The Abdus Salam
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SMR 1760 - 8

COLLEGE ON

PHYSICS OF NANO-DEVICES

10 - 21 July 2006

Electron Correlations in Single Electron Transistors The Kondo Effect

Presented by:

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Electron Correlations in Single Electron Transistors

The Kondo Effect

M. A. Kastner, MIT

Trieste 2006

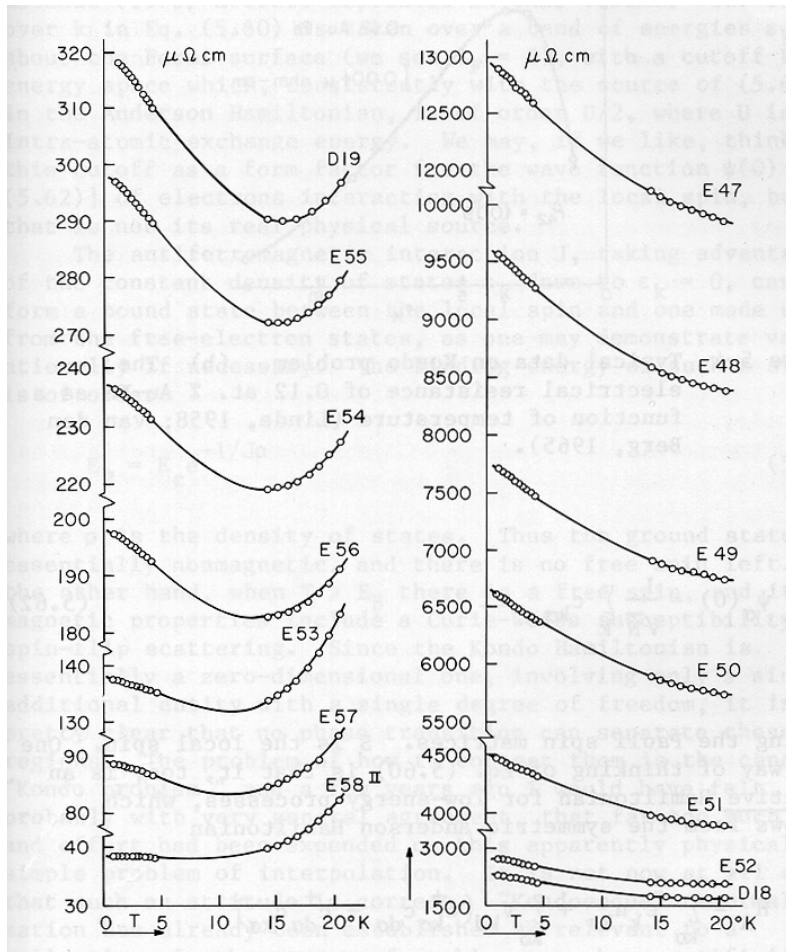
Outline

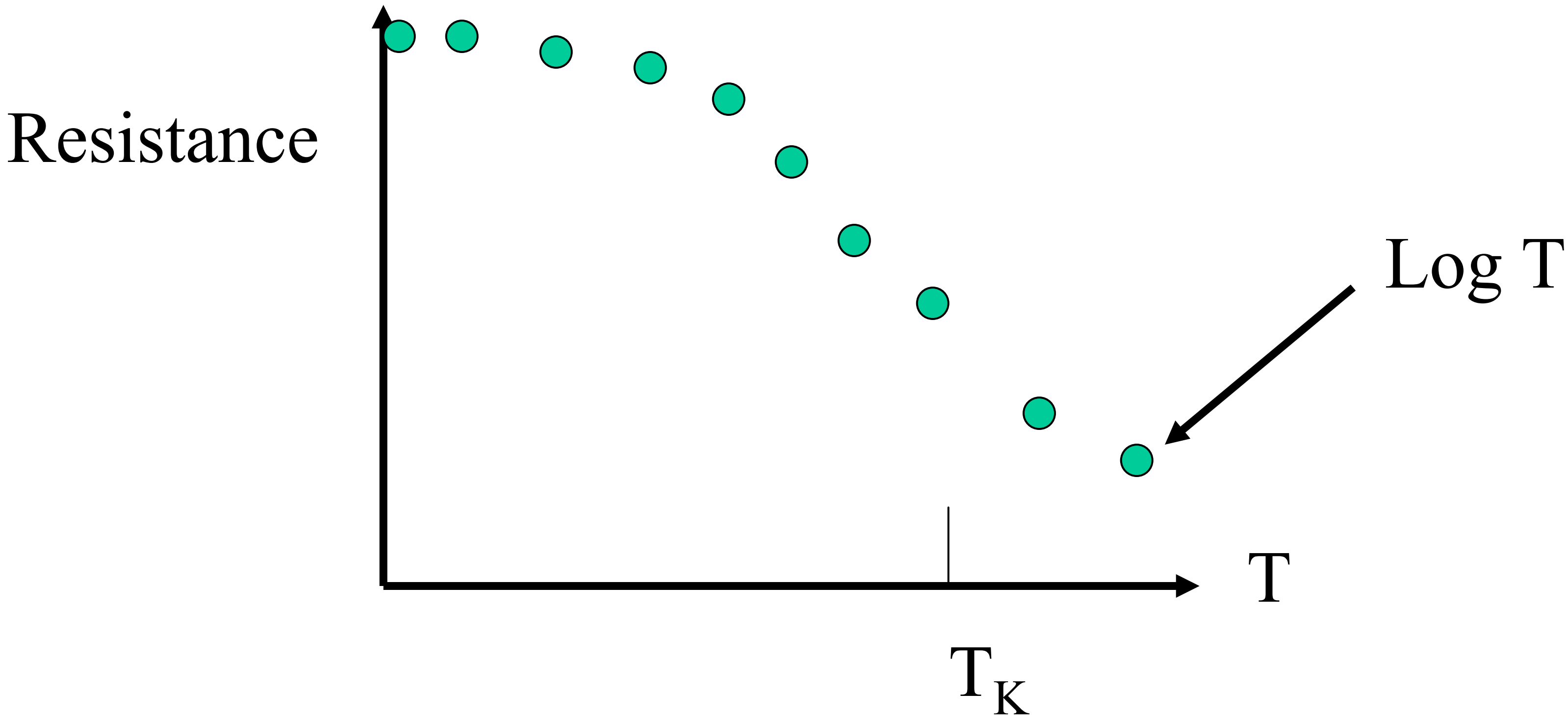
- Traditional Kondo effect
- Analogy between SET and an impurity in a metal
- Theoretical predictions for the Kondo effect
- Comparison with experiment
- Molecular Electronics

Review
M. A. Kastner and D. Goldhaber-Gordon
Solid State Commun.**119**, 245 (2001)

Traditional Kondo Effect

Increasing magnetic impurities



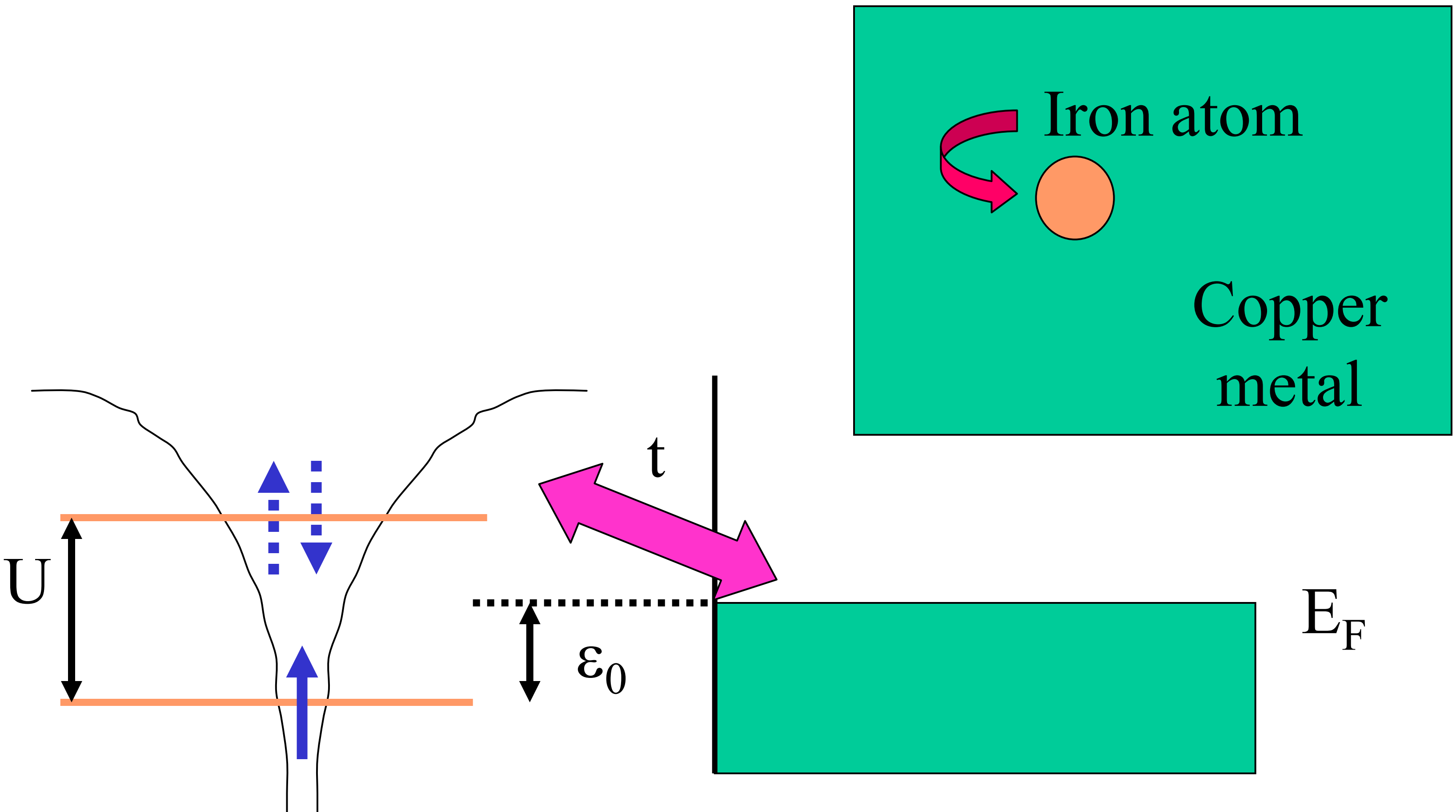


$T > T_K$ → Free spin

$T < T_K$ → Non-magnetic

Kondo problem: how to connect two regions of different behavior

Anderson Model



(Kondo described the problem in terms of the exchange interaction between spins, which depends on t, U and ε_0)

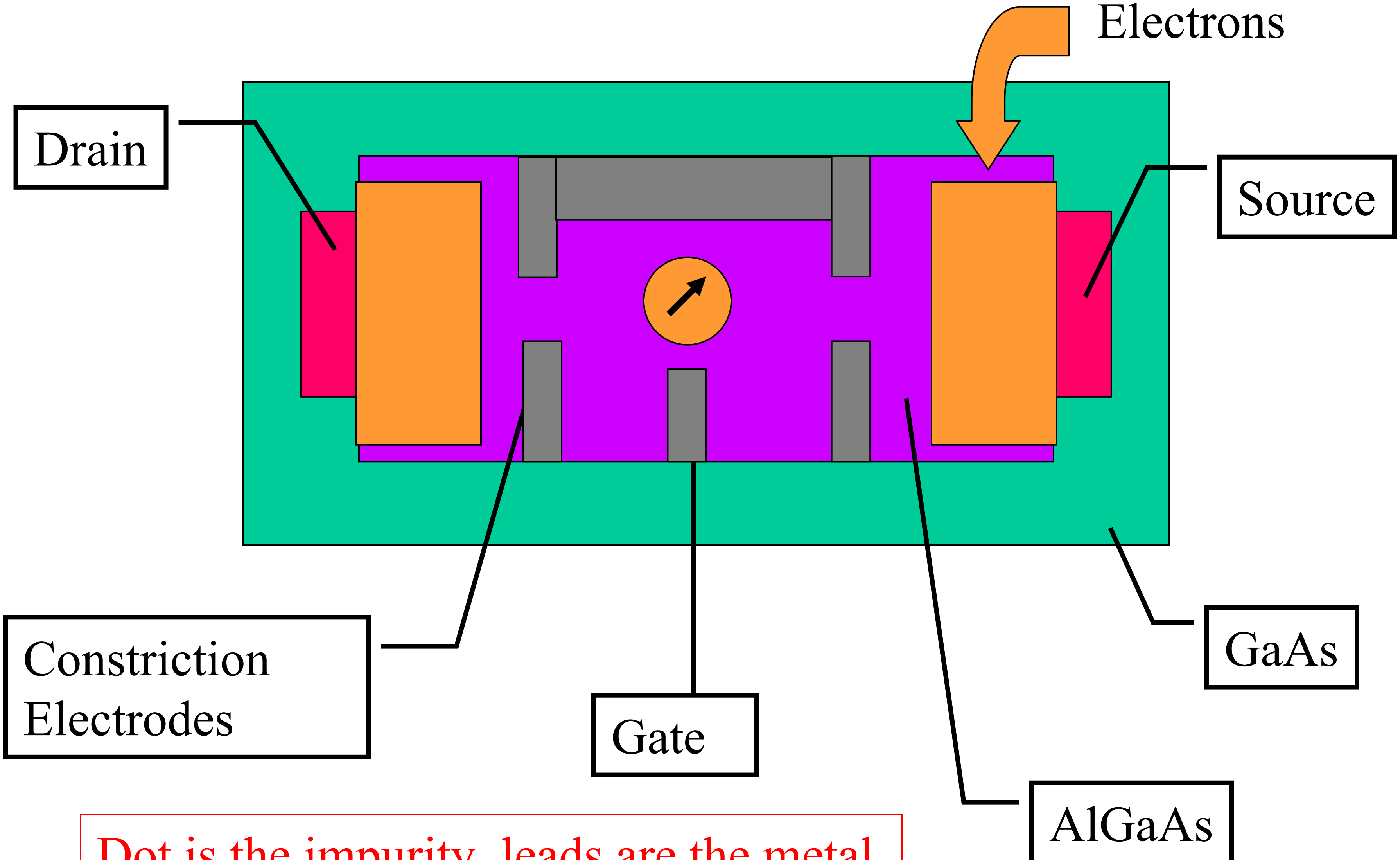
A **GREAT** Physics Problem

- Solution to the Kondo problem was one of the first applications of scaling theory to quantum many-body physics.
- Solution was one of the first applications of renormalization-group theory

Weaknesses of Conventional Kondo Systems

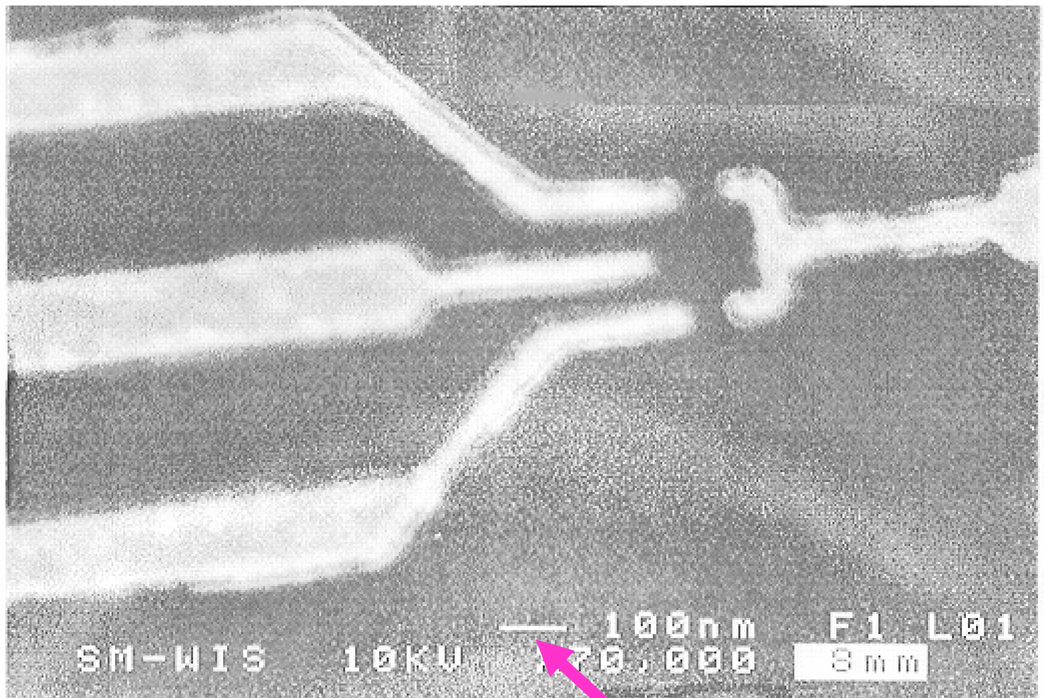
- With natural atoms the dependence on parameters (ε_0, t, U) could not be tested.
- Nonequilibrium Kondo phenomena could not be studied.
- These can be done with SET's.

Single Electron Transistor



Dot is the impurity, leads are the metal.

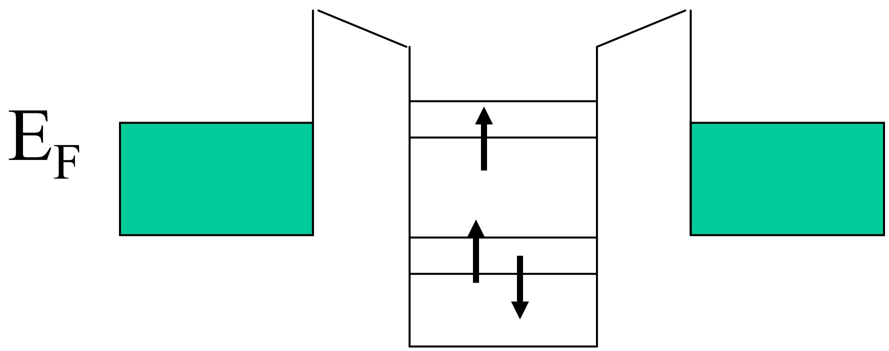
GaAs Single Electron Transistor at 100nm



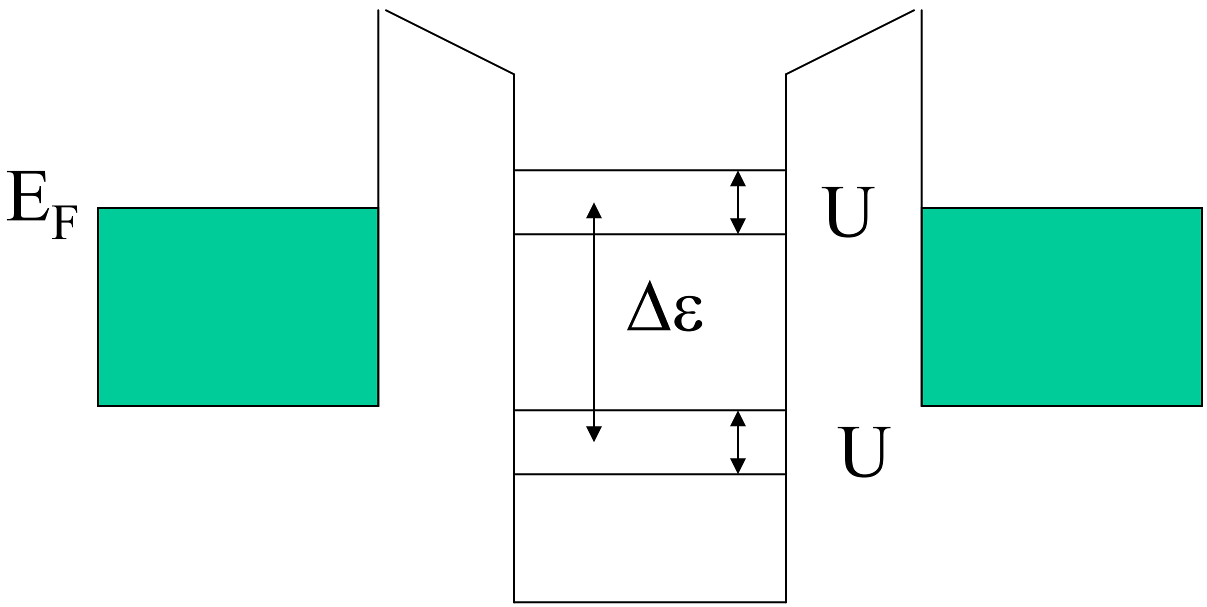
Devices made by Goldhaber-Gordon, Shtrikman and Mahalu, 1998

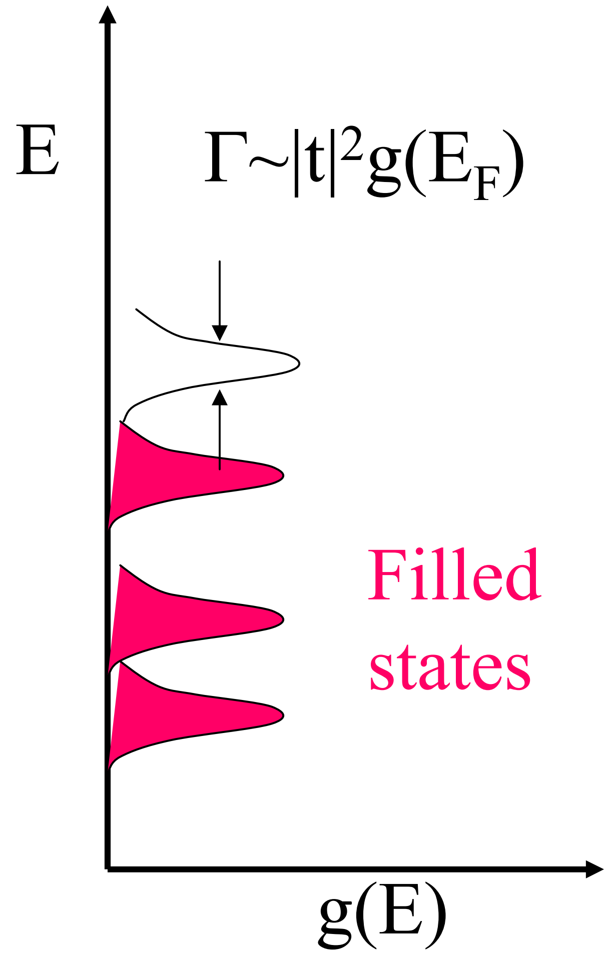
100nm = 1000Å

SET with Odd N



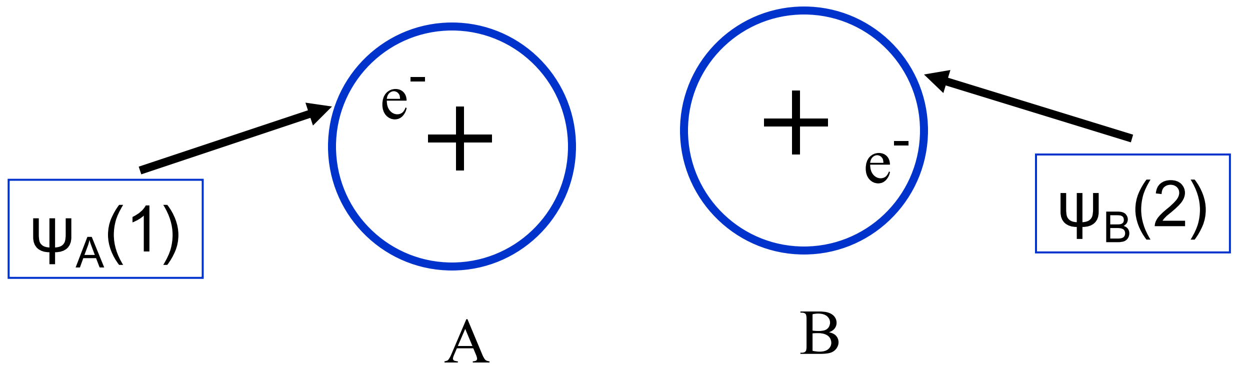
Tunneling Gives Levels a Width





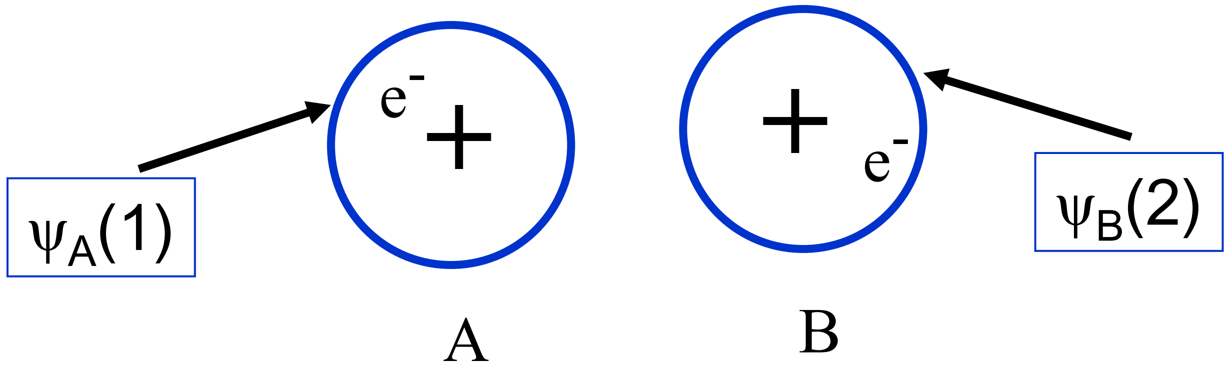
Single Particle
Density of States

Simplest Correlated (Entangled) System: H_2



Binding energy of one electron to a H atom is 13.6 eV, but binding energy of second electron is only ~0.6 eV. Thus, the energy U to put both electrons on the same atom is very large.

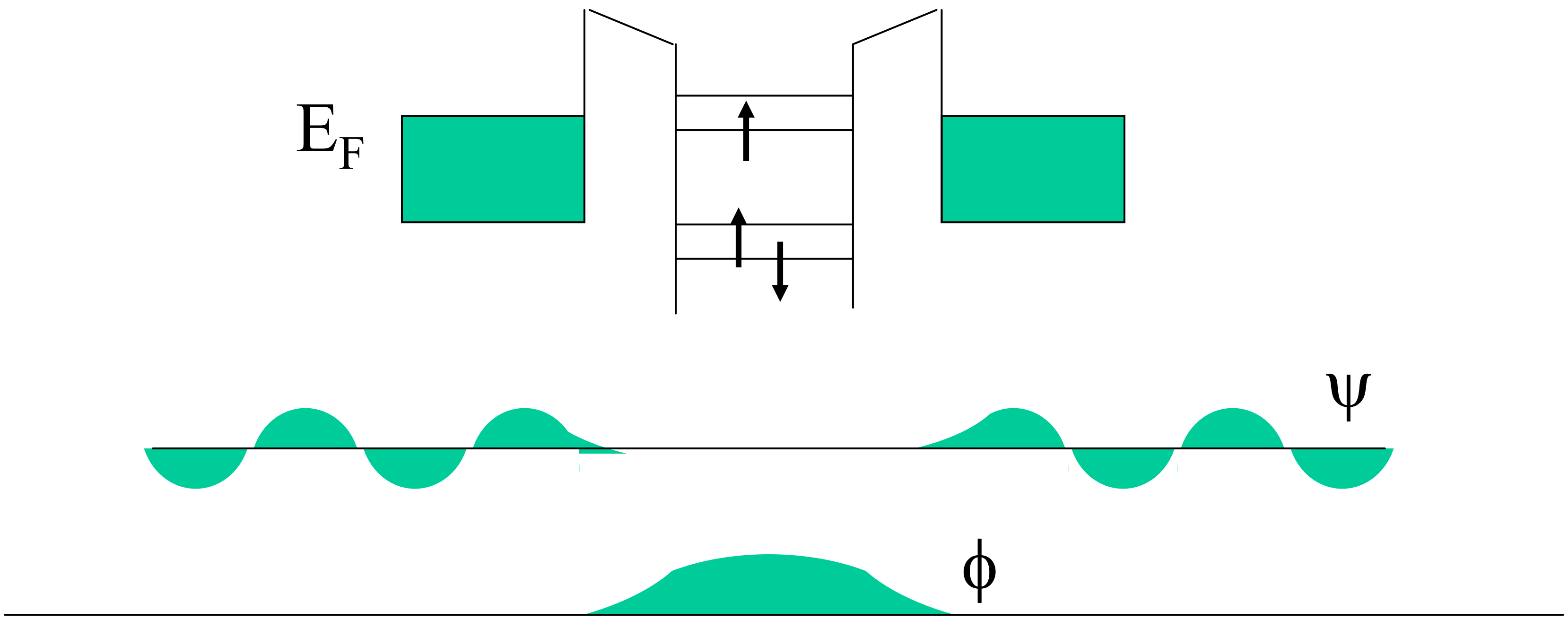
Heitler-London



Ground state: $\Psi(1,2) = [\psi(1)\ \psi(2) + \psi(1)\ \psi(2)]\ [|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle]$

The energy is lowered by exchange. The two spins are entangled in a singlet. The spatial wave function requires that the two electrons are not on the same atom.

Kondo "Chemical Bond"



$$\Psi = \{\phi(1)\psi(2) + \psi(1)\phi(2)\}\ [|\uparrow\downarrow> - |\downarrow\uparrow>]$$

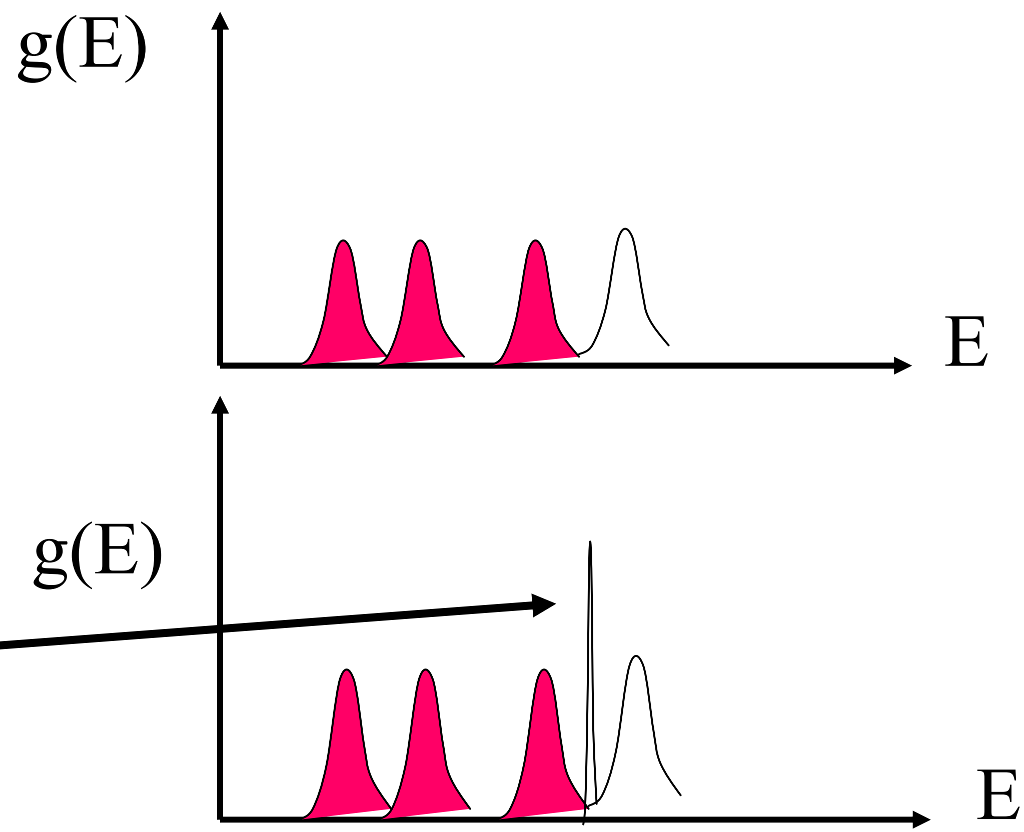
Entangled state: spin inside determines spin outside because the state is a singlet

Symmetric state$\Rightarrow$ perfect transmission $\Rightarrow$ $G = 2e^2/h$

Singlet forms below T_K

$kT_K < kT < \Gamma$

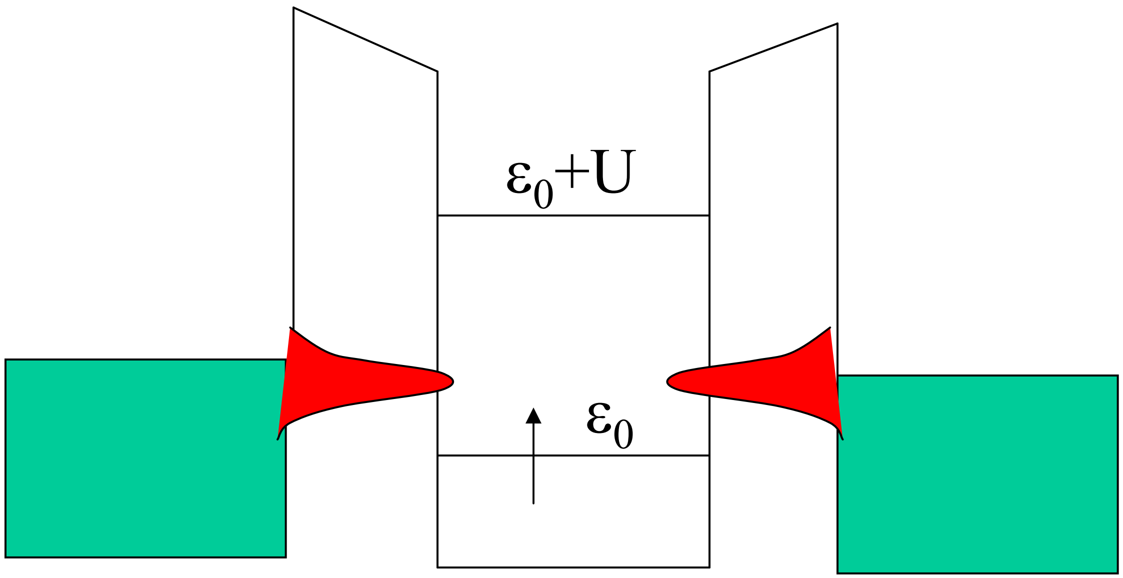
$kT < kT_K < \Gamma$



Kondo resonance at Fermi level for spin 1/2

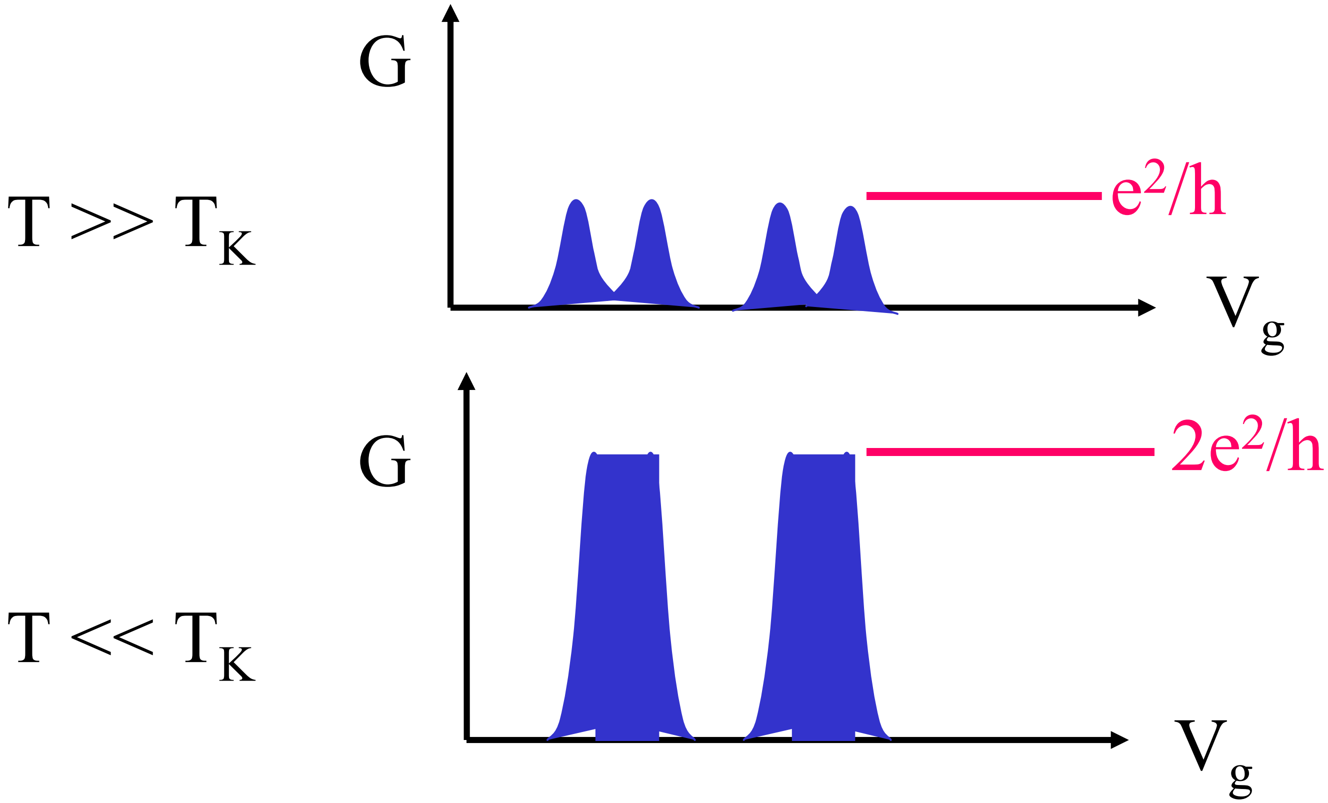
An entangled state of the spatial and spin degrees of freedom

Peaks in Density of States Enhance Tunneling



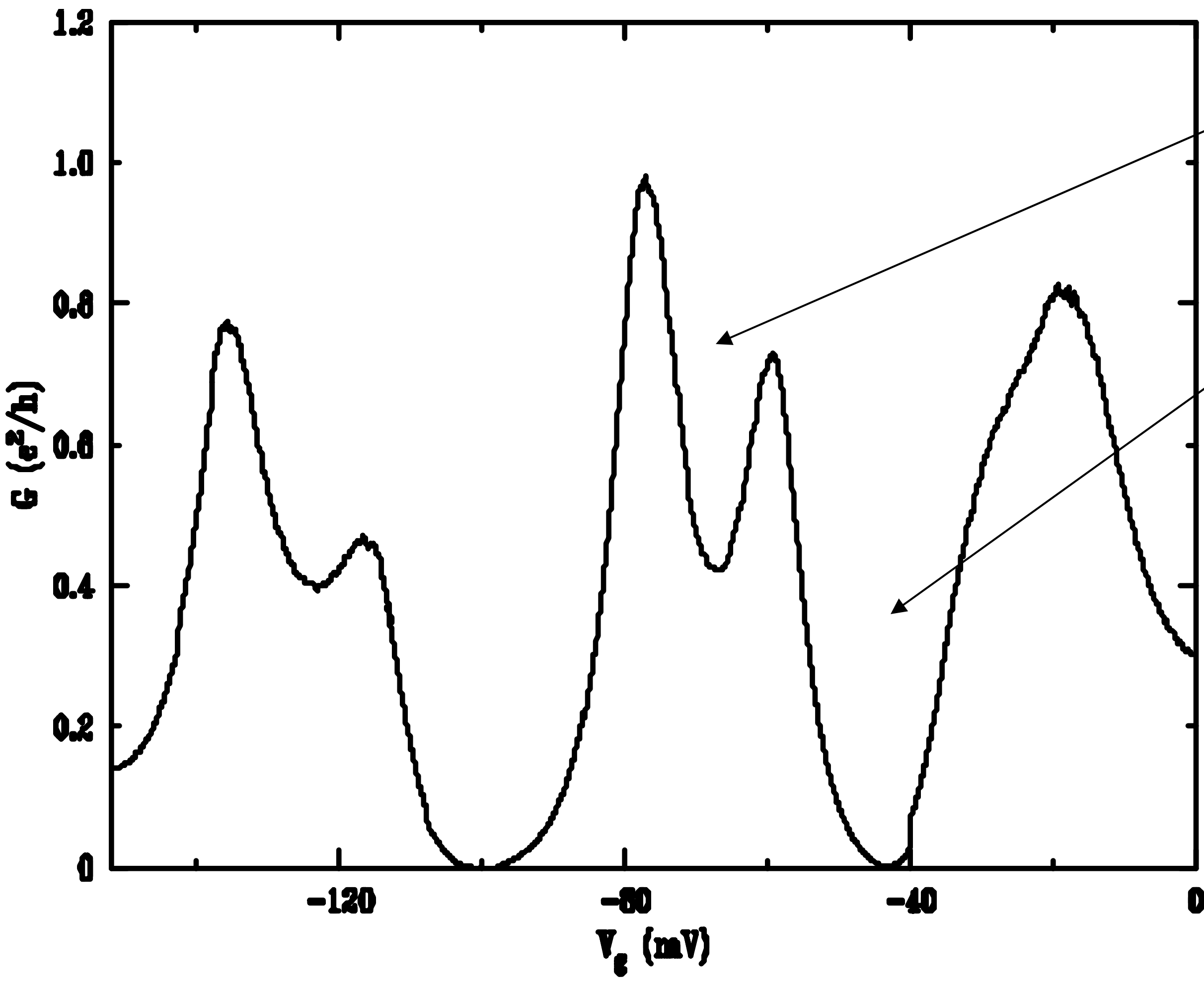
(Focus on one spatial orbital.)

Enhanced Conductance with Unpaired Spins



Forward scattering only ⇒ conductance instead of resistance increases at low T.

Paired Peaks

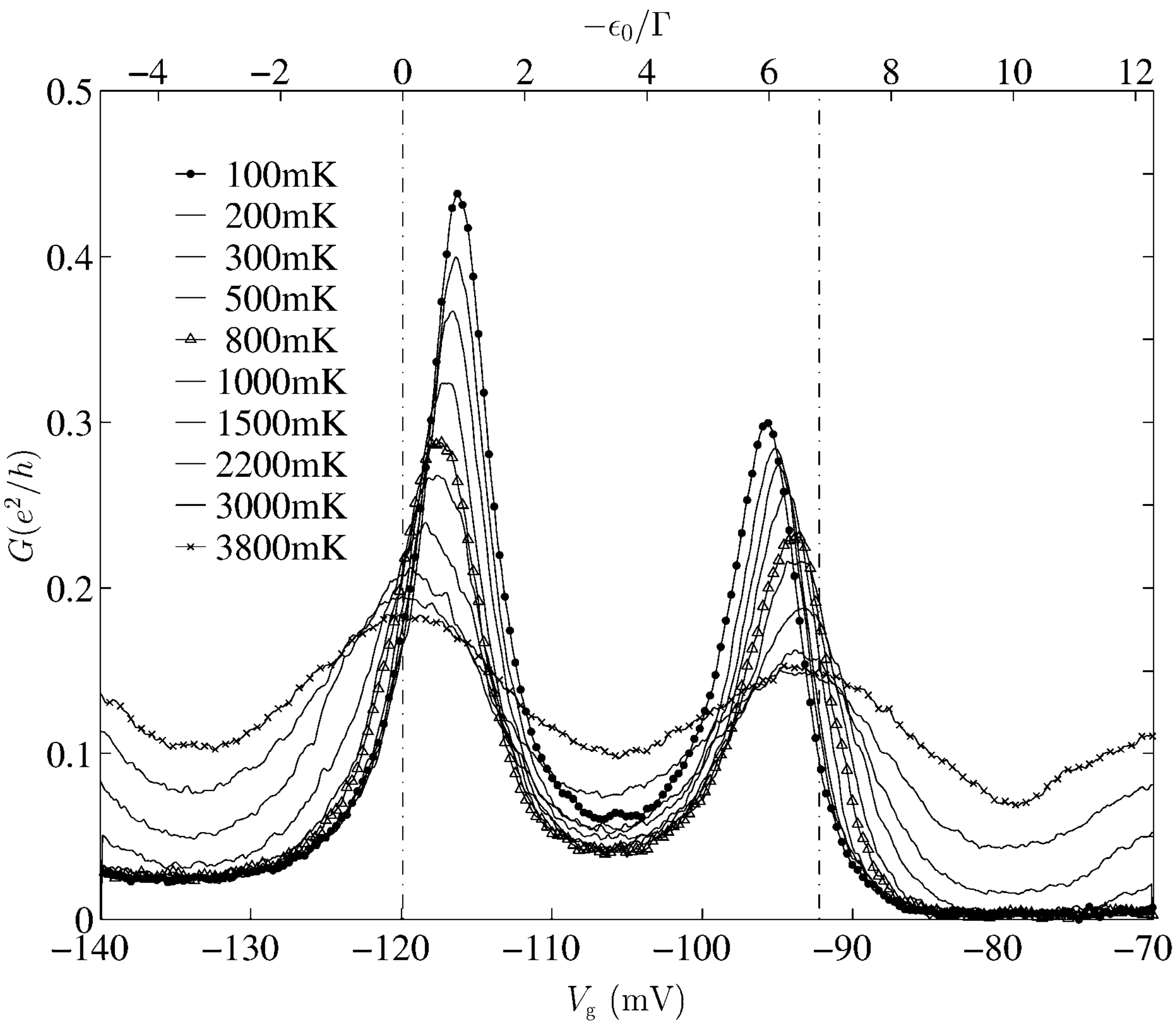


Odd N

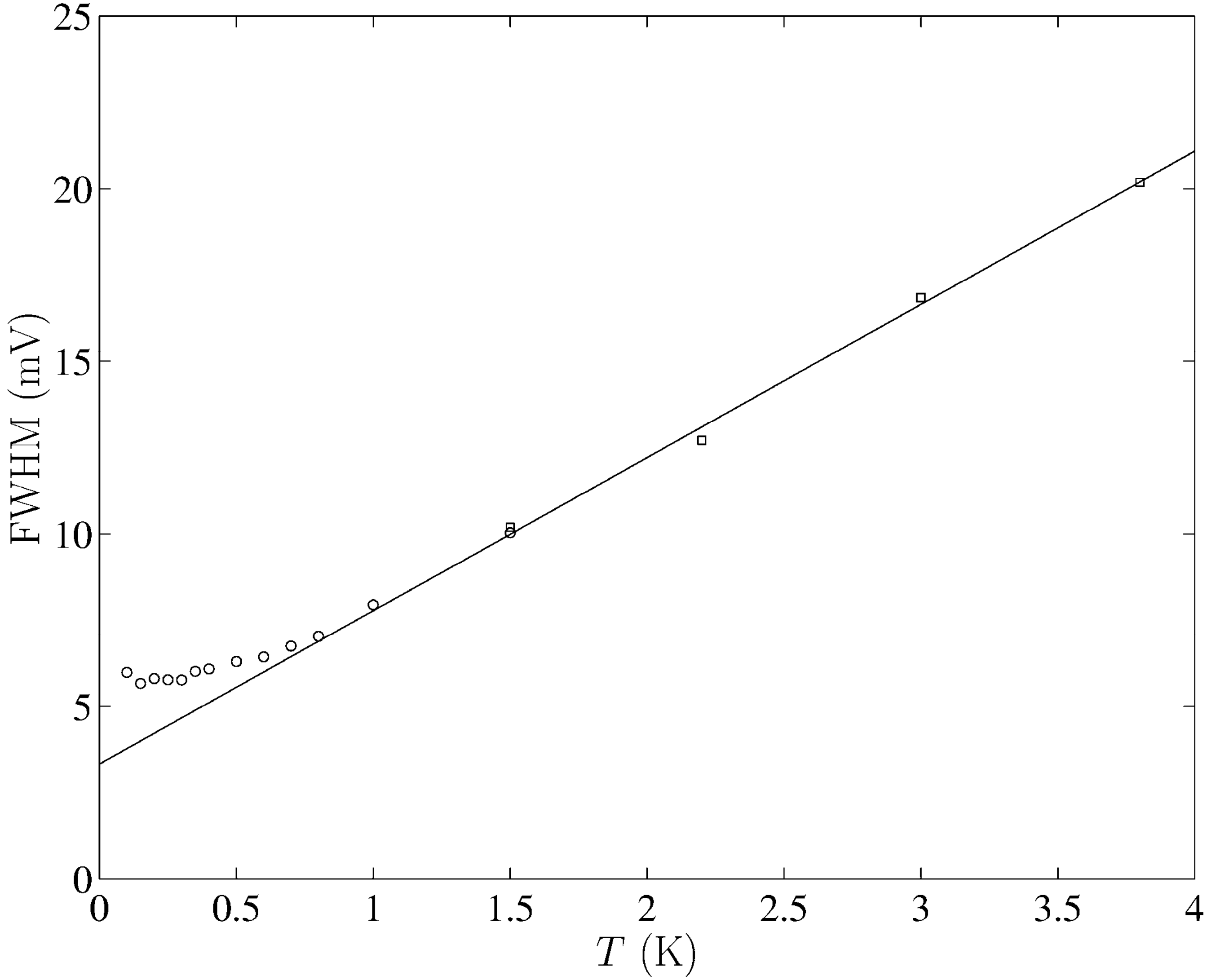
Even N

High conductance for odd N, low for even N.

Temperature Dependence



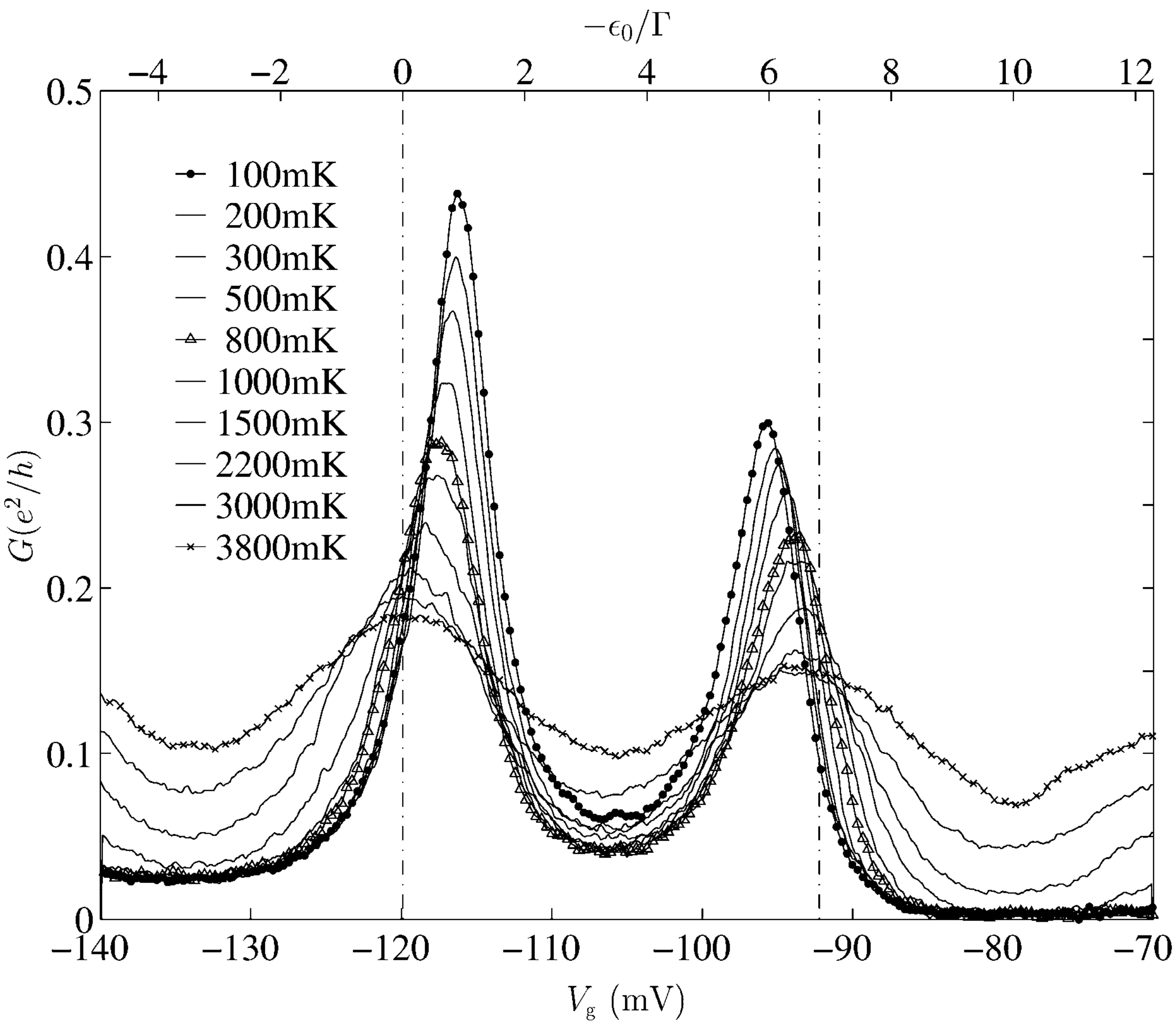
Determining Γ from peak width



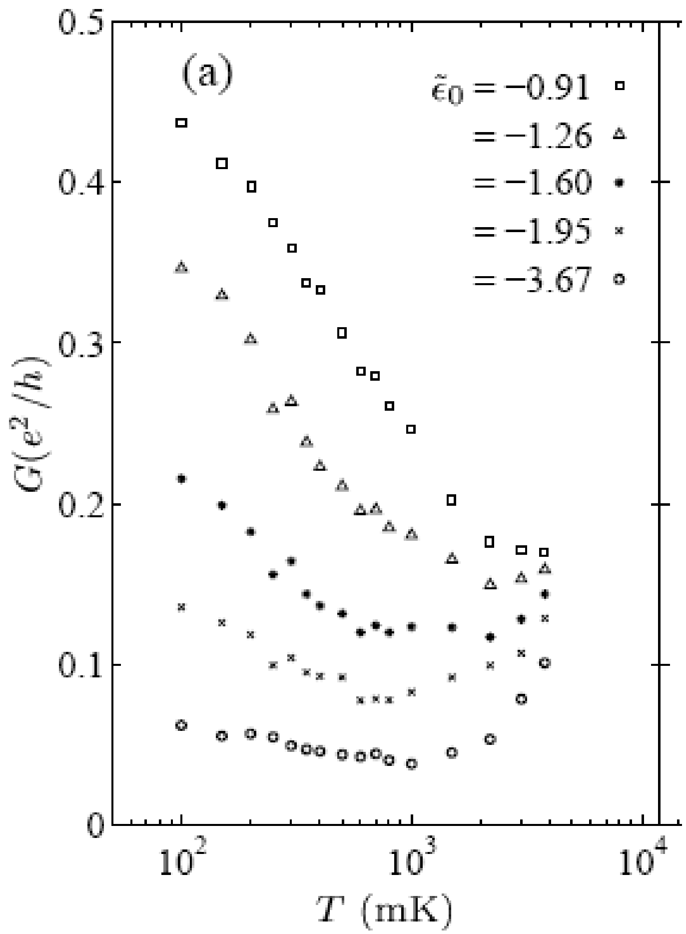
Slope gives conversion of voltage to energy.

T =0 intercept gives Γ

Temperature Dependence

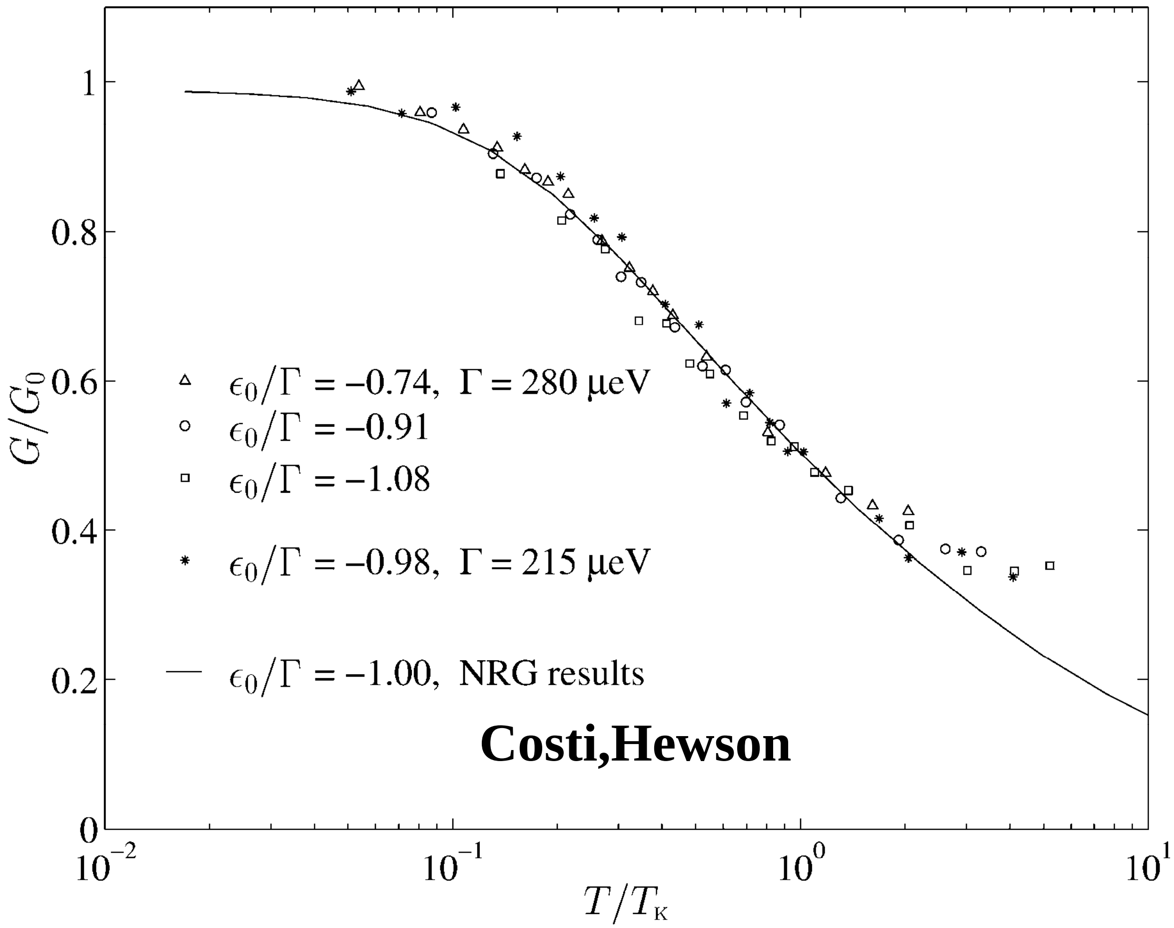


T Dependence at Fixed V_G

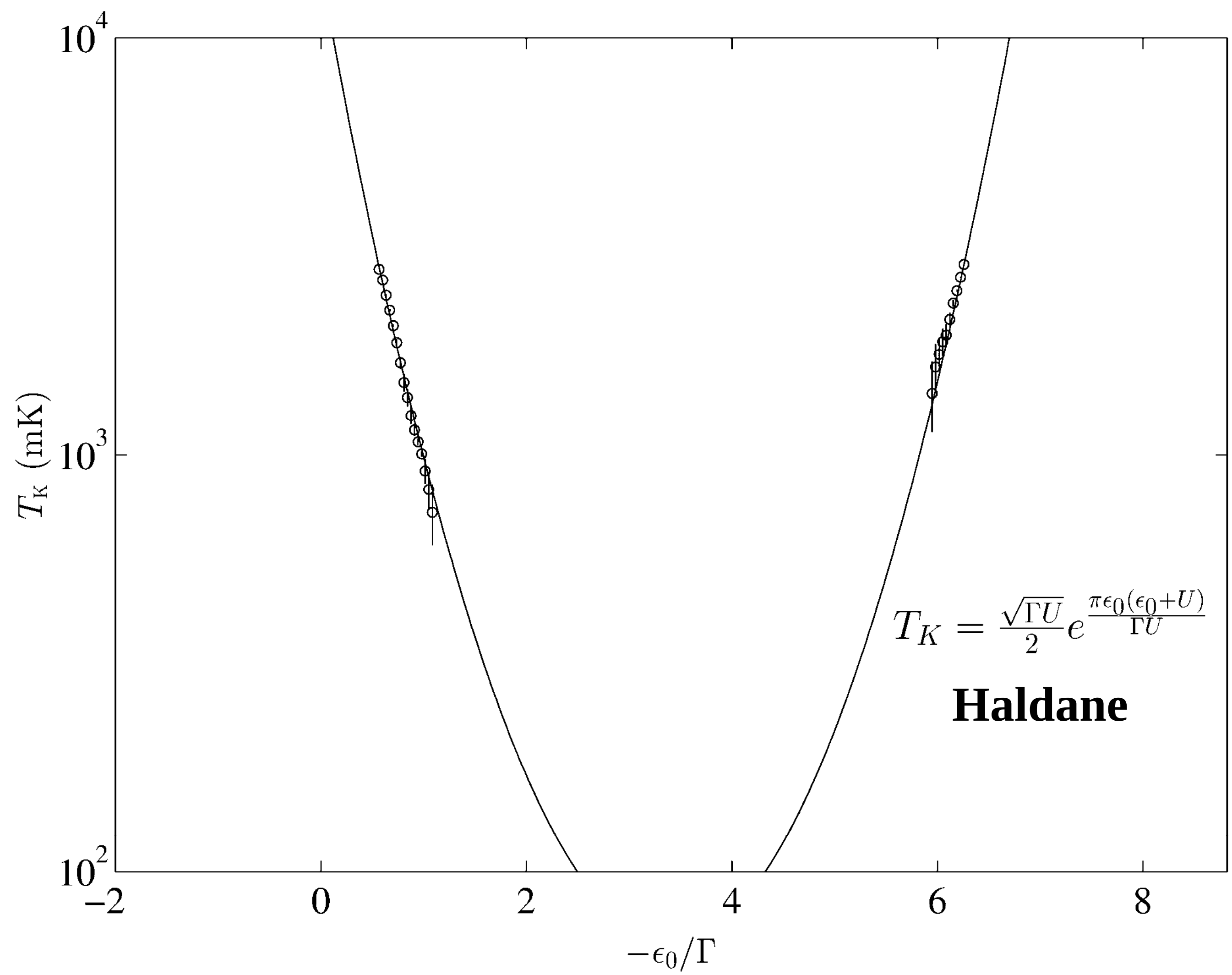


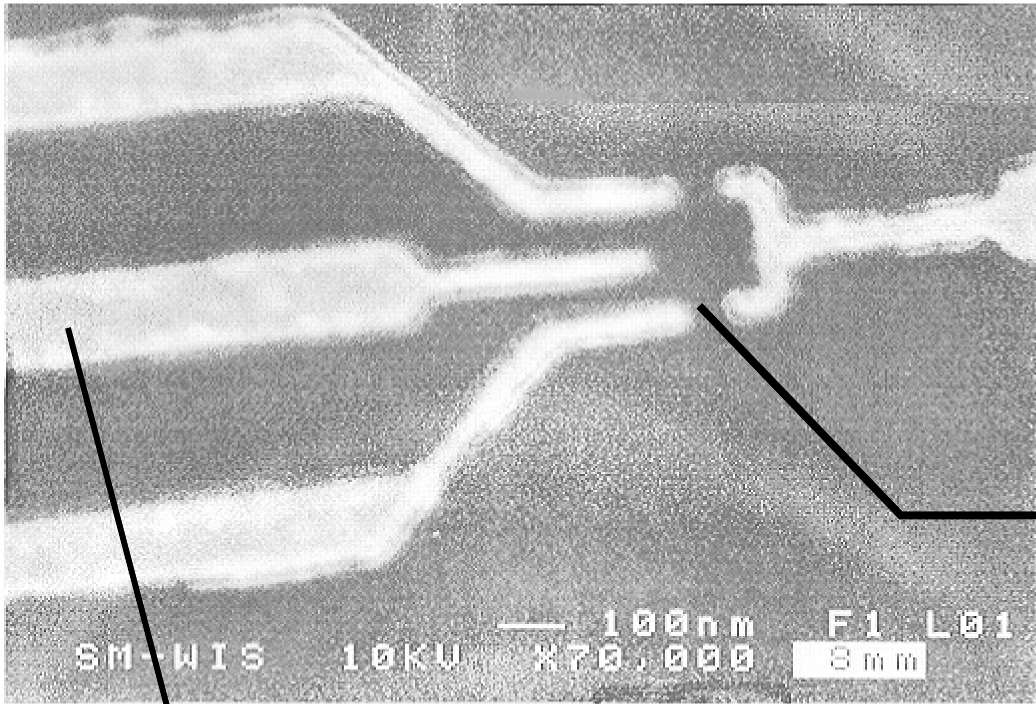
Note logarithmic decrease of conductance with T

Comparison with Renormalization Group Theory



Comparison with Scaling Theory





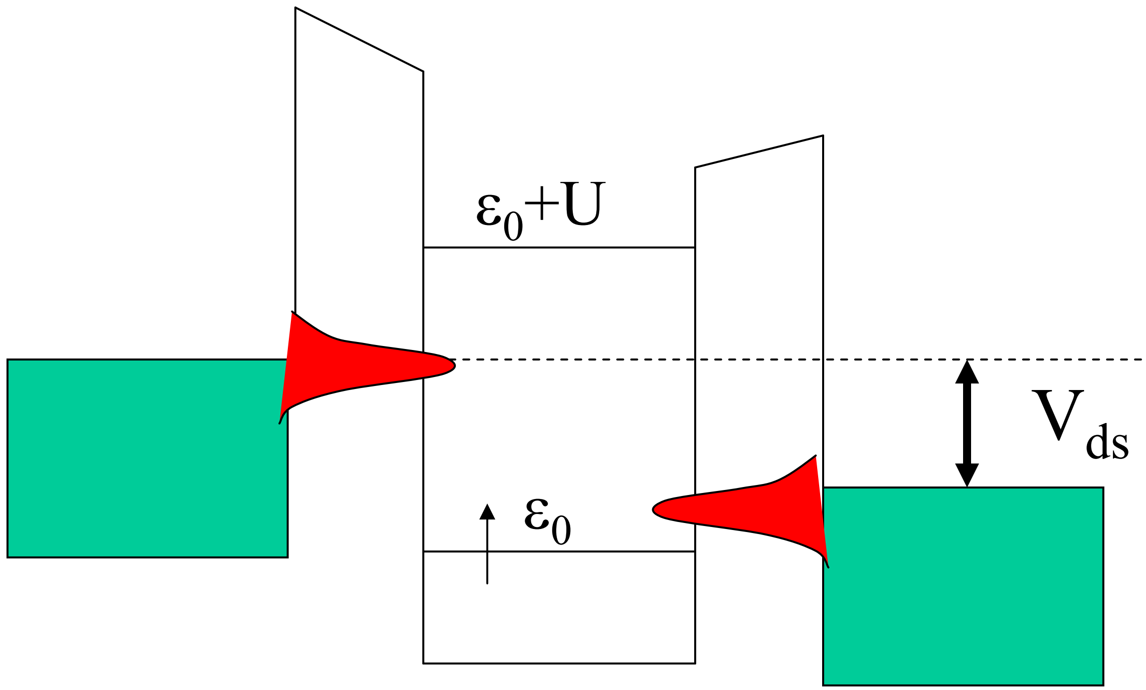
$\Gamma \sim |t|^2 g(E_F)$

$V_g \propto \varepsilon_o$

Anderson Hamiltonian:

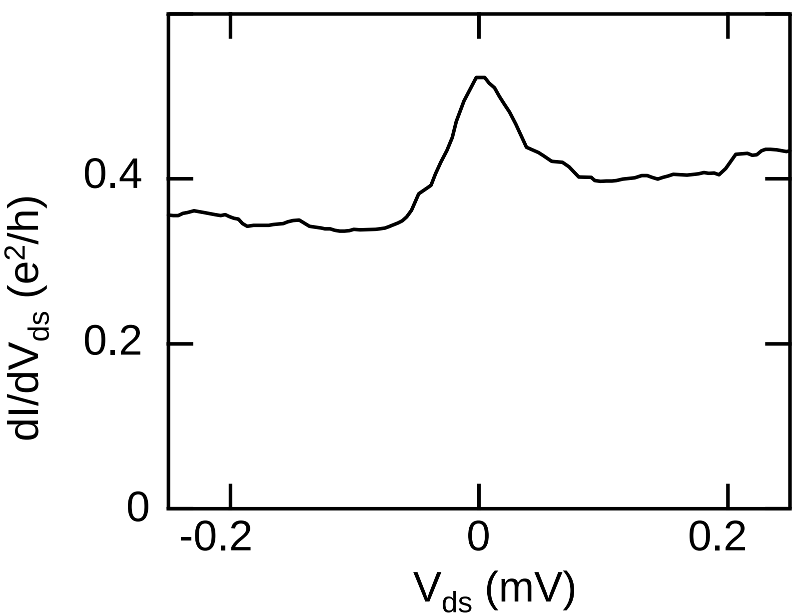
$$H = \sum_{k\sigma} \varepsilon_k a^{+}_{k\sigma} a_{k\sigma} + \varepsilon_0 a^{+}_{0\sigma} a_{0\sigma} + \sum_{k\sigma} (t\, a^{+}_{k\sigma} a_{0\sigma} + cc)$$
$$+ U n_{d\,\sigma} n_{d\,-\sigma}$$

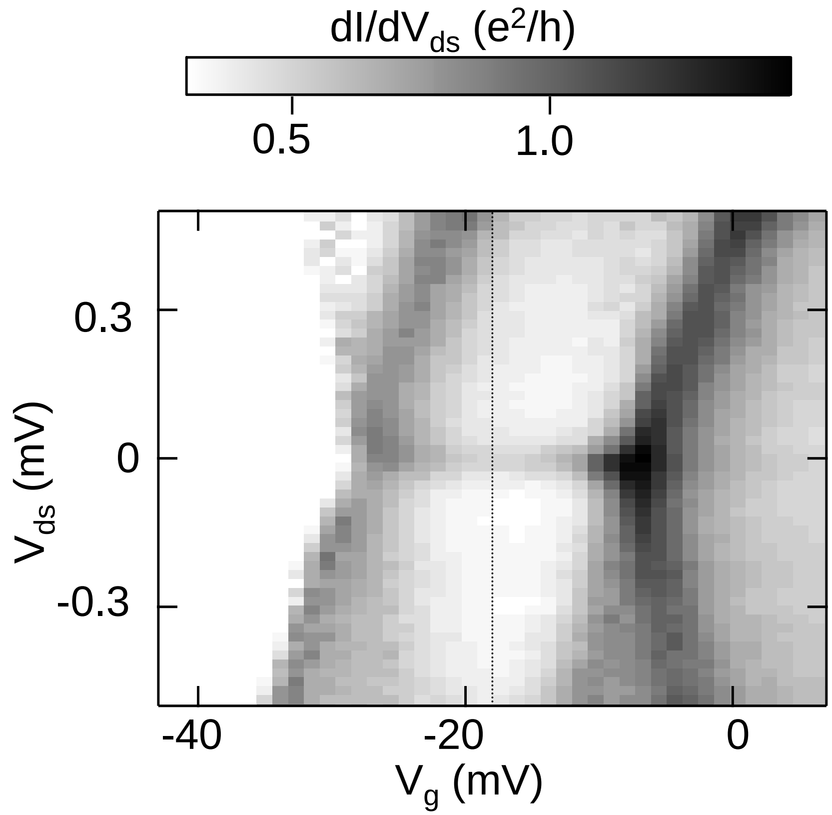
Bias Reduces Differential Conductance



Peak in density of states in left lead is shifted relative to that in right lead, so differential conductance decreases away from V_{ds}=0.

Kondo Effect in dI/dV

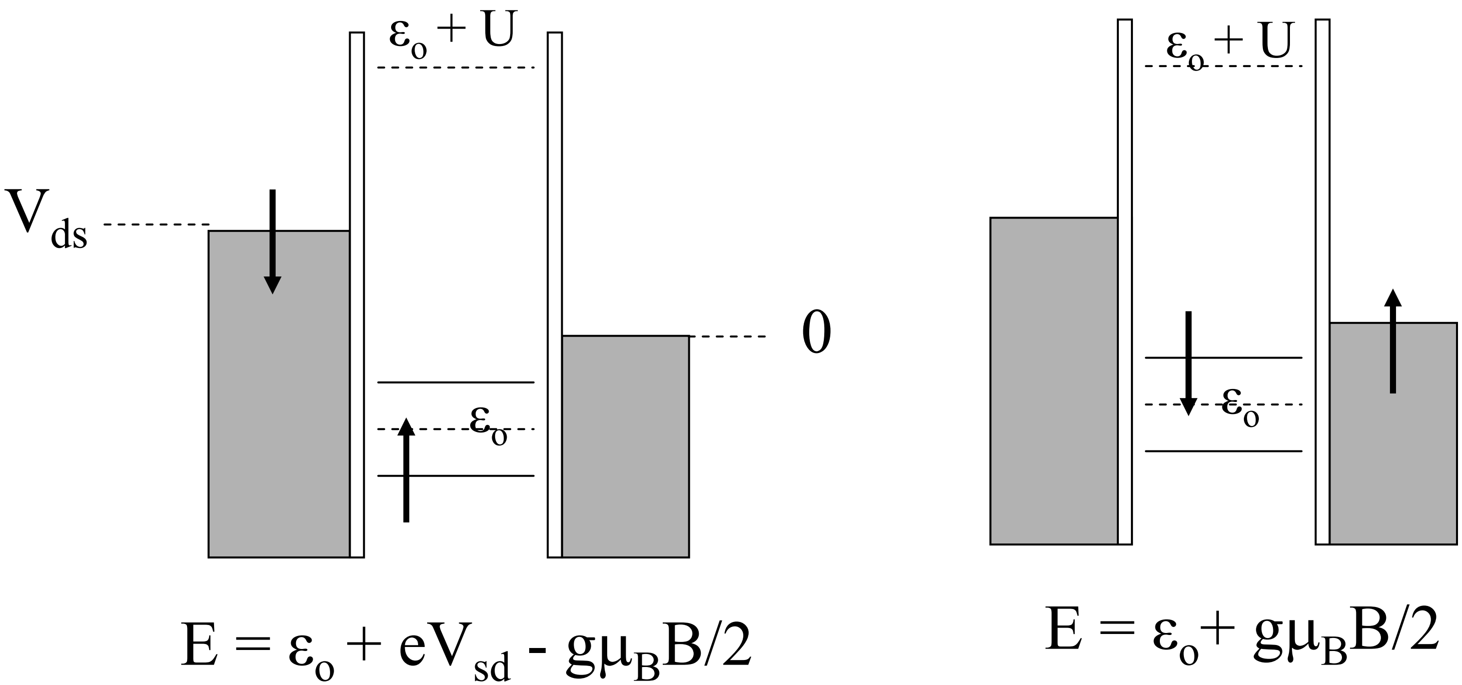




Sharp peak at zero bias because of overlapping resonances.

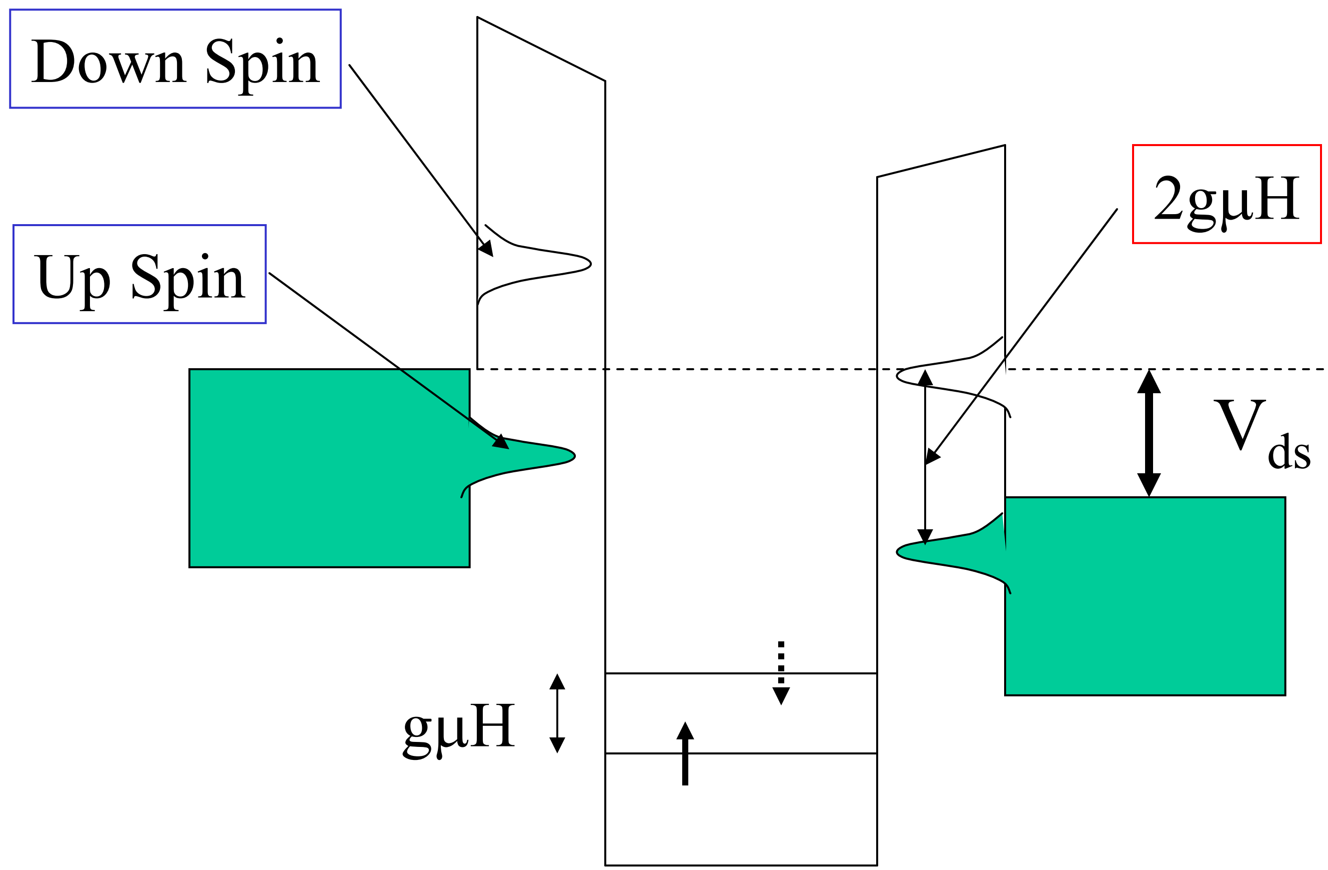
Kondo resonance for odd but not even number of electrons.

Kondo in Magnetic Field

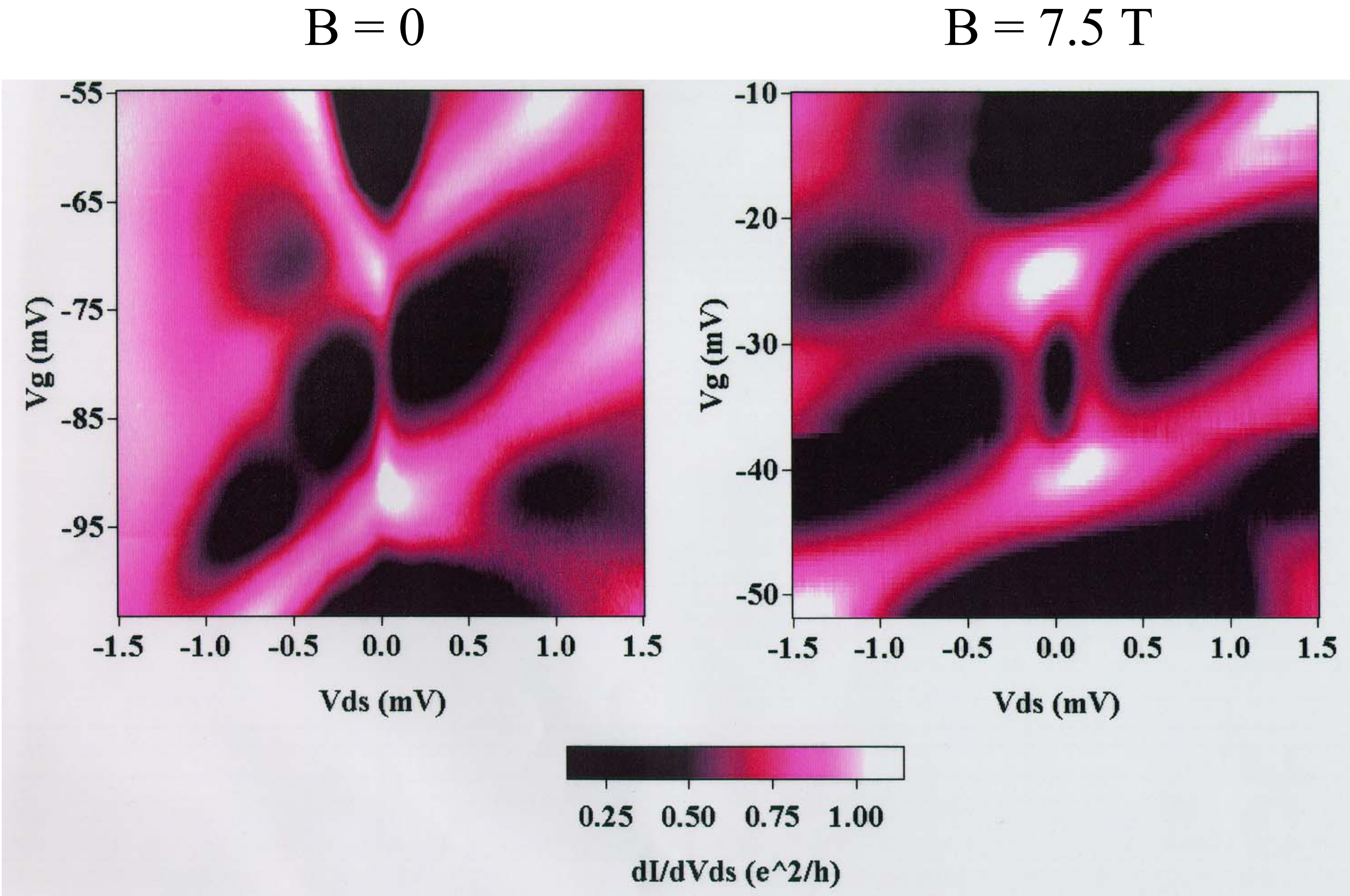


Bias destroys Kondo coupling, but applying a magnetic field with $g\mu_B B = eV_{ds}$ restores it!

Spectral Function in Magnetic Field



Magnetic Splitting of Kondo Resonance

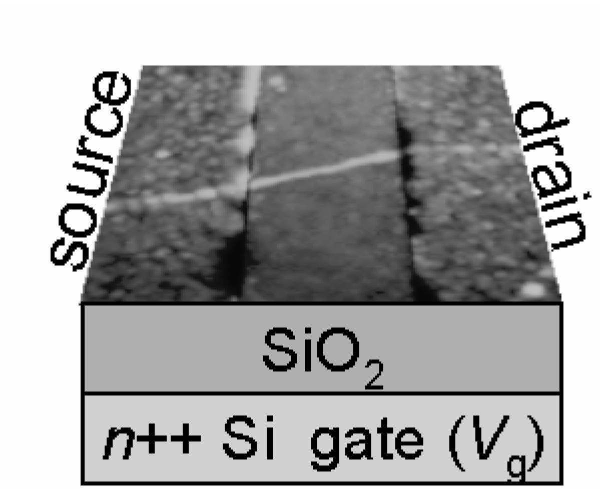


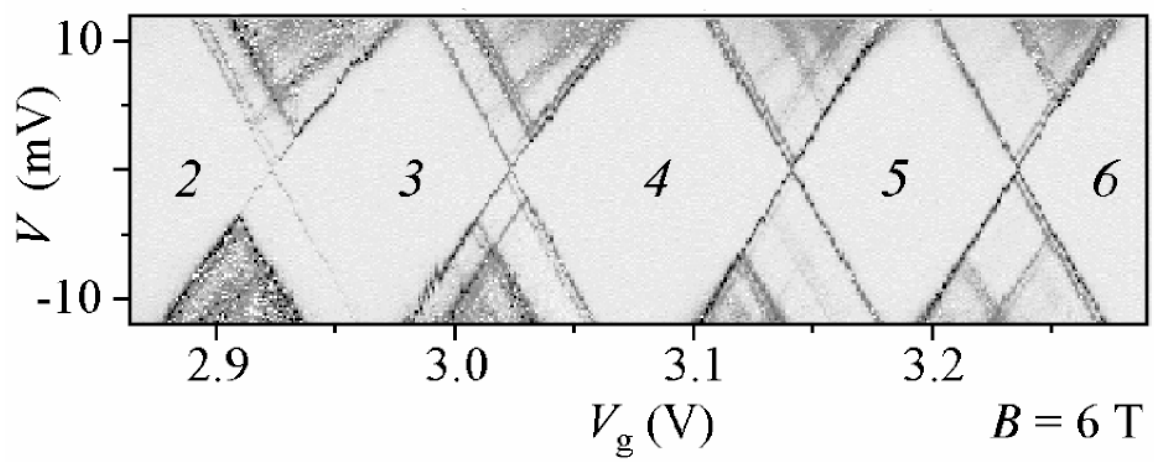
Note: Axes are rotated by 90°

Fancy Kondo Effects

- Triplet (two-stage) Kondo
  - NTT and Delft
- AC (Photon-Coupled) Kondo
- Kondo with additional degeneracies
  - Delft Nanotubes

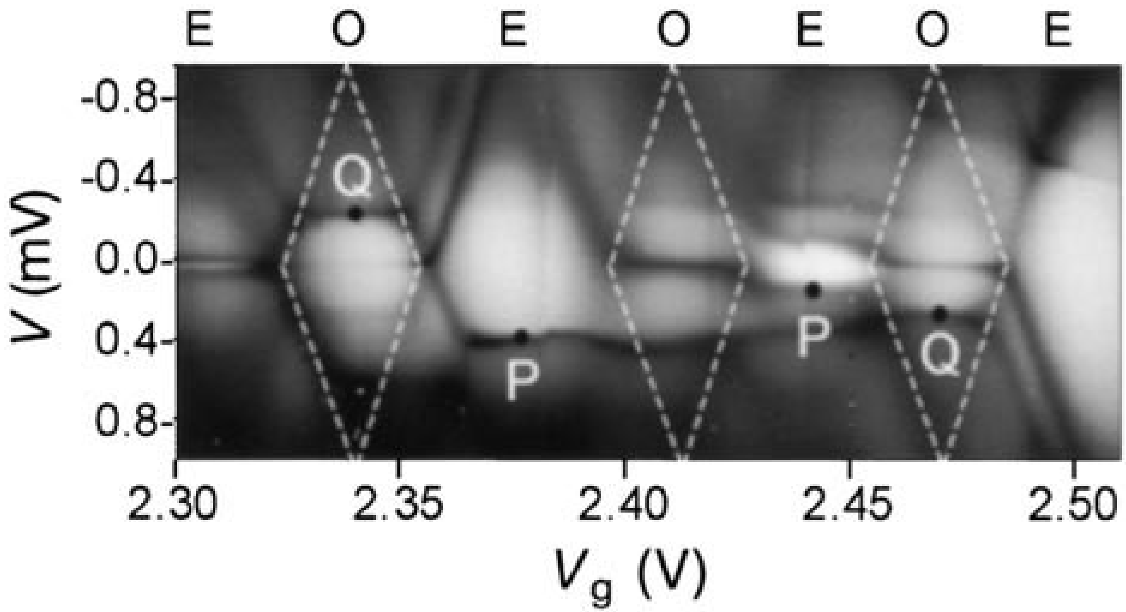
Carbon Nanotube SET





Cobden and Nygard, PRL **89**, 46803 (2002)

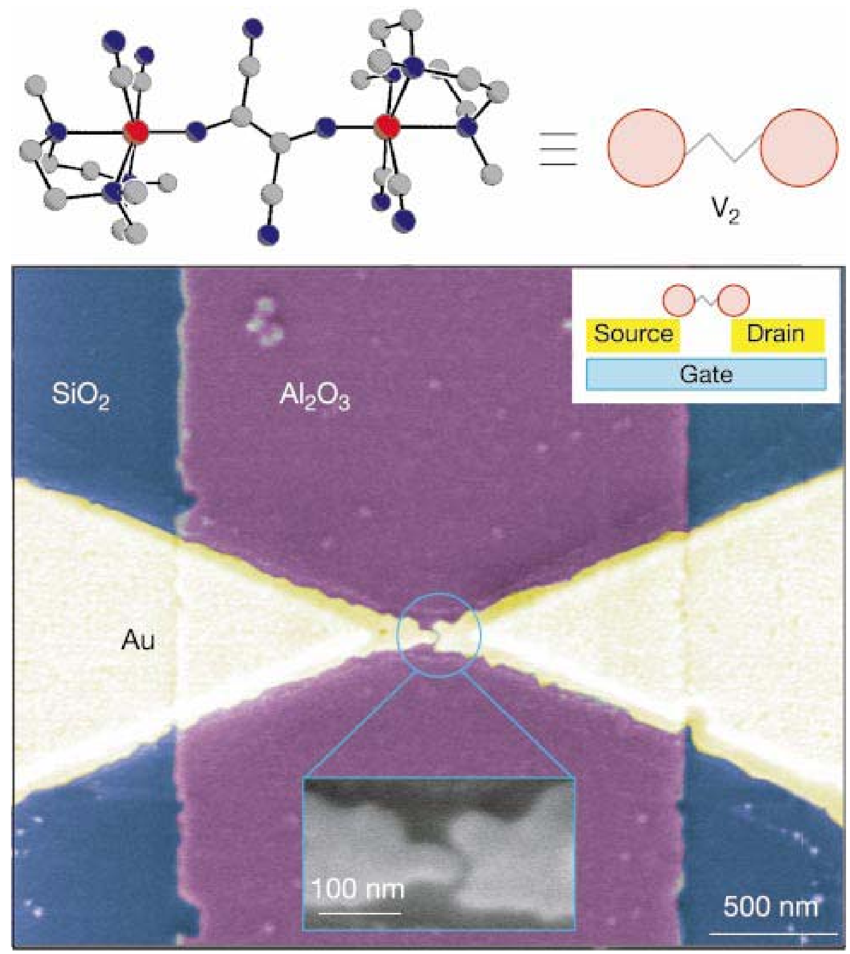
Kondo in Carbon Nanotube SET



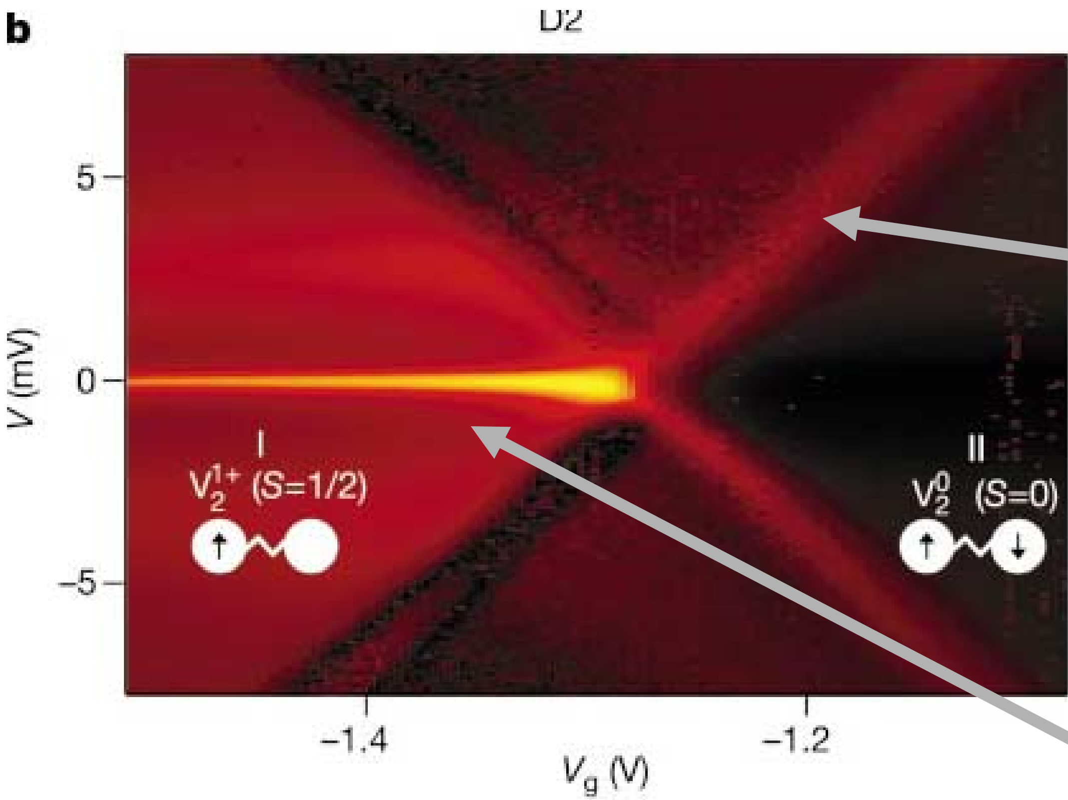
Nygard et al. Nature **408**, 342 (2000)

Single Molecule SET

Liang *et al.*,
Nature **417**, 725 (2002)



Kondo in Single Molecule SET



Coulomb charging threshold

Kondo

Conclusions

- SET is an analogue computer for the Anderson model—an artificial atom connected by tunable tunneling to metallic leads.
- We can study non-equilibrium as well as equilibrium Kondo phenomena.
- Kondo is important in physics of electronic devices at the nanometer length scale.