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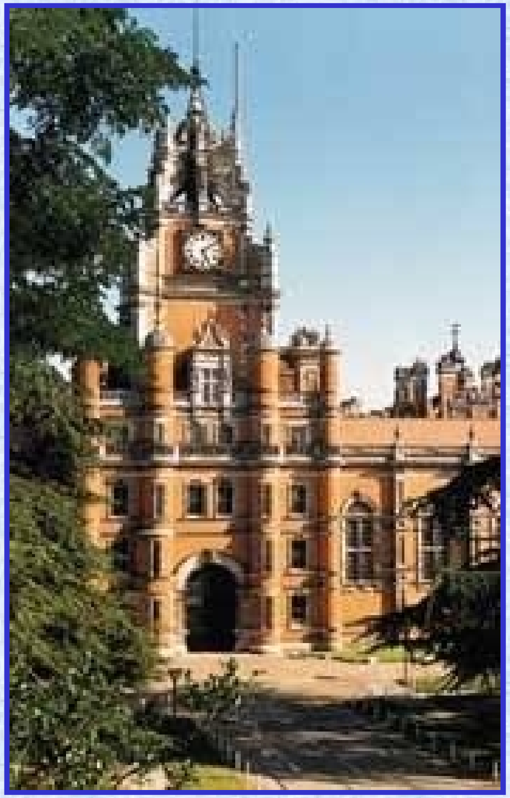
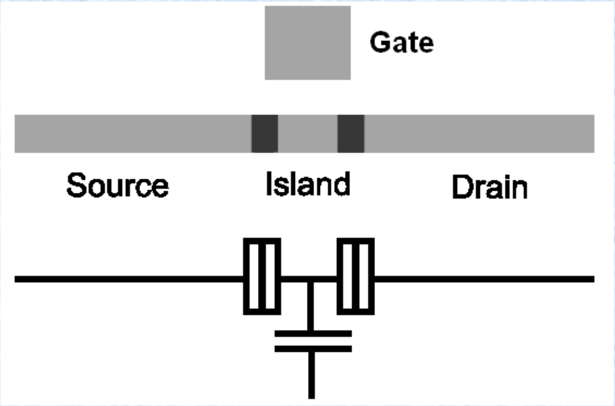
EPSRC



Thermal excitation of large charge offsets in a single-Cooper pair transistor

Luke Simkins, Dave Rees,
Vladimir Antonov, Phil Glasson, Phil Meeson, Mike Lea.
+ Eddy Collin, Grenoble

Single Electron Transistors



Sensitive electrometer theoretical charge sensitivity
$\Delta Q = 5 \times 10^{-7} e\sqrt{Hz}$, typical $\Delta Q = 5 \times 10^{-4} e\sqrt{Hz}$
$\Delta Q = 5 \times 10^{-6} e\sqrt{Hz}$ for rf SET

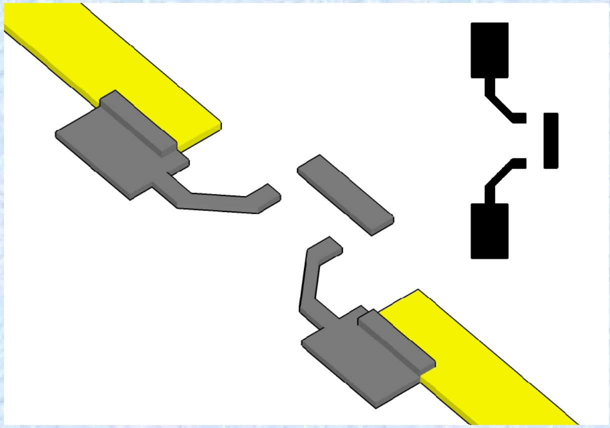
Consists of an island between source and drain electrodes separated by a tunnel junctions

$E_c \equiv e^2/2C_\Sigma$, current will always flow unless $K_b T < E_c$

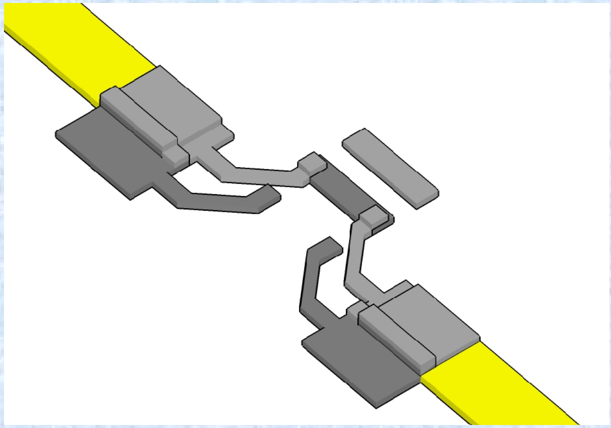
For T=1K $C_\Sigma \sim 1 \times 10^{-15}$ F , junction size 100nm x 100nm

Shadow evaporation technique

- First angled evaporation Al
- Oxidization forms AlO2 layer ~1nm thick



- Second angled evaporation Al
- Leads overlap the oxidized island



Charge defects from substrate, in the Al (not 100% pure), oxygen in the junctions, adsorbed gases and Al grains

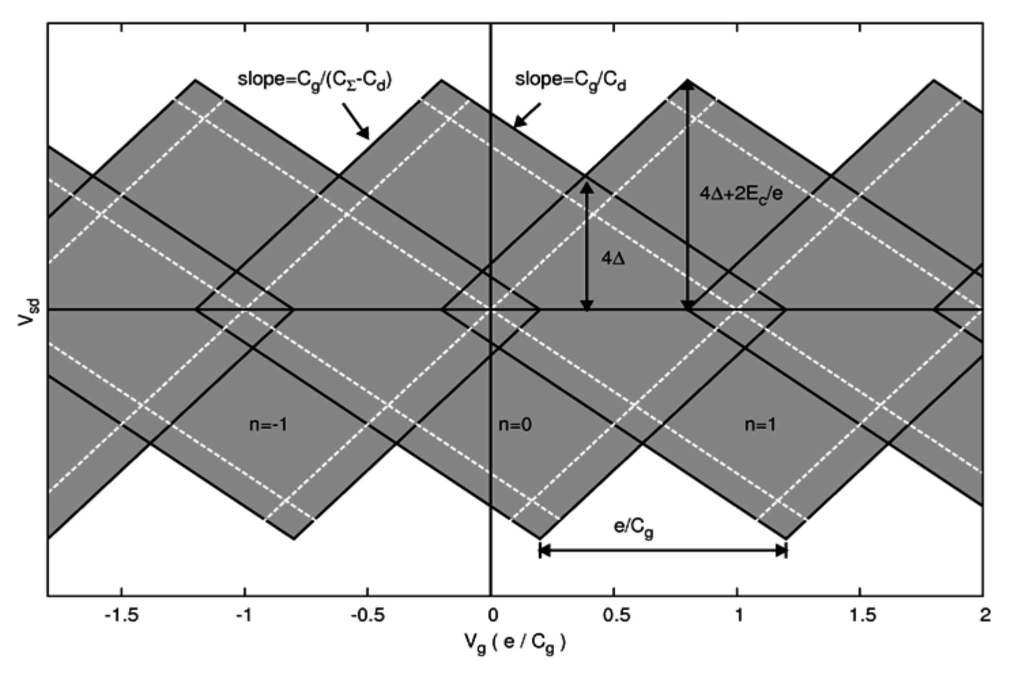
Superconducting SETs

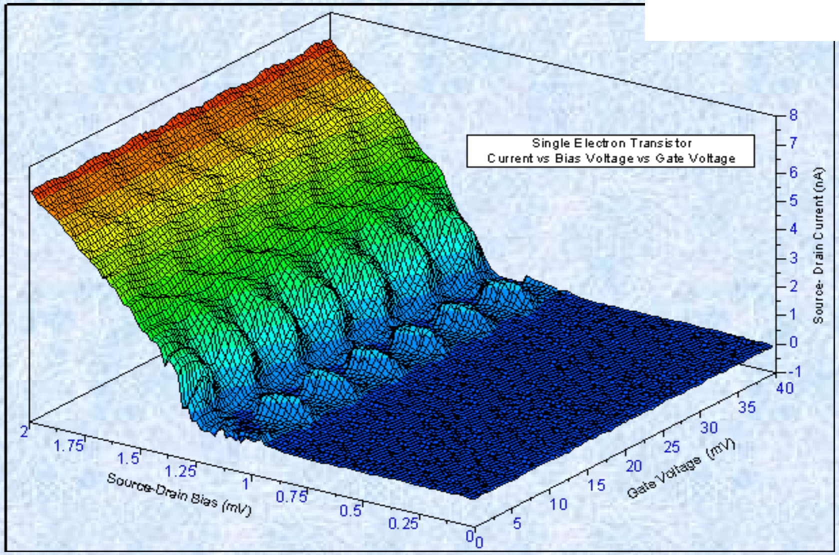
Current flow depends on superconducting energy gap Δ as well as charging energy E_c

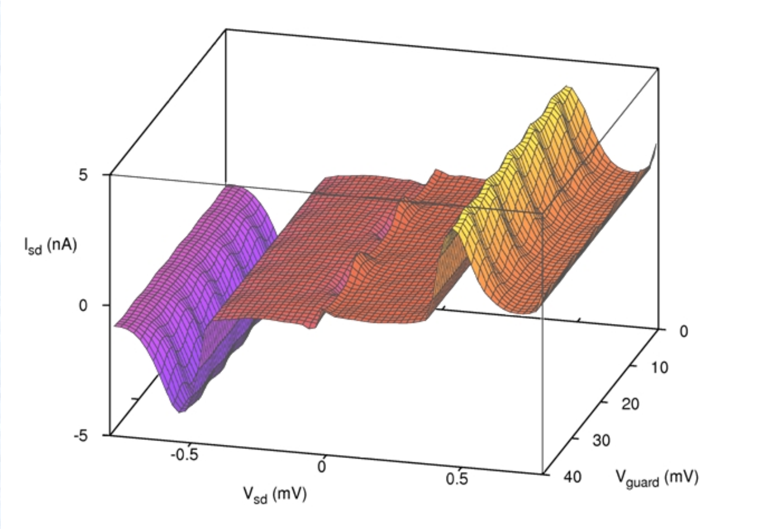
$E_j \equiv \hbar I_c/2e$, I_c is the critical current

E_c and E_j determine the dominate features seen in the response on the SET

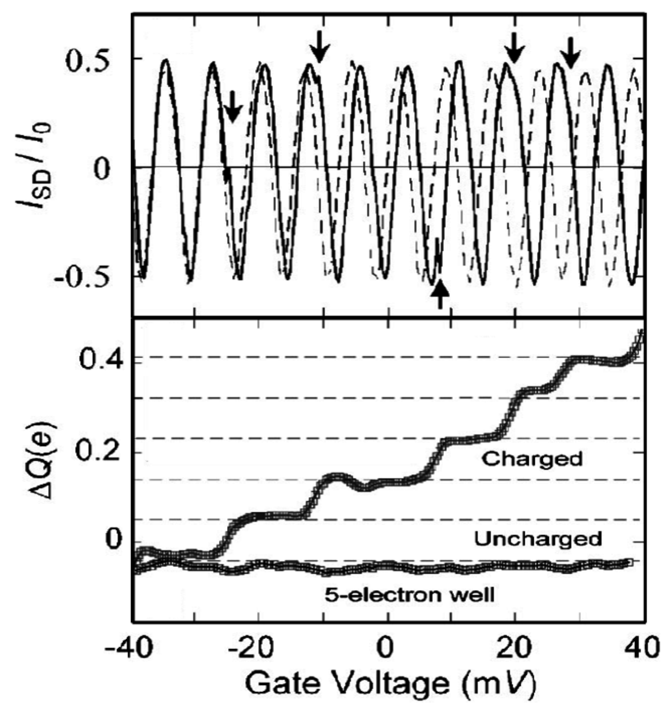
Main superconducting features are the Josephson quasiparticle peak and the Cooper pair peak

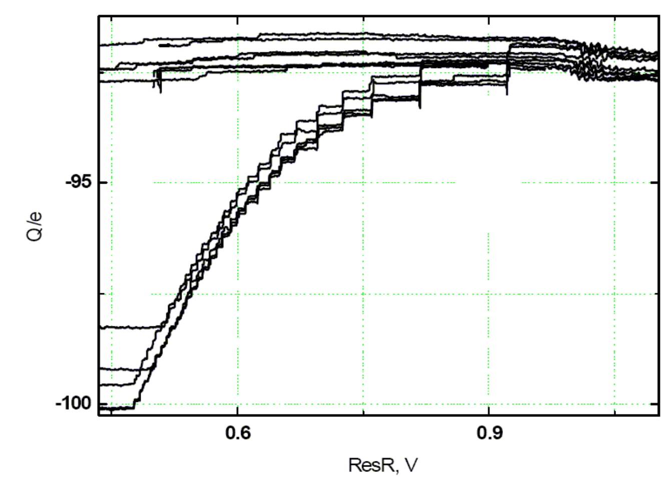




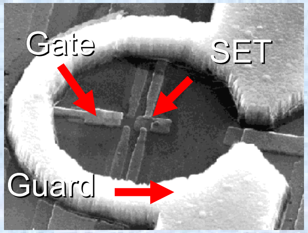


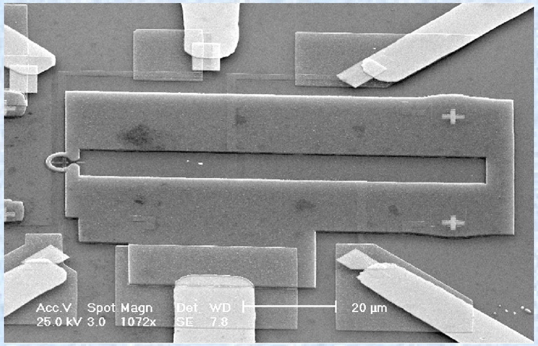
SETs for Electrons on Helium



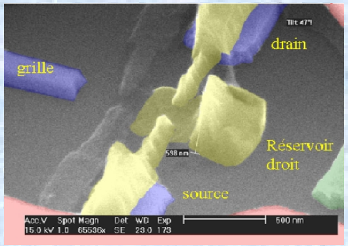


EoH trapped by potential profile of pool above SET. As gate voltage is swept CBOs are seen on SET, and potential profile of pool changes. EoH are lost from the pool, phase jumps seen in CBOs





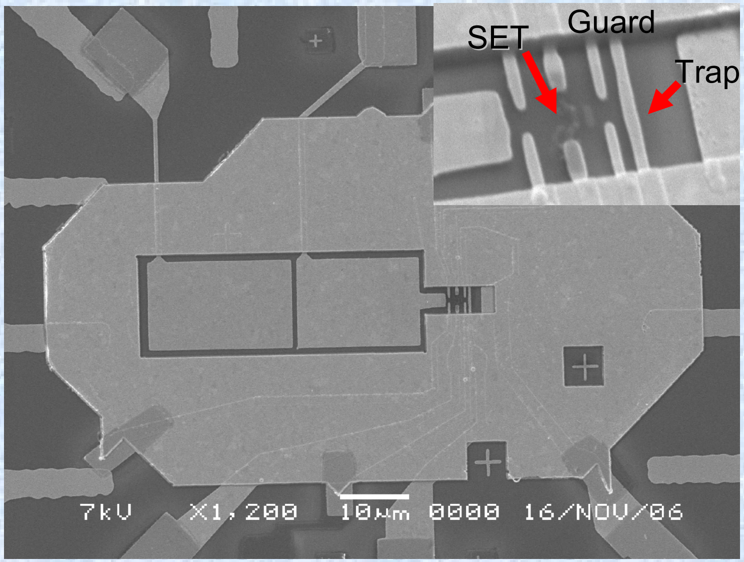
G. Papageorgiou *et al,* APL **86**, 153106 (2005)

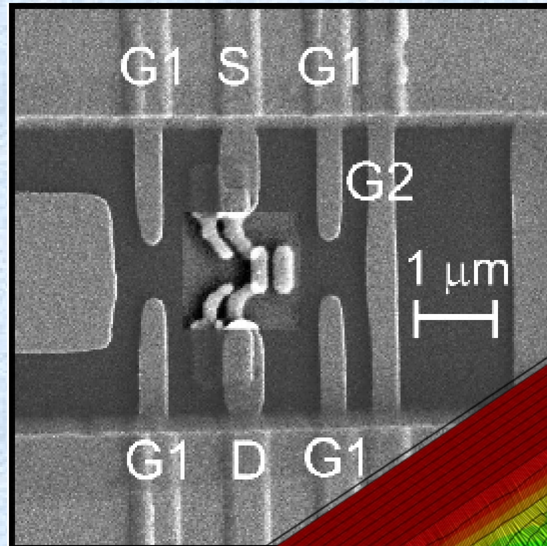


E. Rousseau *et al,* J. Low Temp. Phys. **148**, 193 (2007)

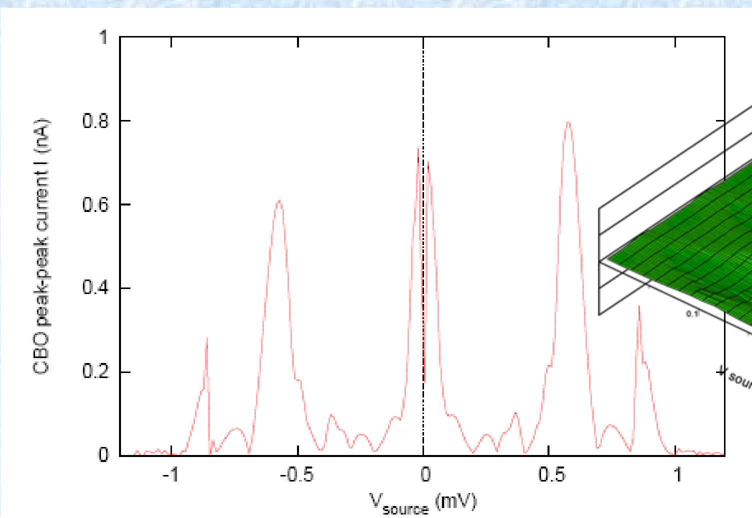
Courtesy of Dr. Y. Mukharsky and E. Rousseau at CEA at Saclay, France.

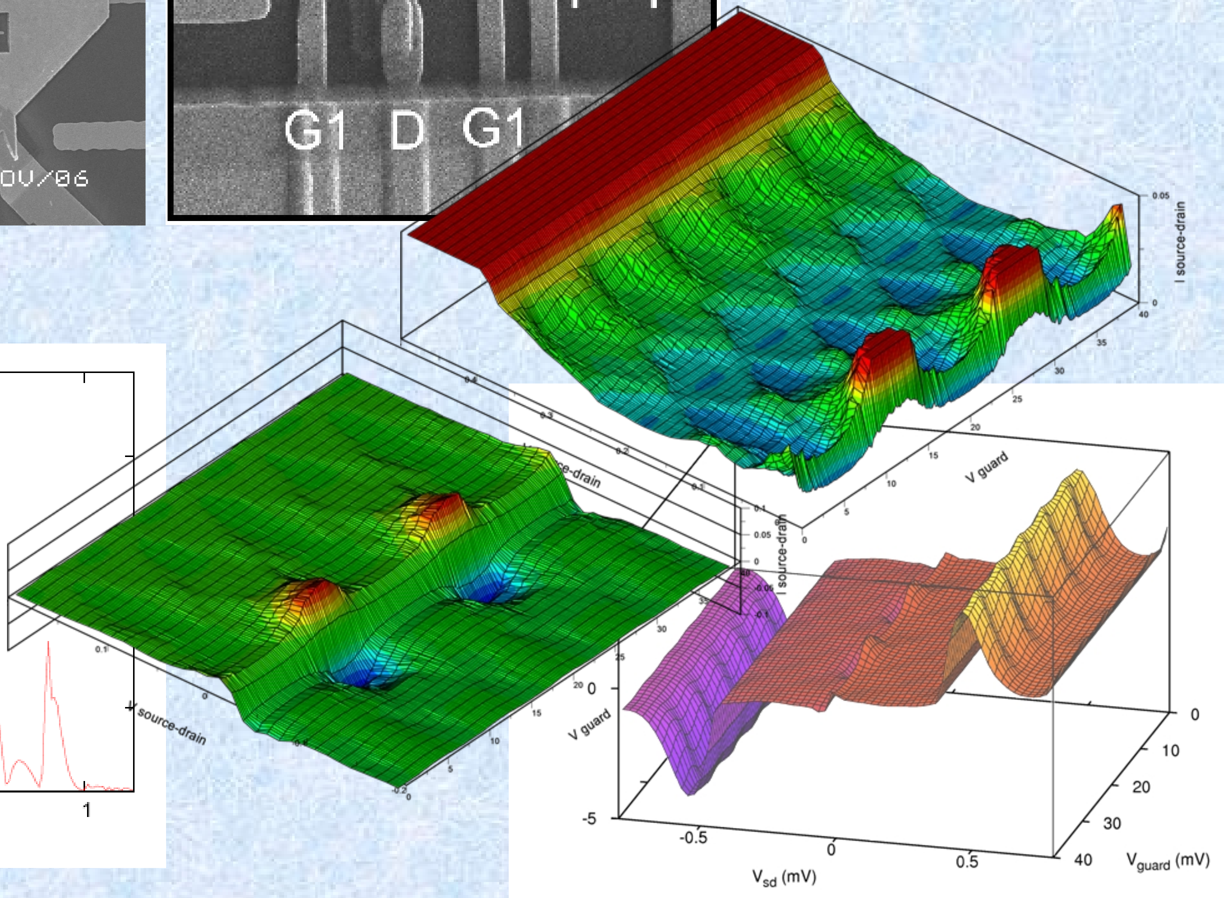
Electron array devices (RHUL)



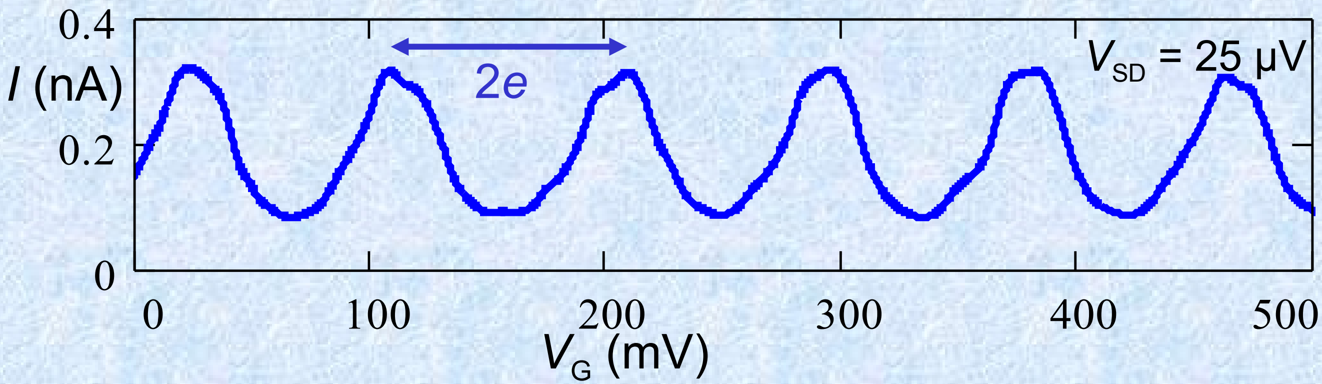


Clean system with large 2e CBOs





2e periodic CBO



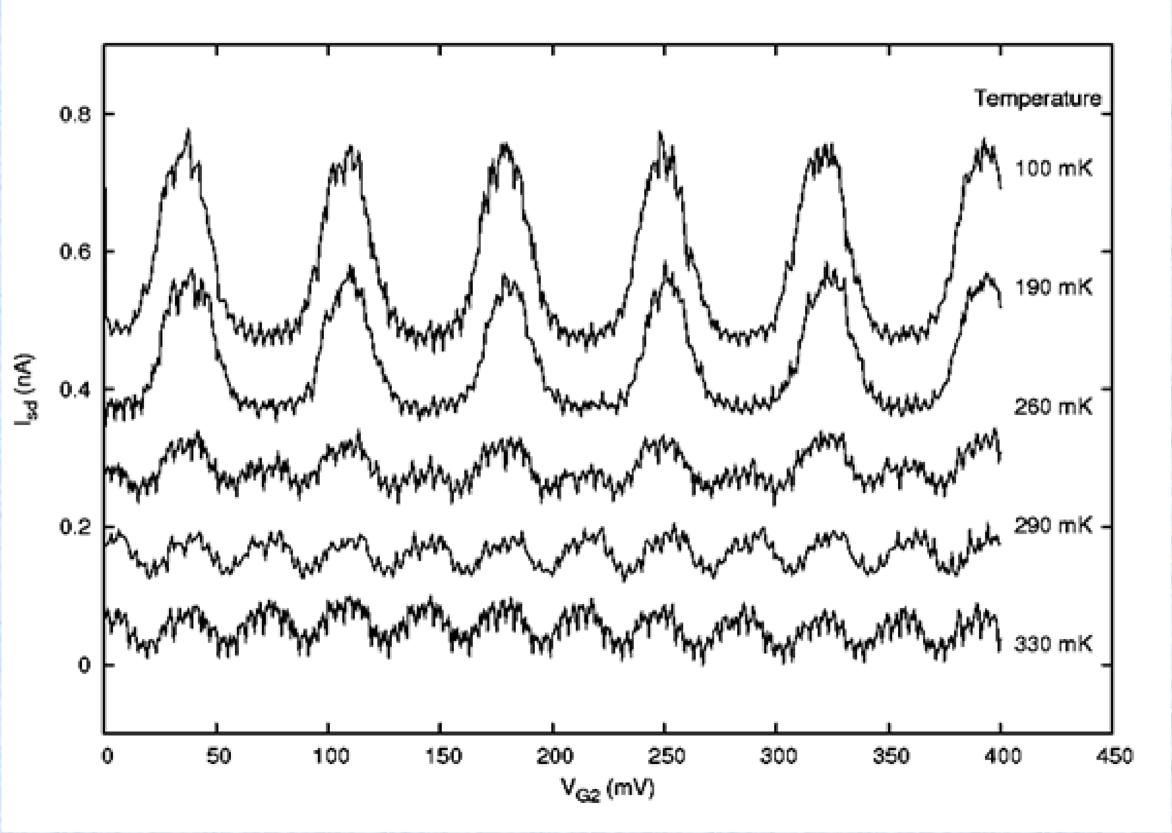
Δ = 190 μeV
E_C = 35 μeV
E_J = 20 μeV
R_N = 30 kΩ

2*e* periodic CBO for even parity on SET island

T **< 0.3 K**
No quasiparticle poisoning
$E_C = e^2/2C_\Sigma \ll \Delta$
$R_N \approx h/e^2 = 26\ \mathrm{k\Omega}$

[Amar *et al.* PRL 72, 3234 (1994)]

Joule heating
1*e*: 2 pW
2*e*: 10 fW



CBO phase jumps

Sweep gate voltages

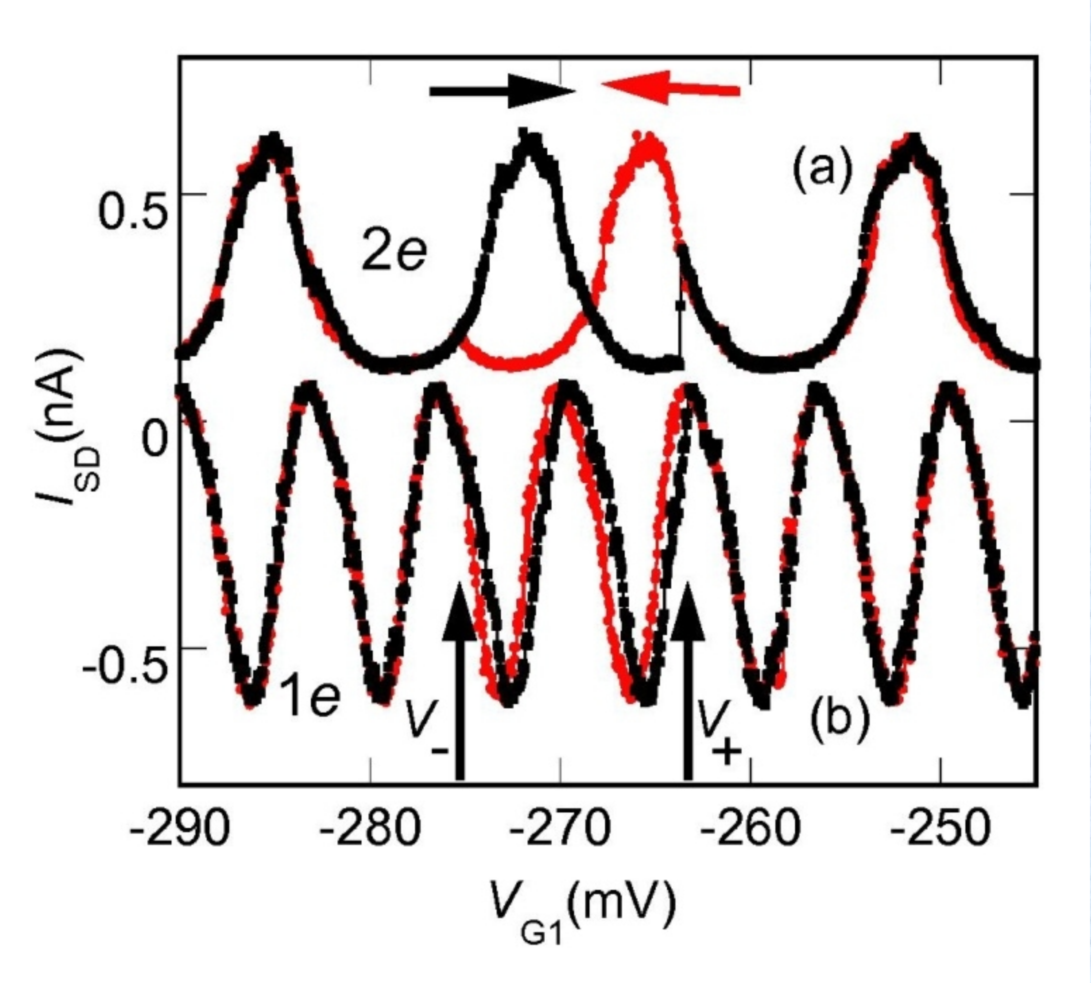
CBO phase shifts

Charge offsets

2*e*:
$\Delta Q = 0.92 \pm 0.02\ e$

1*e*:
$\Delta Q = -0.08 \pm 0.02\ e$

Hysteresis



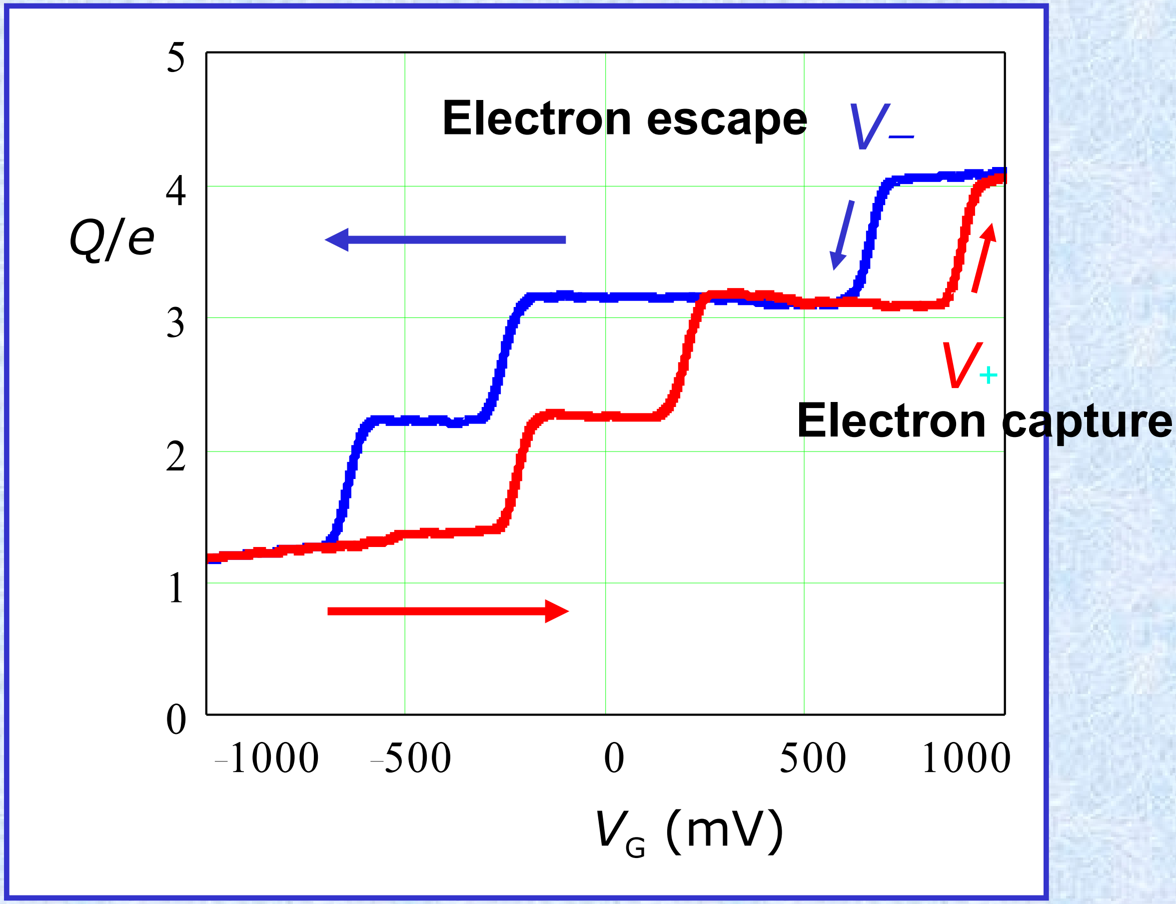
Charge Offsets and Hysteresis

Charge offsets
$0.80 < \Delta Q/e < 1.00$

Hysteresis
$\Delta V = V_+ - V_-$

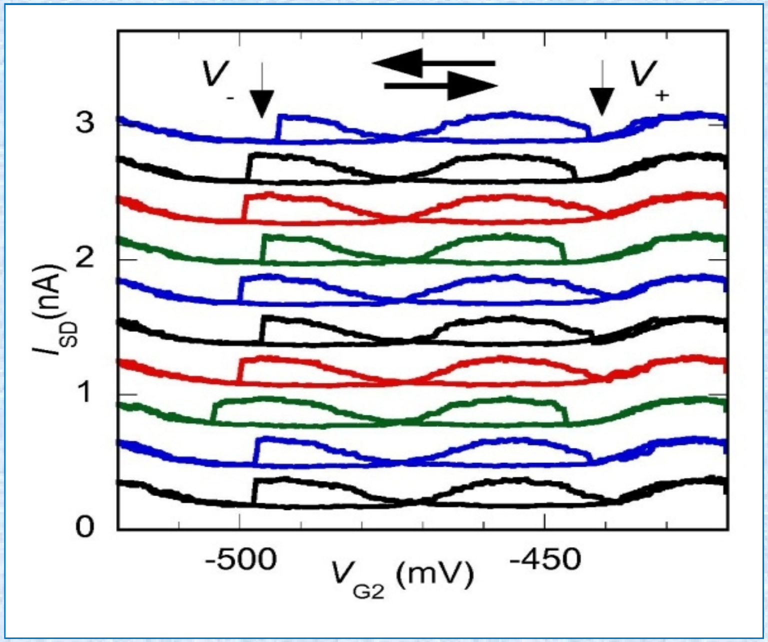
Reproducible thresholds

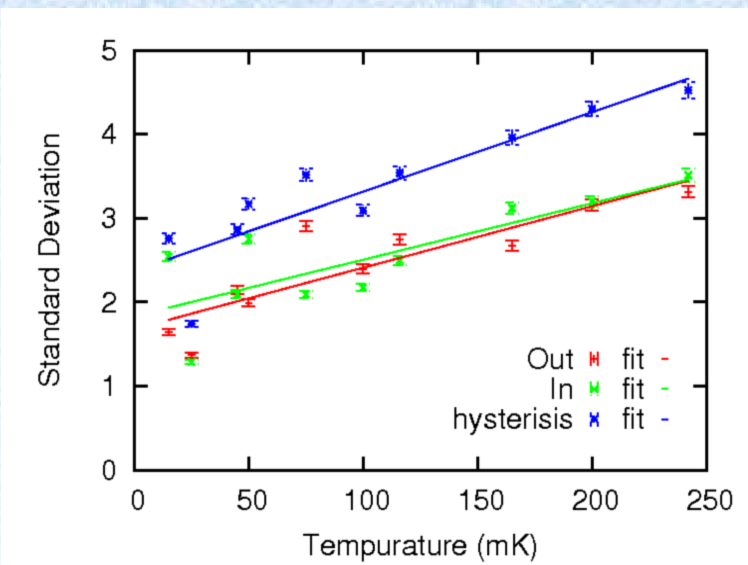
Quasiparticle traps?



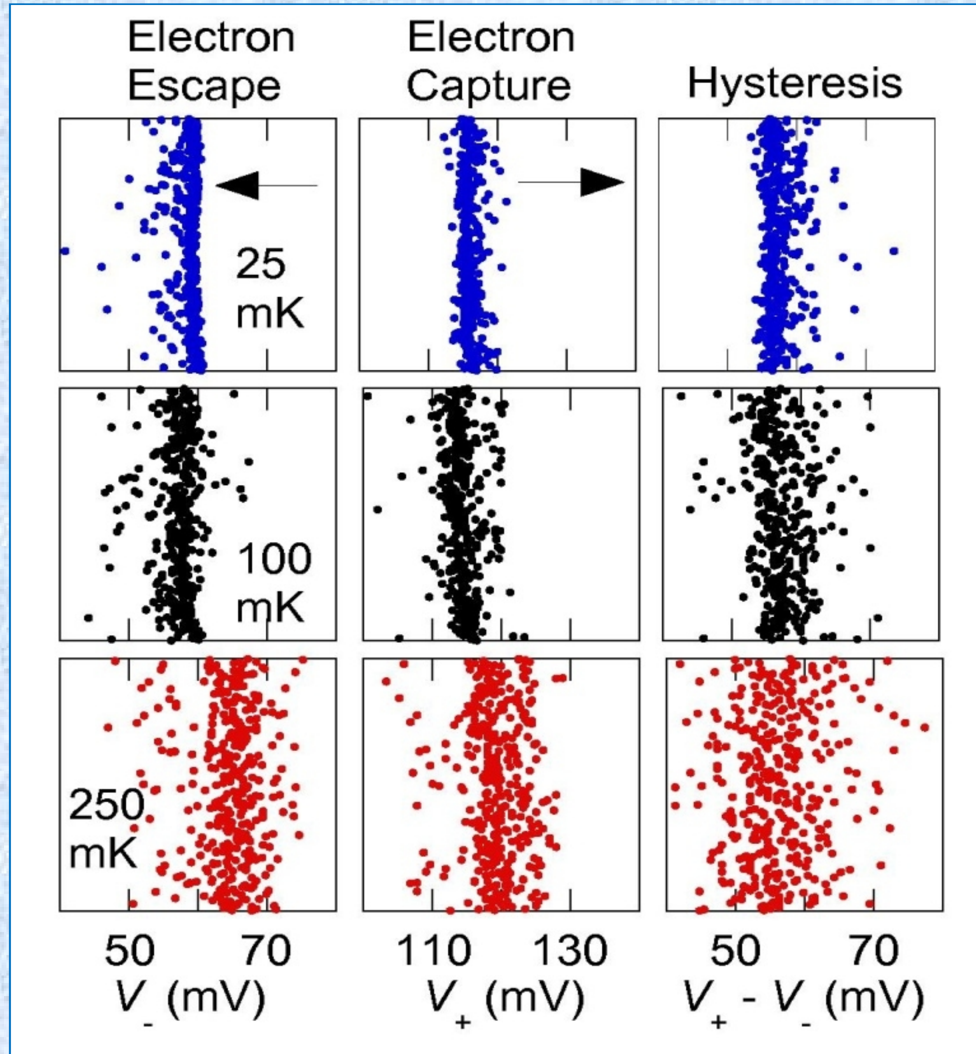
Previous experiments:
$|\Delta Q|/e < 0.09$; hysteresis; 1e periodic CBO (SSS and NNN)
[M.Furlan and S.V.Lotkhov, Phys.Rev. B **67**, 205313 (2003) + others]
$\Delta Q/e = 1.0$; 2e periodic CBO (NSN)
[T.M.Eiles *et al.*, PRL **70**, 1862 (1993)]

Hysteresis





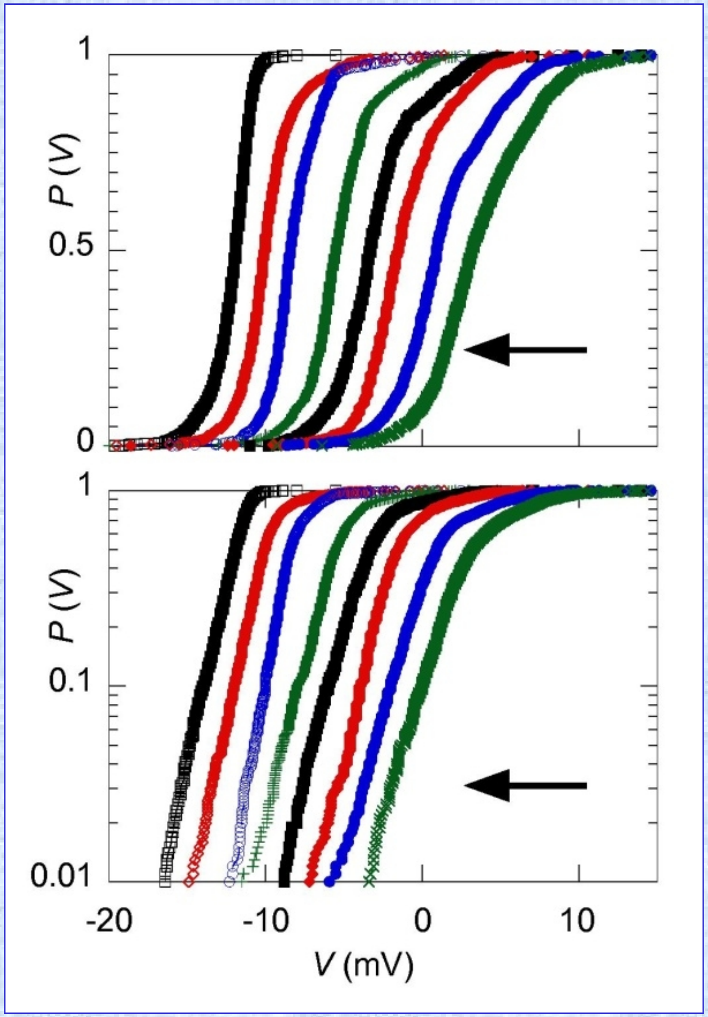
Sweep gate voltage *V*, Measure transition voltage
Reset and repeat 1000 times



Electron Capture and Escape

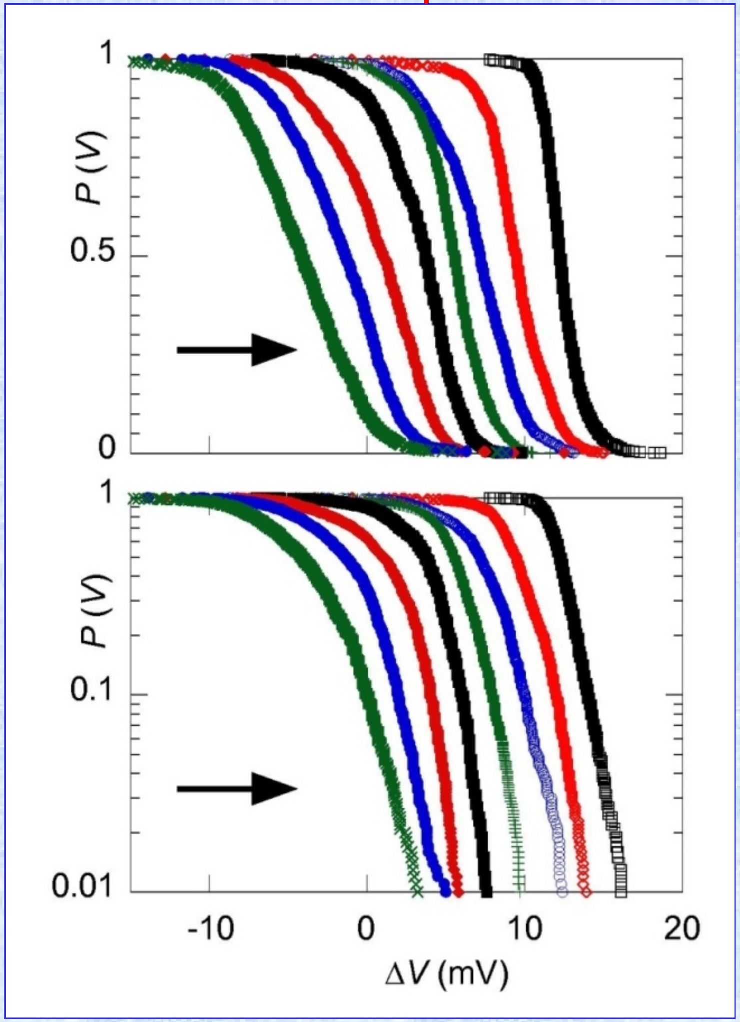
Probability of initial state *P*(*V*)

Electron escape



T = 25, 45, 50, 100, 116, 165, 200, 242 mK

Electron capture



T = 242, 200, 165, 116, 100, 50, 45, 25 mK

Relaxation times

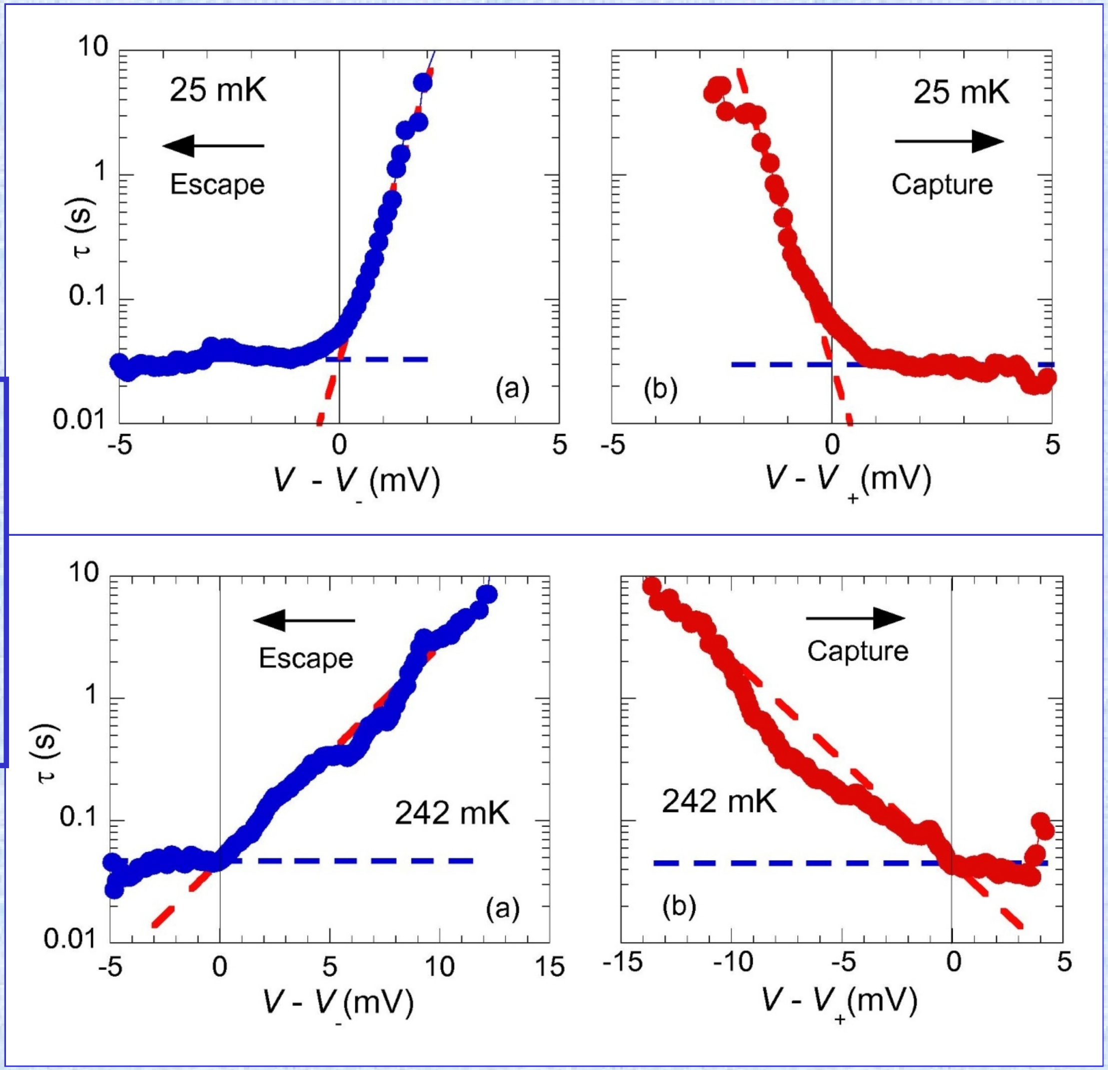
$1/\tau = -(1/P)dP/dt = -(1/a)d\ln P/dV$
Where a is the voltage sweep rate

Experimentally:

for $\Delta V < 0$ **below threshold**
$1/\tau(\Delta V, T) = (1/\tau_0)\exp(e\,\Delta V/\gamma kT)$

for $\Delta V \geq 0$ **above threshold**
$1/\tau(\Delta V, T) = 1/\tau_0$

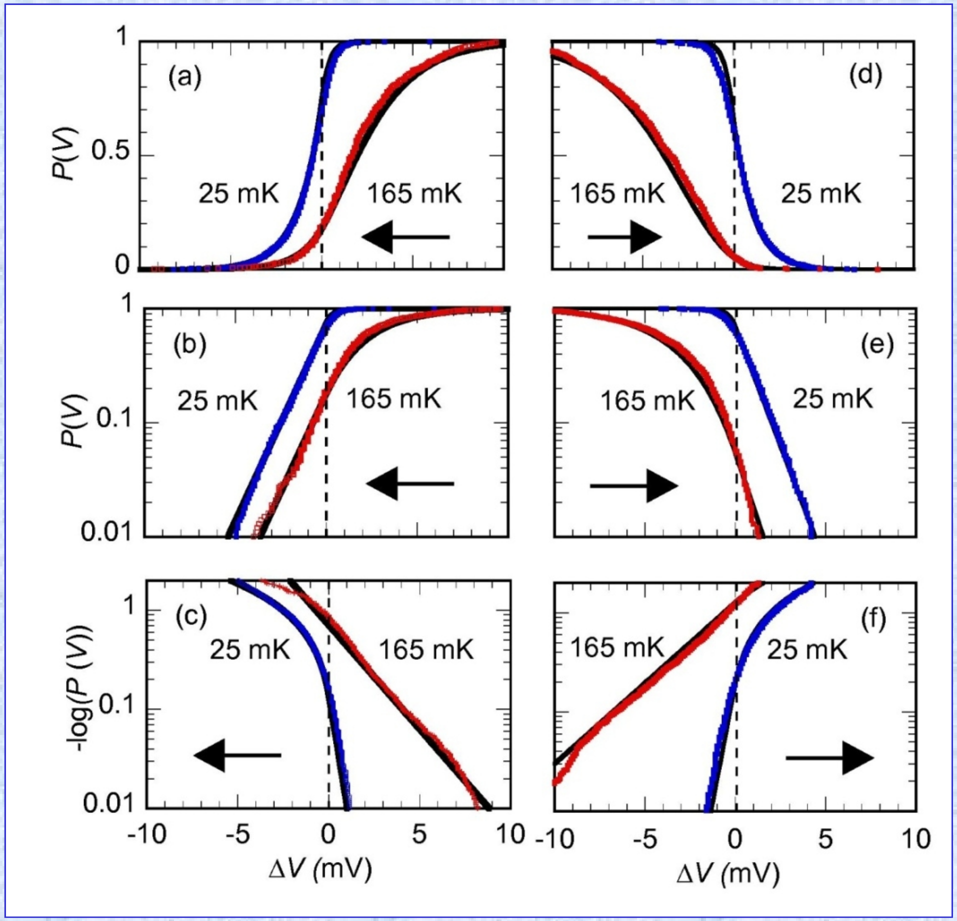
γ is a geometrical scaling factor

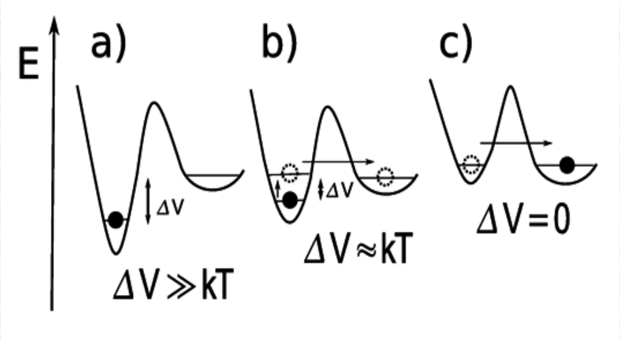


Thermally excited tunnelling

For $\Delta V < 0$, $P(\Delta V\ T) = \exp[(-\gamma kT/ea\tau_0)\exp(e\,\Delta V/\gamma kT)]$
Plot log(log$P$) vs v $\Rightarrow 1/\gamma T$

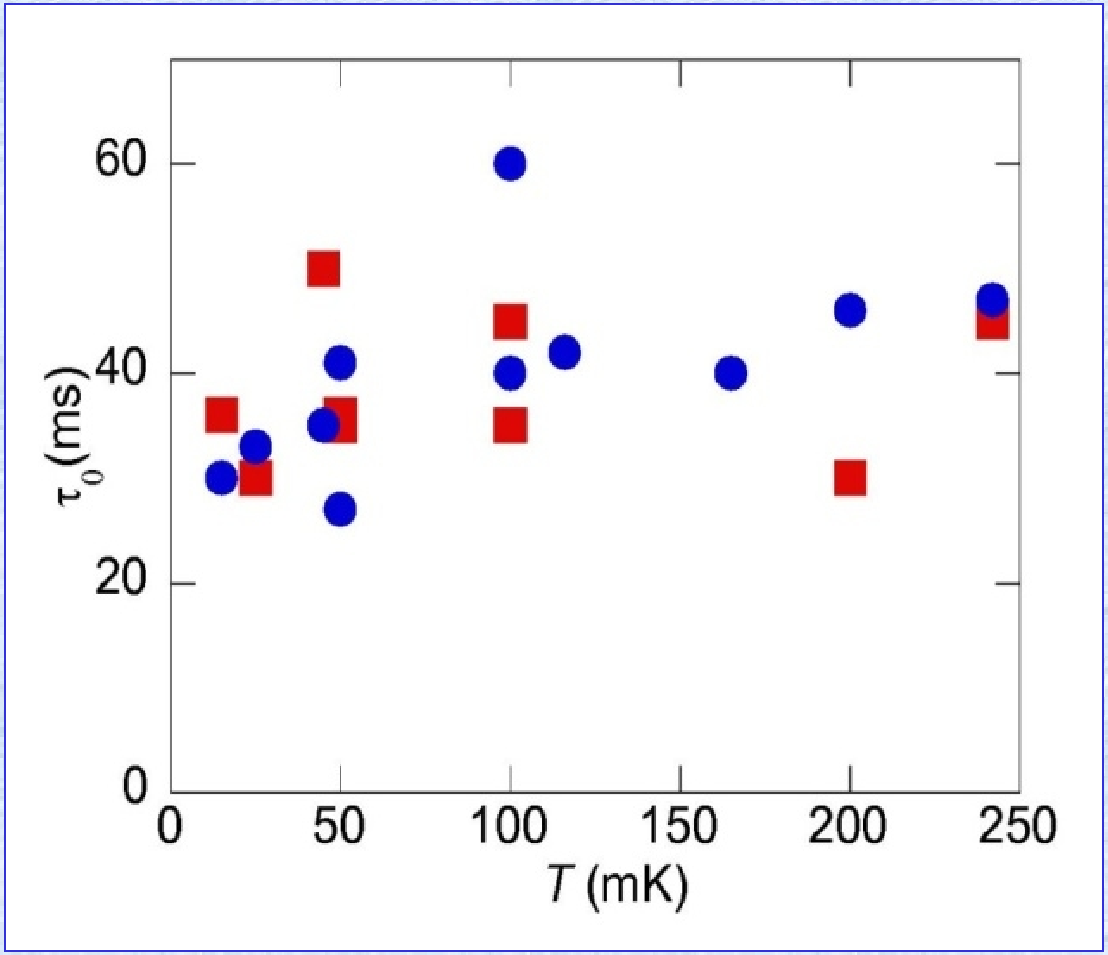
For $\Delta V \geq 0$, $P(\Delta V, T) = \exp(-\gamma kT/ea\tau_0)\exp(-\Delta V/a\tau_0)$
Plot log$P$ vs v $\Rightarrow 1/\tau_0$





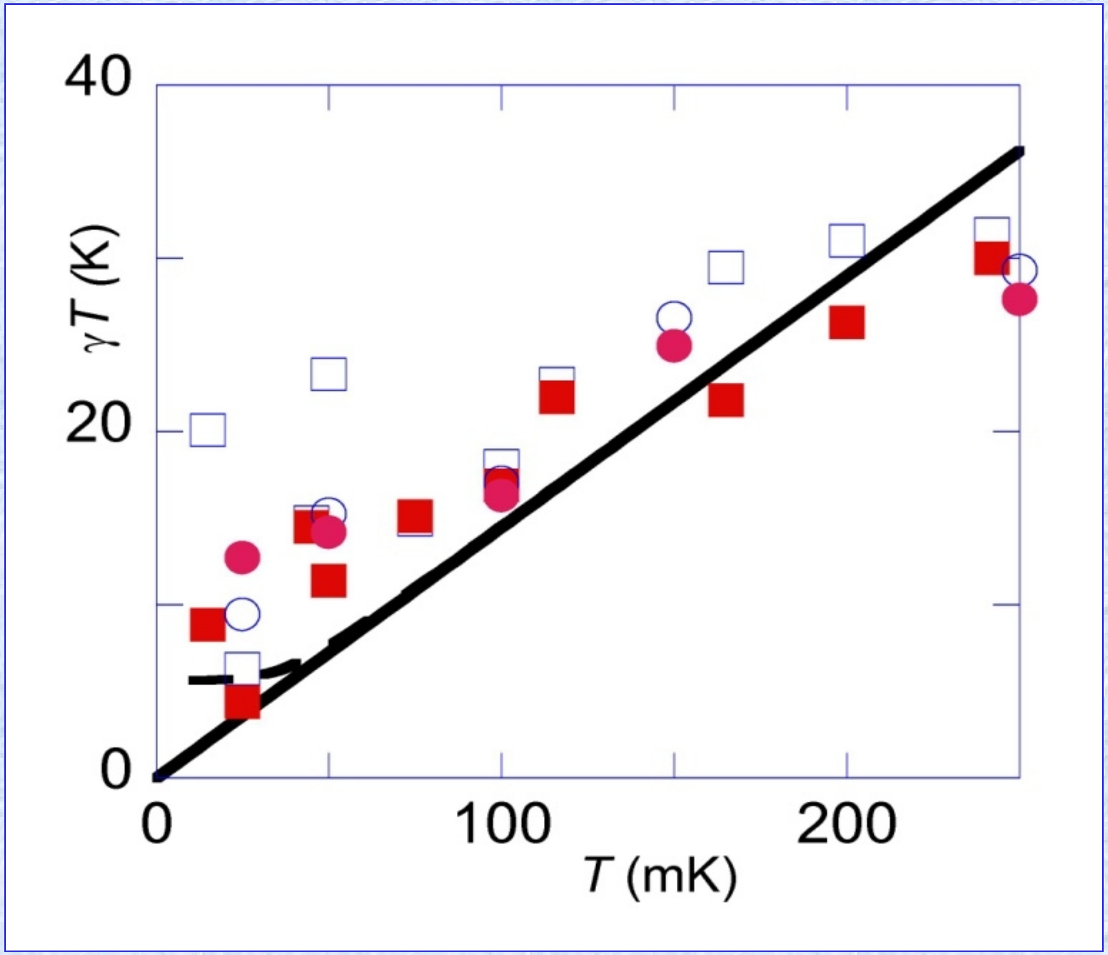
Model of thermally excited tunnelling fits data. Need to explain hysteresis.

Exponential decay – voltage sweeps



- $\tau_0 \approx$ 35 ms (*T*)
- Long time due to tunnelling?
- Scatter in $\tau_0(T)$

Thermal dependence



- $\gamma T \propto T$ above 50 mK
- $\gamma = 145 \pm 5$
- Minimum T_{min} = 39 mK (heating)

Thermal excited tunnelling, a two level system

$$1/\tau(\Delta V, T) = (1/\tau_0)\exp(e\,\Delta V/\gamma kT) \quad \text{for } \Delta V < 0$$ below threshold

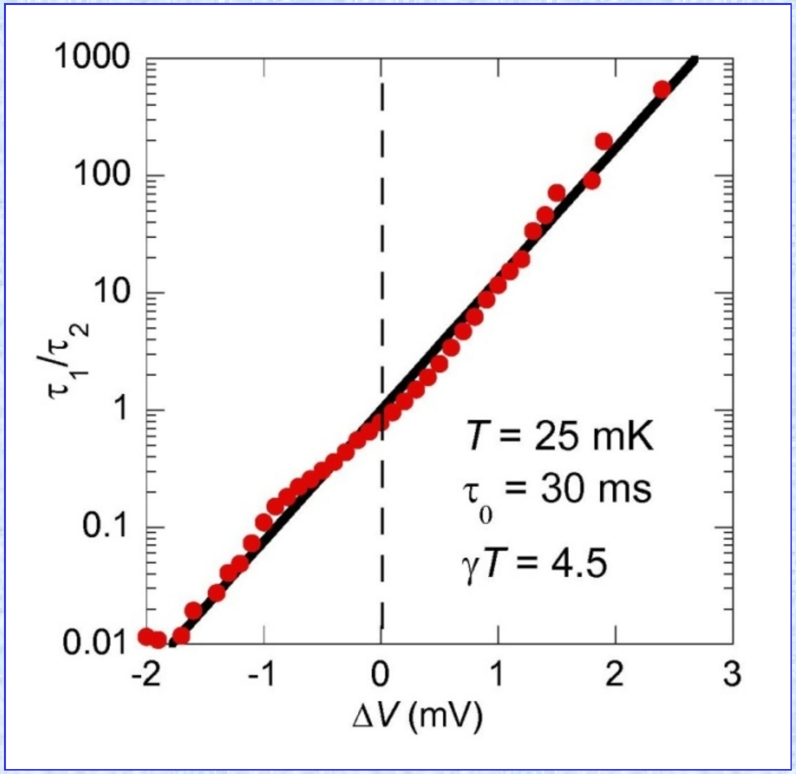
$$1/\tau(\Delta V, T) = 1/\tau_0 \quad \text{for } \Delta V \geq 0$$ above threshold

Compare capture and escape by offsetting data to each threshold

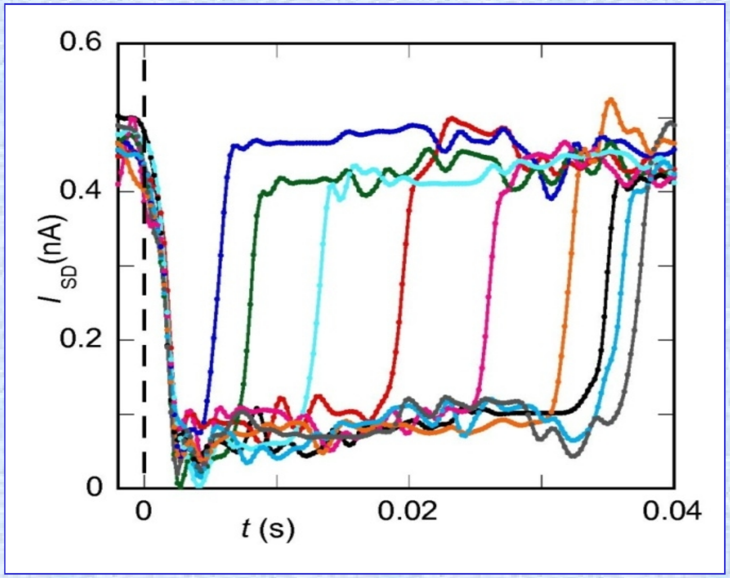
Escape time $\tau_2(\Delta V, T)$
Capture time $\tau_1(\Delta V, T)$
Boltzmann factor

$$\frac{\tau_2(\Delta V, T)}{\tau_1(\Delta V, T)} = \exp(e\,\Delta V/\gamma kT)$$

When ignoring hysteresis, system behaves like a simple two level system



Escape and capture rates

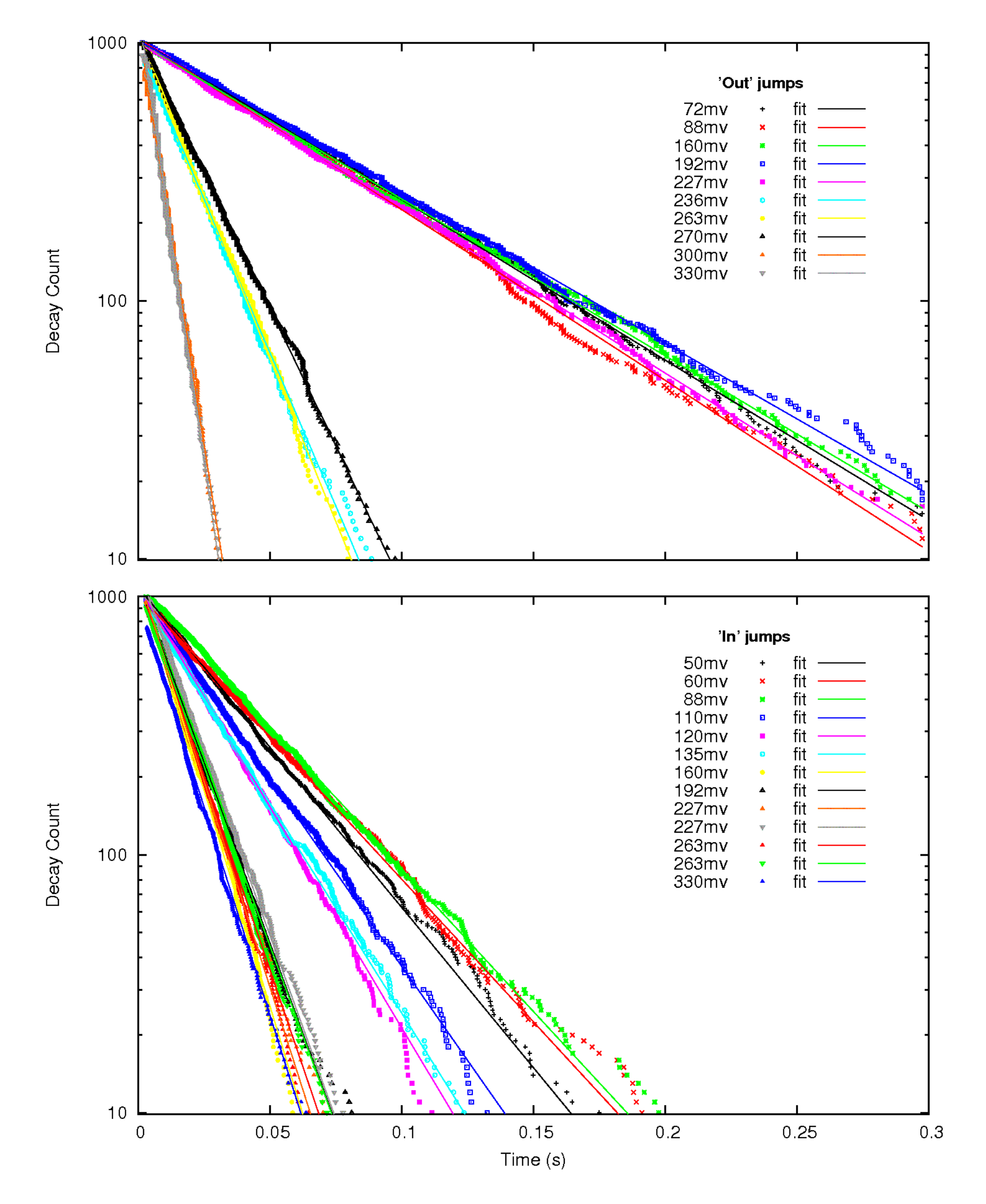


$$P(V_{G2}) = \exp(-t/\tau)$$

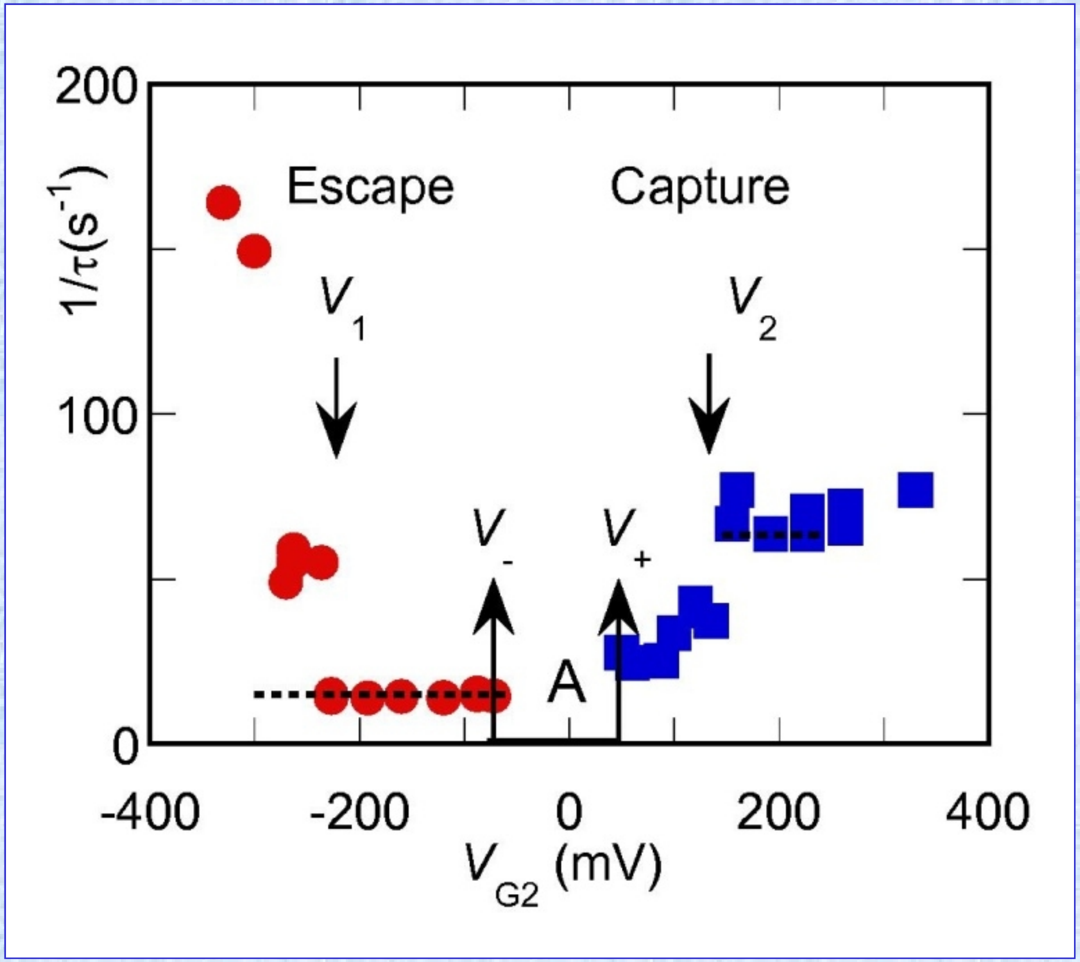
Measure escape rates in real time Sweep gate voltage quickly to a fixed voltage V_{G2}

Measure time before charge shift occurs

Repeat 1000 times – good exponential decay



Escape and capture rates



Hysteresis in region A: stable states between V_+ and V_-
Second thresholds V_1 and V_2 where τ changes

Superconducting tunneling

Need to explain:
- **$\Delta Q/e \approx 1.0$, must be from electron from island or leads to a trap**
- **$1/\tau$, why so long**
- **Hysteresis**

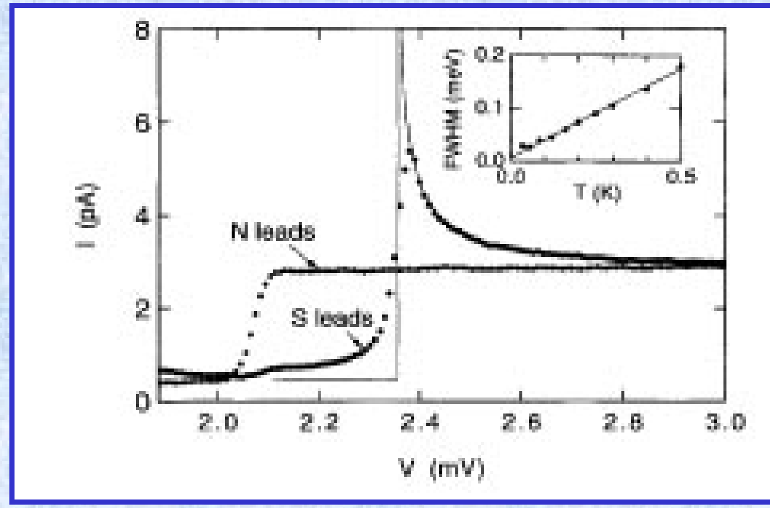
Could hysteresis be due to the superconducting gap of an electron tunnelling to a quasiparticle trap from the SET island?

But s/c to s/c tunnelling:
$1/\tau \propto$ density of states N(E) [red line]

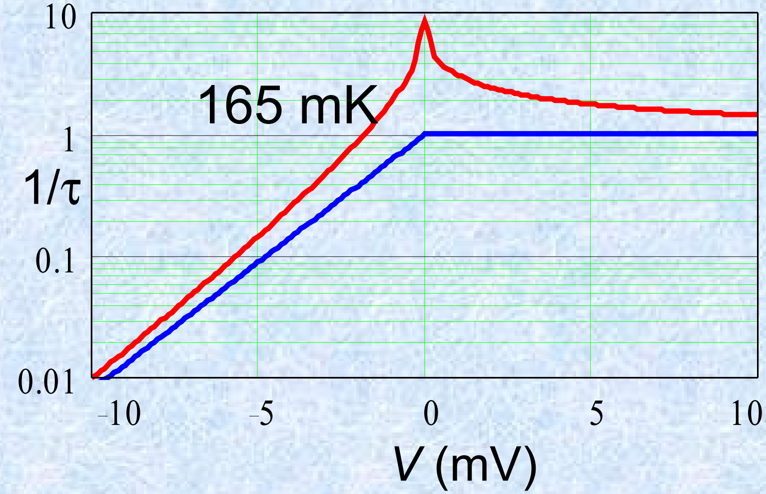
Two-level System (TLS)?
Thermally activated [blue line]

[D.E.Grupp *et al*, PRL **87**, 186805 (2001)]

Tunnelling through an Al grain



D.C.Ralph *et*, al PRL **74**, 3241 (1995)

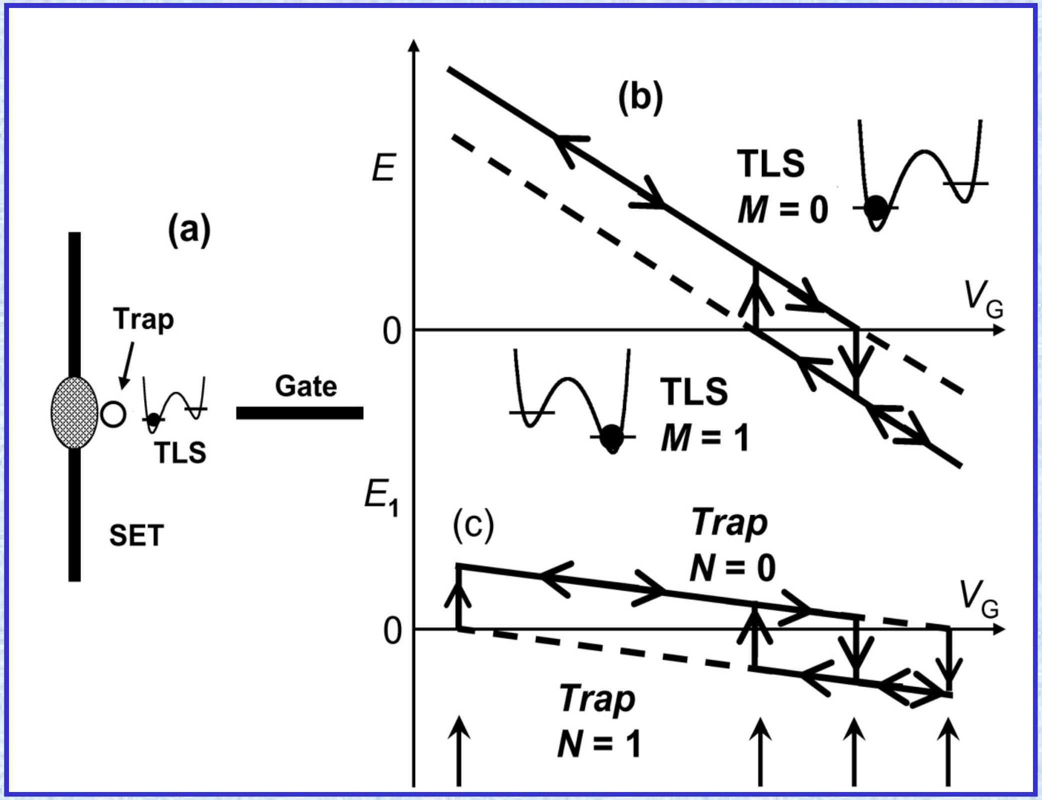


Model

Quasiparticle trap coupled to a TLS?

Activation energies:
TLS: *E*; the trap: E_1
depend on: V_G,
the TLS state (*M* = 0, 1),
the trap occupancy (*N* = 0, 1)

$$E = e(V_+ - V_G)/\gamma - N\Delta E$$
$$E_1 = e(V_1 - V_G)/\gamma_1 - M\Delta E$$



Model gives
- **$\Delta Q/e \approx 1.0$**
- **$1/\tau$**
- **Hysteresis**

What is the trap? Al grain?
[K.R.Brown *et al*, APL. **88**, 213118 (2006)]

Conclusions

SCPT – excellent charge detector
Stable, reproducible
BUT
Large charge offsets
Intrinsic to Al SETs?
These could be mistaken for EoH signal,
with SCPT can be distinguished due to 2e sensitivity

D.G.Rees *et al.* Appl.Phys. Lett. **93**, 173508 (2008)
L.R.Simkins *et al.* J.Appl.Phys. **106**, 124502 (2009)