepsilon_1 + \varepsilon_2$ $\qquad$ $E^+ + \varepsilon_3 + \varepsilon_4$



final state

$\varepsilon_1 + \varepsilon_2 + \varepsilon_3 + \varepsilon_4 + eV$

$$Am = T^{(1)}\left(\frac{1}{\varepsilon_1+\varepsilon_2+E^-} \quad \frac{1}{\varepsilon_3+\varepsilon_4+E^+}\right)T^{(2)}$$

$$\Gamma_{(T=0)} = \frac{\hbar}{2\pi e^3}\left[\left(1+\frac{2}{eV}\frac{E^+E^-}{E^++E^-+eV}\right)\left(\sum_{i=+,-}\ln\left(1+eV/E^i\right)\right)-2\right]V$$

(divergency)

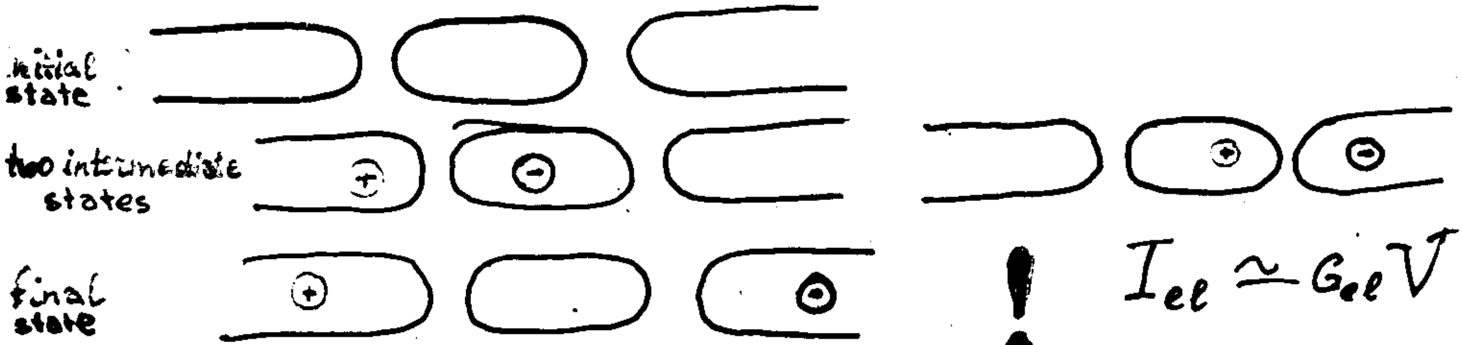
$$I(V) = \frac{\hbar G_1 G_2}{12\pi e^2}\left(\frac{1}{E^+}+\frac{1}{E^-}\right)^2\left[(eV)^2+(2\pi T)^2\right]V$$

(reduction of phase volume)

5. In long chains

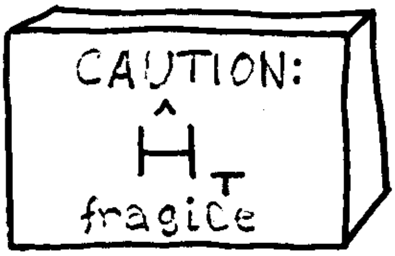
$$\Gamma = \frac{2\pi}{\hbar}\left(\frac{R_K G}{4\pi^2}\right)^N \frac{N^N}{(2N-1)!\,N!}\left(\frac{eV}{E_c}\right)^{2N-1}E_c$$

5. Elastic q-MQT

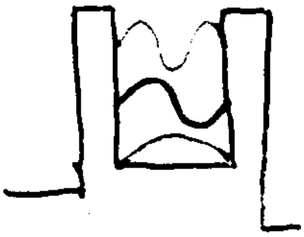


! $I_{el} \simeq G_{el} V$

Looks like an elastic scattering of one electron

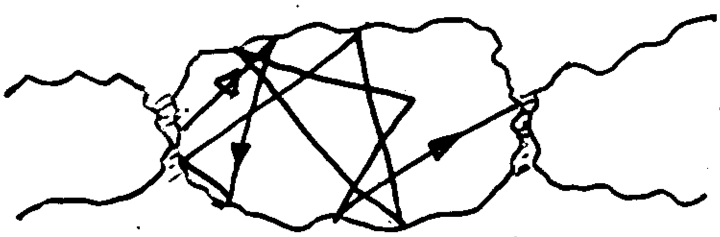


Example: → island = 1D well



$T_1 = T_2$
or
$T_1 = -T_2$

7. Semiclassical methods



Virtual motion during the time given by Heisenberg: $\hbar / E^{+,-}$

two cases:

1. $\hbar/E_c \gg t_{trav}$

universal

$$G_{el} = \frac{G_1 G_2 R_k}{8\pi^2}\,\delta\left(\frac{1}{E^+} + \frac{1}{E^-}\right)$$

2. $\hbar/E_c \ll t_{trav}$

non-universal

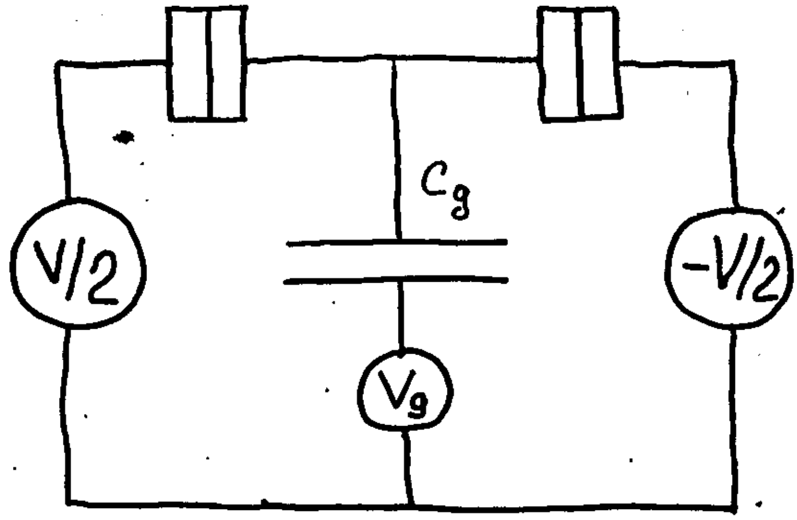
$$G_{el} \approx G_1 G_2 R_k \left(\frac{\delta}{E_c}\right) \frac{1}{E_c\, t_{trav}}$$

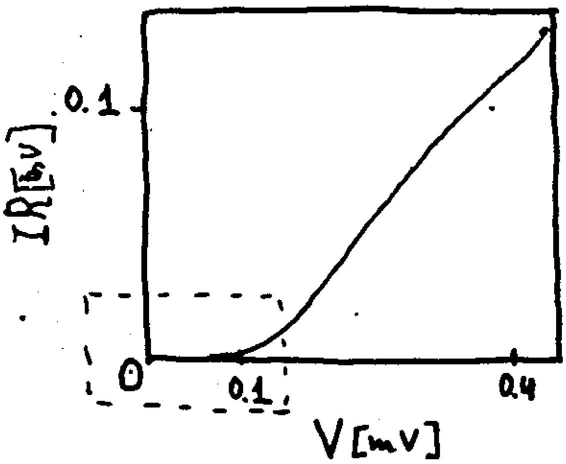
$\delta \rightarrow$ mean level spacing

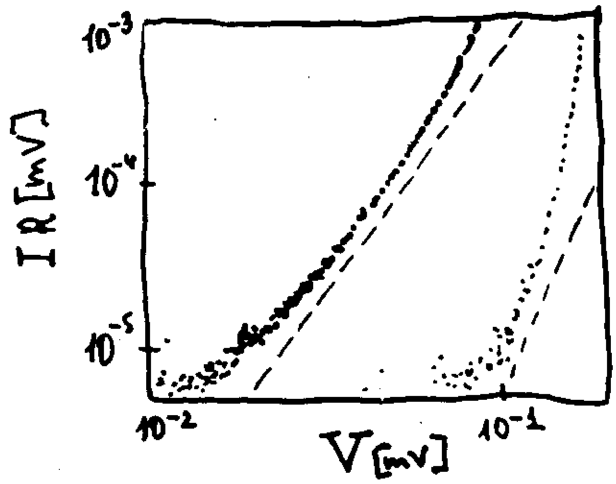
Crossover between elastic an inelastic

$$eV, T \approx \sqrt{\delta E_c} \ll E_c$$

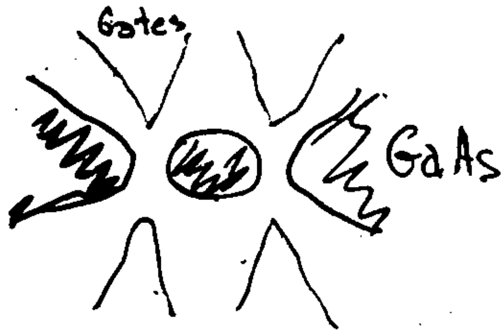
Geerligs / Averin
Mooij 1990







2 jn, $I \sim V^3$ 3 jn, $I \sim V^5$



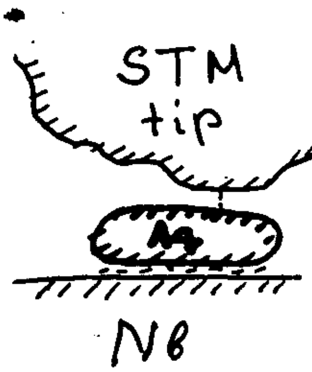
Glatti et al
1991

10% accuracy
of the formulas

Eiles Jensen
Zimmerli Martinis
1992

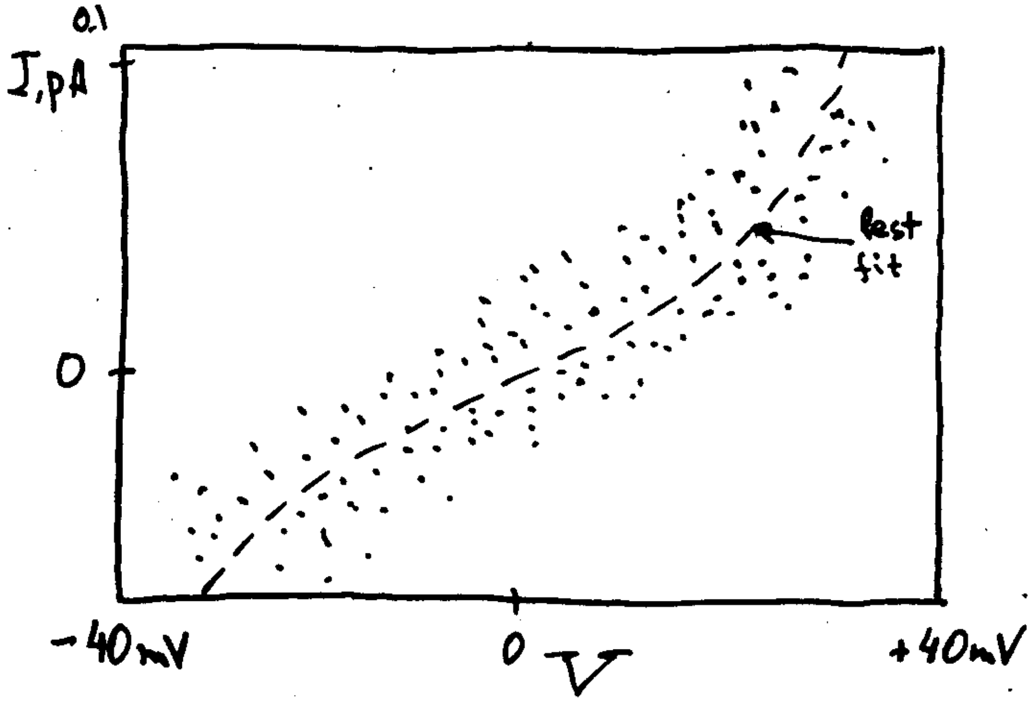
3. Experimental: Elastic

to raise δ/E_c to reasonable values



M. Tinkham et al 1992

estimated
size $10 \div 30$ Å
$E_c \sim 0.5V$

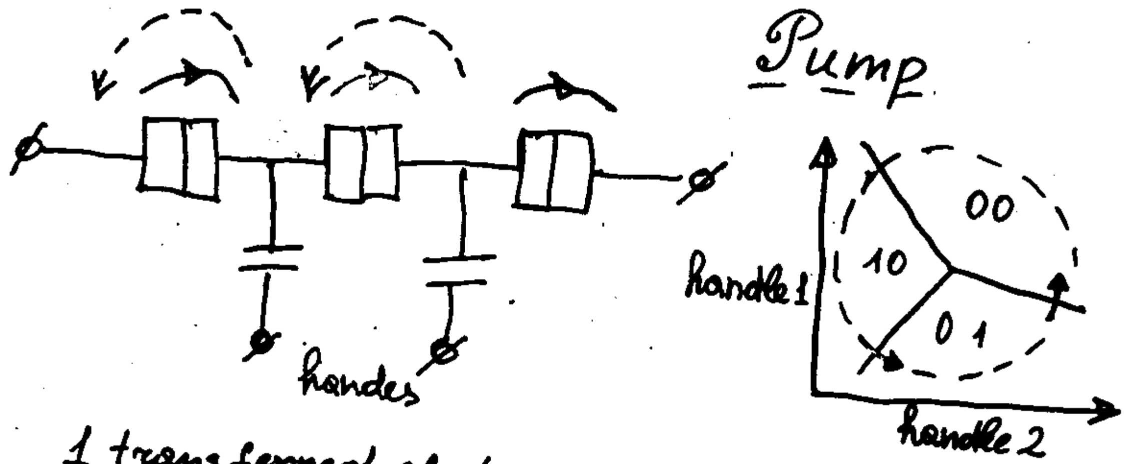


Despite of these fact,
agreement with theory is unexpectably reasonable
(order of the value)

manipulation and trapping

Everything is being done on purpose...

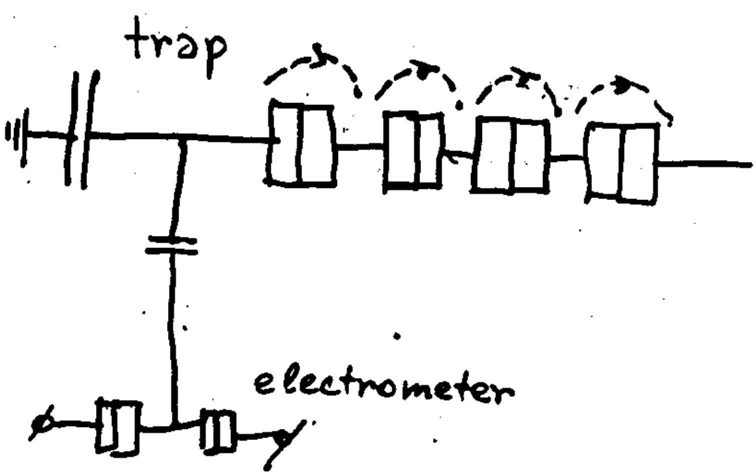
Purpose: to control charge transport (Applications?)



1 transferred electron per cycle

Cotunneling: mistakes

Trapping

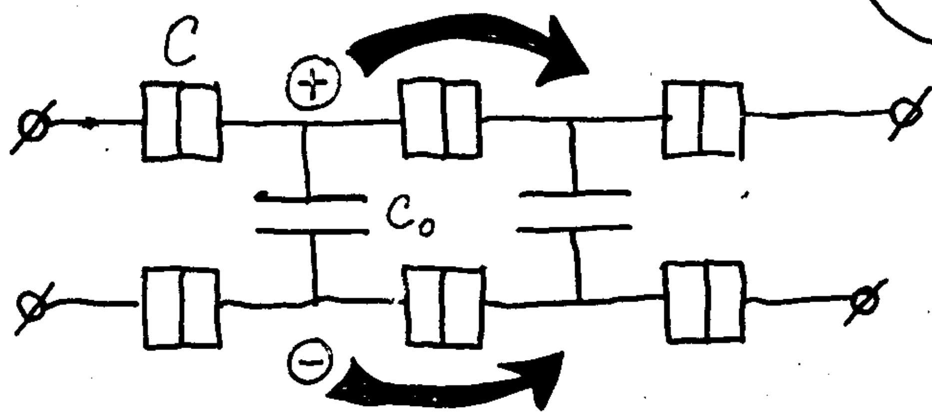


Co-tunneling, decay of metastable states

Co-tunneling: a sort of noise

Copying of the current

Averin Korotkov Nazarov 1991



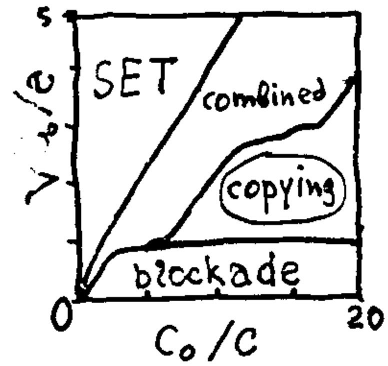
$C_0 \gg C$

electron + hole = pair,

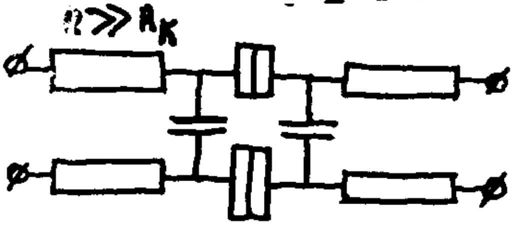
Co-tunneling moves it as a whole:

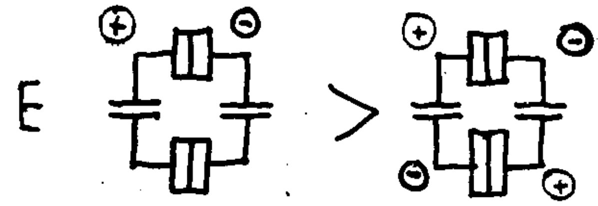
$$I_{up} = -I_{low}$$

in a region



Similiar circuit:



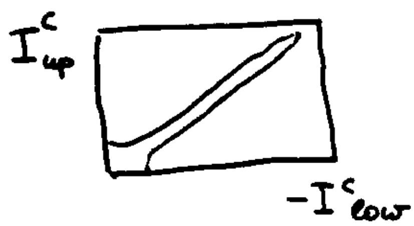


Geigenmüller Nazarov 1991

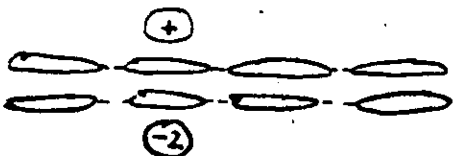
11. Compound particles: building of

long N arrays:

long Superconductive arrays



long Super + Normal arrays



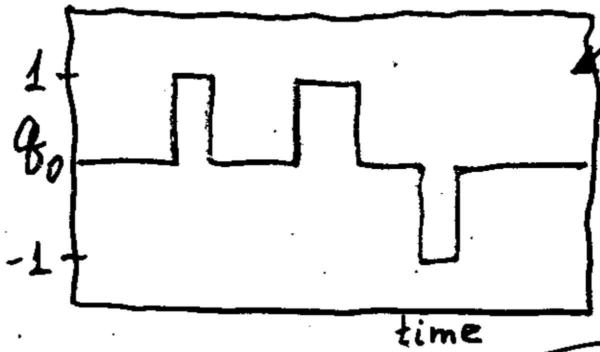
dissipative vs elastic motion ⟺ charge vs electron

Crossover: transport thru the array of 2D lakes

Experimental – from freedom to anarchy

> Electrons like freedom too much...
> Esteve 1992

1 Trapping

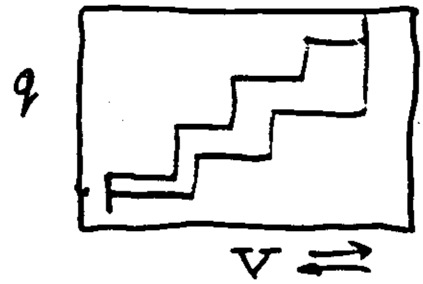


[jumping between metastable states

1. rates are too high! (0.1–10s)
2. **No detailed balance!**

2. Hysteresis (Fulton 1991)

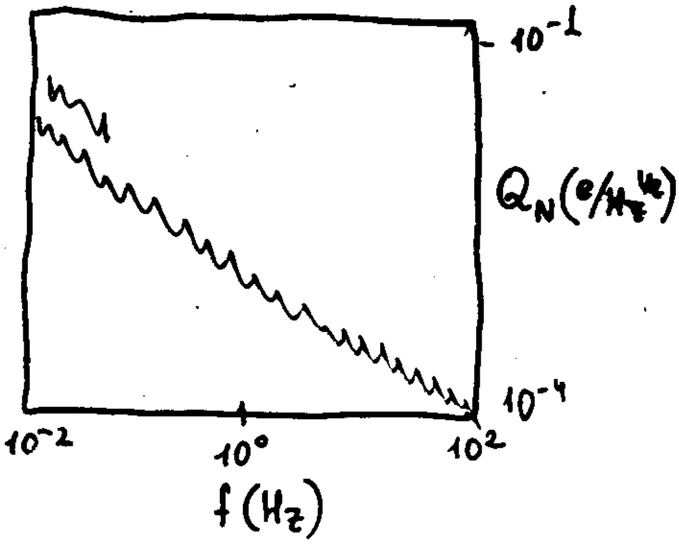
it's possible to measure delays sweeping voltage



1. rates are too low! (0.1 – 10s)
2. Up to noticeable temperatures (thermal activation)

3. Equilibrium? 1/f noise

(Zimmerli et al 1992)

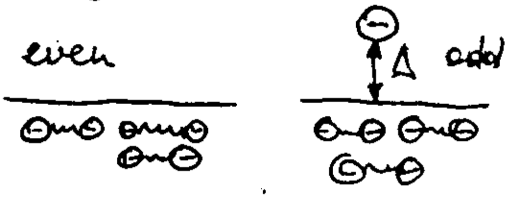


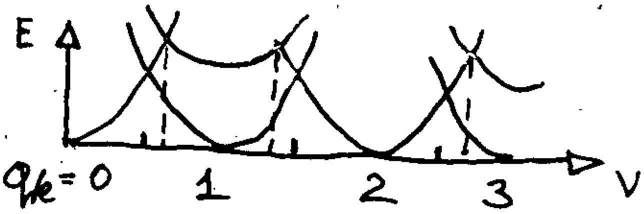
Charge traps in the barriers

plain THEORY:

1. Parity effect: uncoupled electron costs Δ

Matveev 1989





2. Transport properties: no co-tunneling at small voltages

price: 2Δ

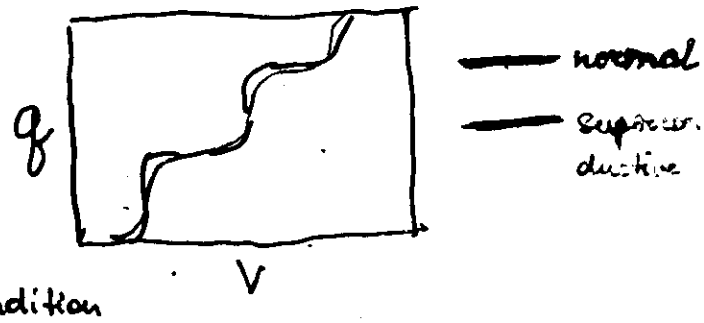
Averin Nazarov 1991

elastic contribution: small containing δ
inelastic contribution: if odd number of electrons. Also small containing δ

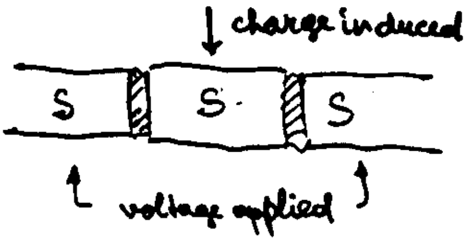
EXPERIMENTS:

1. No parity effect at equilibrium conditions

Esteve et all 1991



2. Parity effect under non-equilibrium condition



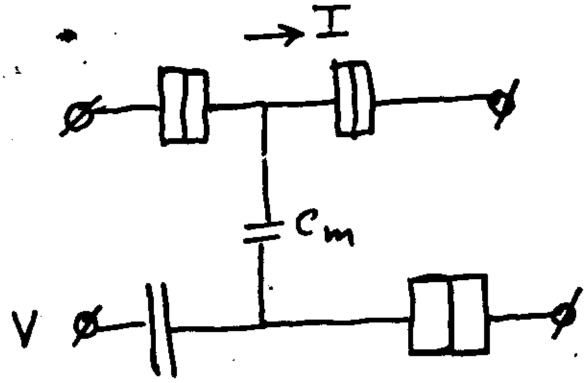
small voltage: 2e - periodicity
larger voltages: e - periodicity

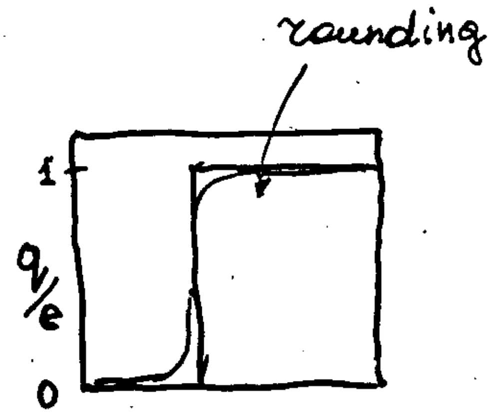
3. Trapping: escape rates: no much difference between normal and superconductive

Esteve 1992 - faster escape

Fulton 1991 - slower escape

feedback of measuring device





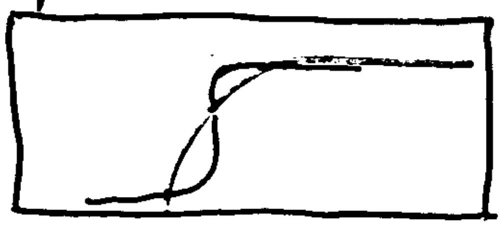
a) Equilibrium quantum effects (Matveev 1990)

resembles multi-channel Kondo problem

rounding $\approx \exp(-\frac{4\alpha}{R_K G})$ ⟶ not relevant for experiments.

b) Feedback of electrometer: it shakes the box

classical rounding $\sim C_m/C$



quantum limit (like NMR) narrower but longer tails

c) Feed back of co-tunneling electrometer: no shaking: no classical limit

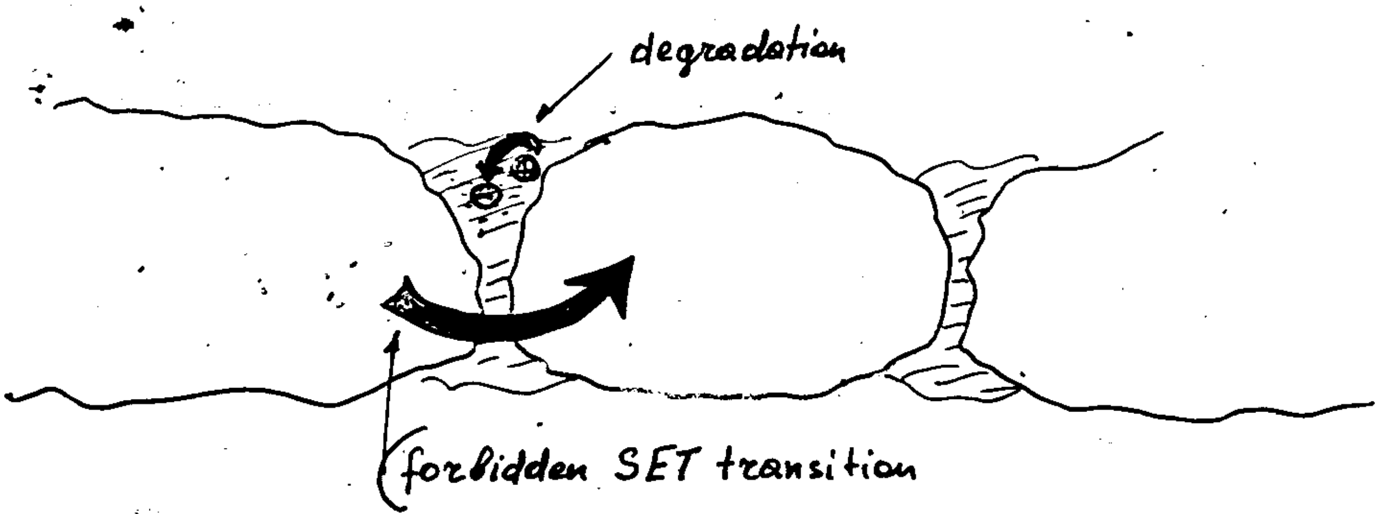
rounding $\sim (C_m/C)^2 \, I/E_c$

d) <u>Tempation:</u>

Measurement
⇓
extra noise
⇓
forbidden transitions
⇓
anarchy

but ⟹ Some experiments are in contradiction working hypothesis:

Degradation causes anarchy



1. An elementary degradation process disposes large Energy (volts)
2. it induces a voltage V at a certain function
3. if a forbidden SET pro. lacks energy E_{th}

p – probability to accompany degradation

$$p = \left(\frac{G\hbar}{24\pi e^2}\right)\left(\frac{eV}{E_{th}}\right)^2$$

Superconductivity → no much changes

$$P_s = \left(\frac{G\hbar}{2\pi e^2}\right)(eV)^2 \int_0^\infty d\varepsilon \, \frac{I(\varepsilon)}{(E_{th}+\varepsilon)^4}$$

Such a stimulation of forbidden gumps may cause an anarchy observed.