Non-linearities in quantum circuits

Serge Florens [Néel Institute - CNRS/UGA Grenoble]

"A gentle journey into not-so-gentle quantum many-body problems"

Organization of the lectures

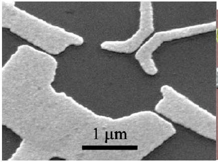
Superconducting nanocircuits

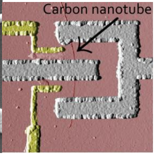
- Lecture 1 : i) General circuitry ; ii) From Josephson junctions chains to spin-boson model
- Lecture 2 : i) Scattering theory with dynamical emitter ; ii) Frequency conversion beyond RWA ; iii) Renormalization from many-body entanglement ; iv) Many-body inelastic scattering theory

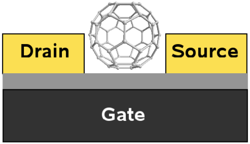
Metallic nanocircuits

- Lecture 3 : i) Anderson and Kondo models ; ii) DC Transport ; iii) Non Fermi liquid extensions
- Lecture 4 (closing the loop) : i) Boson-fermion connection in first quantization (using quantum optics concepts) ; ii) Insights into the Kondo wave-function ; iii) Emergent Majorana fermions

Various quantum dot systems



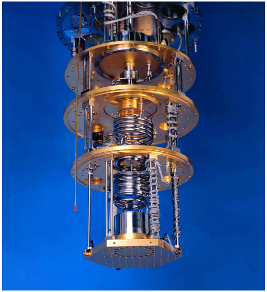




Rules of the game

What kind of experimental system does one need ?

- 1. Good tunability
- 2. Reasonable energy scales

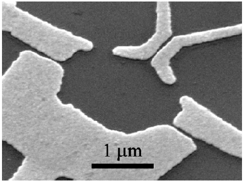


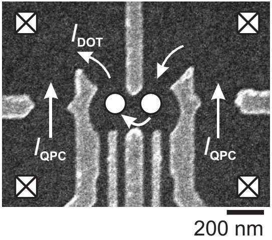
Reminder : Helium dilution fridges work for $T \gtrsim 20$mK
(1K $\simeq$ 0.1 meV $\simeq$ 20 GHz)

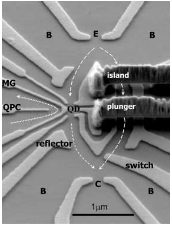
Semiconducting quantum dots

- System : 2D electron gas (GaAs, InAs, S, Ge...)
- $++$ great tunability and scalability by electric gates
- $--$ small charging (Coulomb) energy :
  - $U = 40\text{K}$ for spin qbit experiments
  - $U < 10\text{K}$ for Kondo experiments

    Ultra-small Kondo temperature $\Longrightarrow T_K < 300\text{mK}$

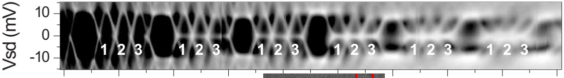


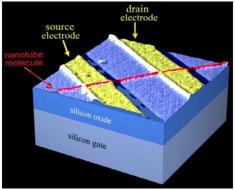


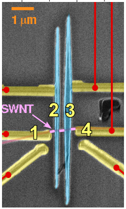


Carbon nanotube quantum dots

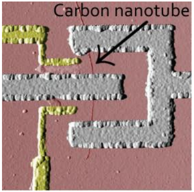
- System : 1D carbon molecule with gates on top
- ++ tunable & hydrid : metal, ferro or superconducting leads
- + intermediate charging energy $U = 10K - 100K$
- ± orbital degeneracy : SU(4) vs SU(2) physics







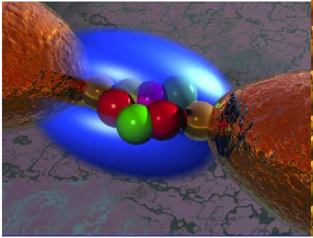
Ferro [ENS-Paris]

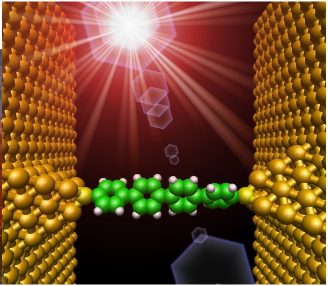


SQUID [Grenoble]

Molecular devices

- System : nanometer size molecule inbetween metal contacts
- - limited tunability (no local gates, but some surprises...)
- $++$ more tunability from chemistry
- $--$ lack of reproducibility
- $++$ very large energy scales $U = 1000K - 10000K$
  $\Longrightarrow$ good playground for Kondo physics !

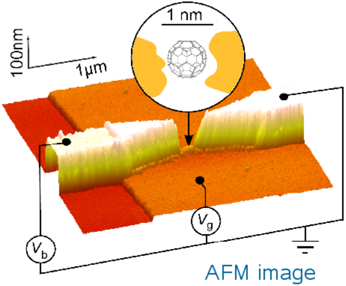


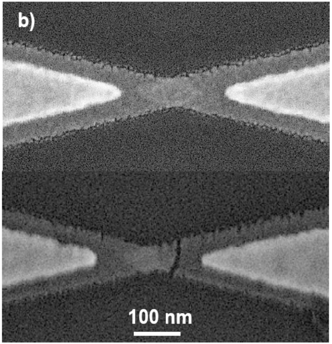


Molecular electronics HOWTO : electromigration

Basic idea :

- E-beam lithography cannot reach single molecule size
- Solution : open a metal junction via electromigration
- Back gate : molecular transistor

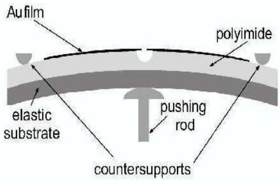




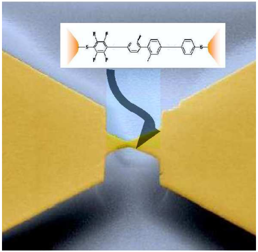
Molecular electronics HOWTO : break junctions

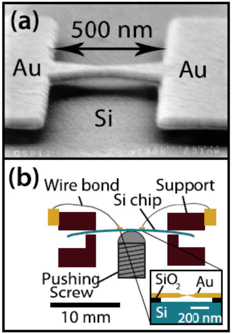
Basic idea :

- Solution : open mechanically a metal junction
- No back gate, but strain changes tunnel couplings



J. v. Ruitenbeek, Leiden '95





[D. Ralph (Cornell)]

Overview of regular (screened) Kondo effect

Kondo chronology

Textbook stuff in solid state physics :

- 1934 : observation of resistance anomalies in metals
- 1964 : Kondo proposes his model
- 1975 : Wilson solves the “Kondo problem”

The Kondo revival :

- 1988 : Glazman-Raikh & Ng-Lee predict Kondo anomalies in quantum dots
- 1998 : First observation by Goldhaber-Gordon & Kouwenhoven
- Now : it is routinely observed in all kinds of nanostructures !

Some good references to dig deeper :

- Coleman : “Heavy electron systems” cond-mat/0206003
- Glazman&Pustilnik : “Les Houches 2004” cond-mat/0501007

The essence of the Kondo problem

Question : what becomes a magnetic atom in a metal ?
Experimental fact : magnetic impurities not always show a moment

Simplified atom : $H_U = \epsilon_d(n_{d\uparrow} + n_{d\downarrow}) + U n_{d\uparrow} n_{d\downarrow}$
$\Rightarrow$ Moment stabilized by U, high energy excitations

Resonant level : $H_t = \sum_{k\sigma}[\epsilon_k c^\dagger_{k\sigma} c_{k\sigma} + t d^\dagger_\sigma c_{k\sigma} + h.c]$
$\Rightarrow$ No moment, resonant level at low energy

Anderson model : $H = H_U + H_t$
$\Rightarrow$ Competition localized/delocalized

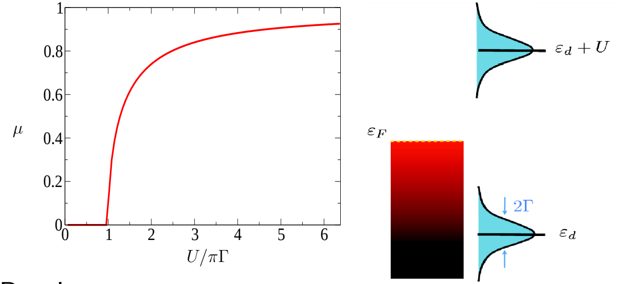
Captures the physics between the two above limits

On the board : Atomic limit $t = 0$

Local moment formation : $t \neq 0$ ($\epsilon_d = -U/2$ here)

Mean field theory [Anderson 1950] :

Assumes a frozen moment $\mu = \langle n_{d\uparrow} - n_{d\downarrow} \rangle$

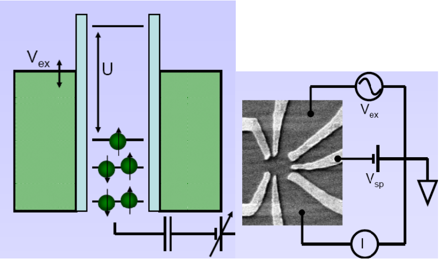


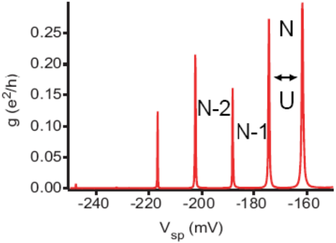
Results :

- Local moment $\mu \neq 0$ for $U > \pi\Gamma = \pi t^2 \rho_0$
  $\Rightarrow$ need relatively closed quantum dot
- Broadened high energy features
  (Hubbard bands $\Leftrightarrow$ Coulomb blockade edges)

Coulomb blockade : weakly open quantum dot

Conductance vs. gate :

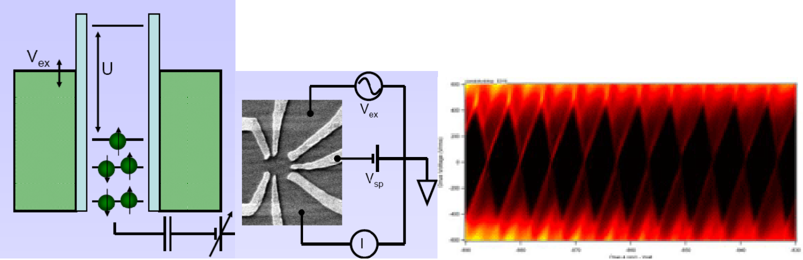




- Charging energy dominates : $H = \frac{U}{2}(Q_{\rm dot} - \alpha e V_g/U)^2$
- Frozen charge fluctuations : transport suppressed
- Conductance has peaks at charge degeneracy

Coulomb blockade : weakly open quantum dot

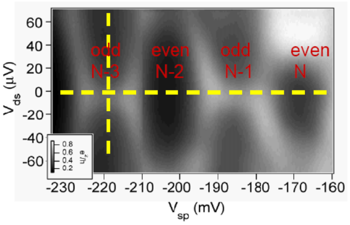
Conductance vs. gate and bias :

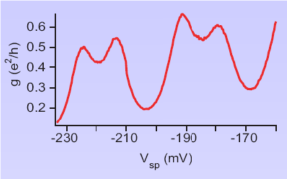


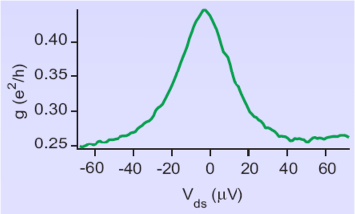
- Coulomb diamonds with low conductance
- Totally generic observation !
- Single charge transistor

Coulomb blockade suppression : Kondo anomaly

Moderately open quantum dot : [data from Goldhaber-Gordon group]



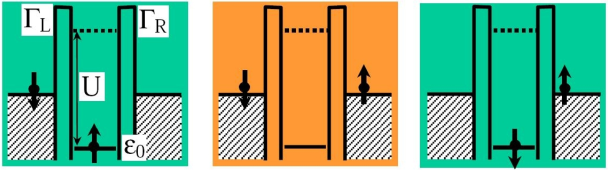


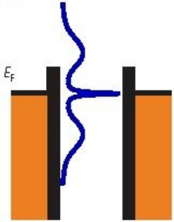


- Zero-bias transport is restored for odd charge

Physical origin of Kondo effect

- General idea : lifting of a degeneracy by a Fermi sea through exchange interaction
- Odd charge quantum dots : resonant spin flip processes





- Resonant binding of electrons near Fermi level
- Open channel for transport

Theory : Glazman&Raikh, Ng&Lee (1988)

Experiment : Goldhaber-Gordon, Kouwenhoven (1998)

On the board : perturbation at order U^2

Fermi liquid description [Langreth, Nozières, Yosida,...]

Small U : perturbation theory in U well-behaved

$\Rightarrow$ Self-energy : $\Sigma_d(\omega) = (1 - Z^{-1})\omega + iA\omega^2$ for $\omega \to 0$

$\Rightarrow$ Effective width : $T_K = Z\Gamma$ Renormalized quasiparticles

Conductance from linear-response : Landauer-like

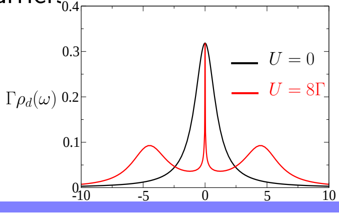
$$G(T) \;=\; \frac{2e^2}{h}\frac{4t_L^2 t_R^2}{(t_L^2 + t_R^2)^2}\int \mathrm{d}\omega\, n_F'(\omega)\, \pi\Gamma\, \mathrm{Im}[G(\omega)]$$

Friedel sum rule : $\mathrm{Im}[G(0)] = \frac{1}{\Gamma}$ at $T = 0$ and $\epsilon_d = -U/2$

$\Rightarrow G(T = 0) = \frac{2e^2}{h}$ for symmetric barriers

Key question :

does that remain true for $U \gg \Gamma$?

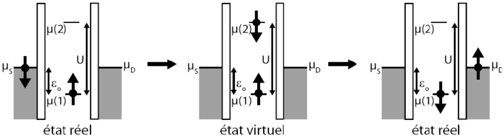


On the board : Schrieffer-Wolff transformation

On the board : Schrieffer-Wolff transformation

Schrieffer-Wolff transformation : keep only spin states at large U

$\Rightarrow$ Antiferromagnetic coupling $J_K = 8\frac{t^2}{U}$ to the Fermi sea



Kondo model :

$$H = \sum_{k\sigma} \epsilon_k c^\dagger_{k\sigma} c_{k\sigma} + J\vec{S} \cdot \sum_{kk'\sigma\sigma'} c^\dagger_{k\sigma} \frac{\vec{\tau}_{\sigma\sigma'}}{2} c_{k'\sigma'}$$

$$H = \sum_{k\sigma} \epsilon_k c^\dagger_{k\sigma} c_{k\sigma} + J\vec{S} \cdot \sum_{\sigma\sigma'} c^\dagger_{\sigma}(x=0) \frac{\vec{\tau}_{\sigma\sigma'}}{2} c_{\sigma'}(x=0)$$

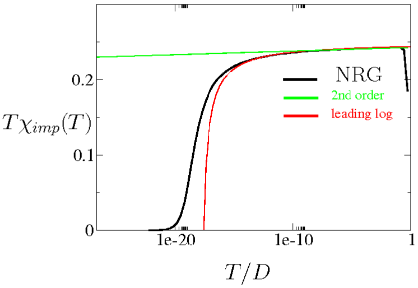
Kondo logarithms [Abrikosov, Suhl, Nagaoka, Kondo, Anderson...]

Perturbation in $j = J/D$: logarithmic divergent at low T

$$\chi_{spin}(T) = \frac{3}{4T}\left[1 - j - j^2 \log\frac{D}{T} + \ldots\right] \simeq \frac{3}{4T}\left[1 - j_R(T) + \ldots\right]$$

$$G(T) = \frac{2e^2}{h}\frac{3\pi^2}{16}\left[j^2 + j^3 \log\frac{D}{T} + \ldots\right] \simeq \frac{2e^2}{h}\frac{3\pi^2}{16}\left[j_R^2(T) + \ldots\right]$$

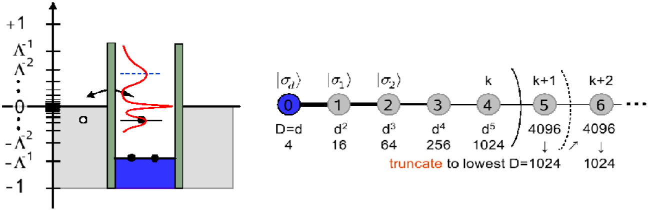
- Kondo temperature : $T_K = De^{-D/J} = De^{-\pi U/8\Gamma}$
- Renormalized coupling : $j_R(T) = \frac{1}{\frac{D}{J} + \log(T/D)} = \frac{1}{\log(T/T_K)}$ grows
- Hints that local moment does not survive at $T \ll T_K$



Solution of the Kondo problem : an NRG primer

Algorithm : [Wilson (1975)]

- Logarithmic discretization of the Fermi sea : $[\Lambda^{-k-1}, \Lambda^{k}]$
- Mapping of a chain with exponential vanishing couplings
- Iterative solution : diagonalize + truncate Hilbert space



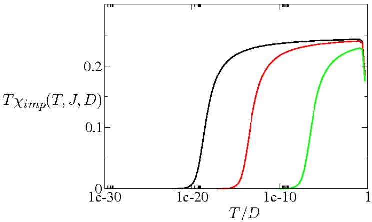
Remarks :

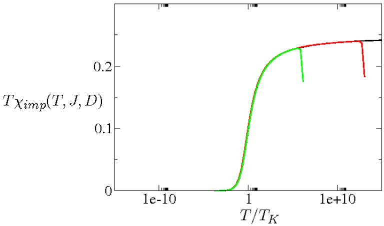
- Resolves low energy features (Kondo peak)
- Stability requires scale separation : $\Lambda > 2$
- Discretization errors $\simeq e^{-\pi^2/\log(\Lambda)} \to$ small !

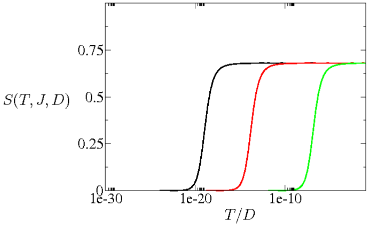
Illustration of the universal crossover

Curie constant and entropy from NRG calculations :

- Three large values of U/Γ







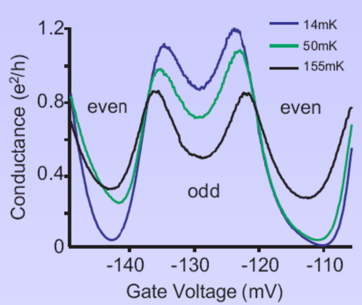
Perfect data collapse :

all observables are functions of T/T_K only

$\Rightarrow$ universality !

Back to the experiments

- Conductance is large at $T \lesssim T_K$: Kondo prevails
- Coulomb blockade is recovered at $T \gg T_K$

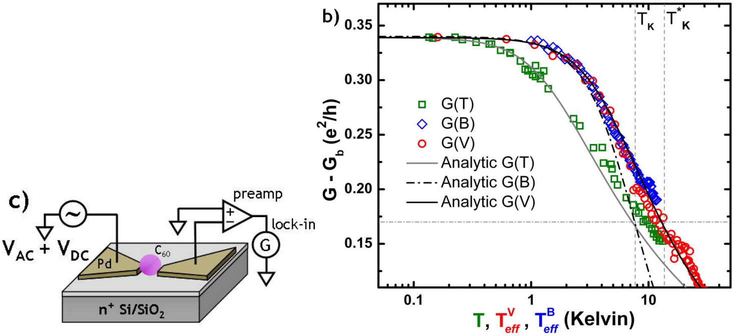


General Friedel sum rule at $T\!=\!0$:

$$G = \frac{2e^2}{h}\frac{4t_L^2 t_R^2}{(t_L^2+t_R^2)^2}\sin^2\left(\frac{\pi}{2}Q_{\rm dot}\right)$$

Testing the theory with experiments : $G(B)$ and $G(T)$

C_{60} molecular device [Scott et al. PRB 2013] (Rice)

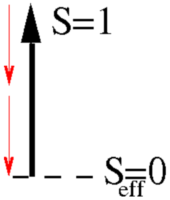


Successful fit of $G(T)$ and $G(B)$ with consistent $T_K \simeq 10K$

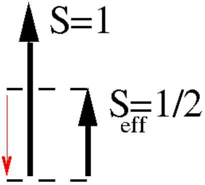
Non-Fermi liquid extensions

Spin $S = 1$: screening versus underscreening

Two screening channels : full quenching $\Longrightarrow$ regular Kondo effect

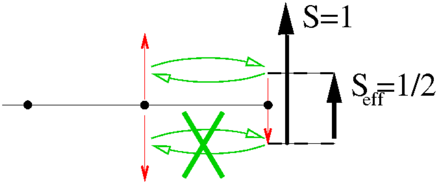


One screening channel : residual spin $\Longrightarrow$ anomalous Kondo effect



Under screening : Nozières-Blandin argument

Spin $S = 1$ and single screening channel :



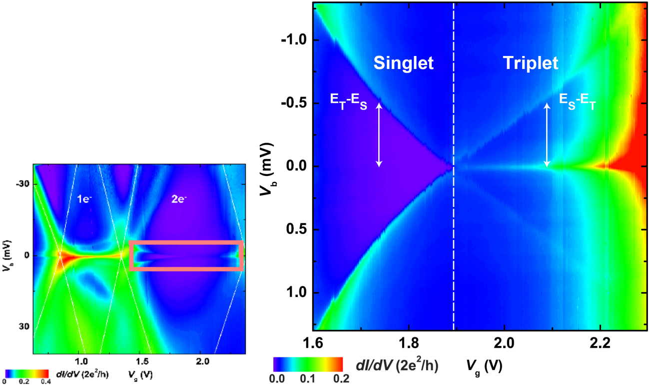
- Effective spin $S_{eff} = 1/2$ (residual entropy)
- Effective Kondo coupling $J_{eff} \propto -t^2/J$: ferromagnetic !
  $\Longrightarrow$ temperature dependence : $J_{eff}(T) \propto \frac{1}{-\frac{D}{J_{eff}} + \log(T/T_0)}$
  $\Longrightarrow$ $J_{eff}(T)$ vanishes at low T

Transport : logarithmic approach to unitarity

$$G(T) = \frac{2e^2}{h}\left[1 - \frac{c}{\log^2(T/T_K)}\right]$$

First experimental evidence of underscreening

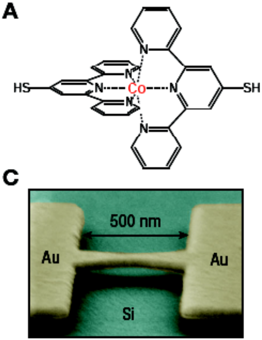
C_{60} device : [Roch *et al.*, Nature (2008)] (Grenoble)

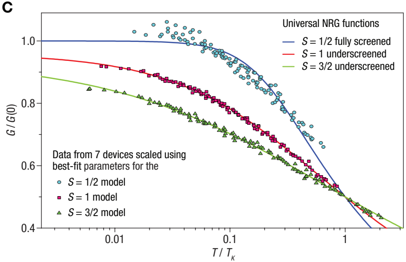


- Surprising gate effect on the singlet-triplet gap
- All transport signatures now well-understood

A second experiment : break junction device

Cobalt in a “cage” : [Parks *et al.* cond-mat (2010)] (Cornell)





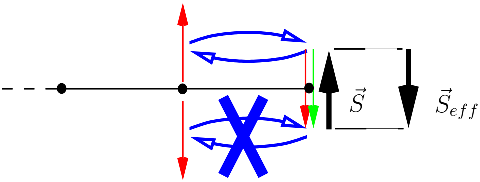
Underscreened Kondo anomaly : clearly logarithmic below T_K

Two-channel Kondo effect

Spin $S = 1/2$ but two independent Fermi seas (m=1,2) :

$$H = H_1 + H_2 + \sum_{kk'} \sum_{\sigma\sigma'} \sum_{m} J_m \, c^\dagger_{k\sigma m} \frac{\vec{\tau}_{\sigma\sigma'}}{2} c_{k'\sigma' m} \cdot \vec{S}$$

Strong coupling argument : at $J_1 = J_2$ large



- Effective spin $S_{eff} = 1/2$ (residual entropy)
- Effective Kondo coupling $J_{eff} \propto +t^2/J$: antiferromagnetic !
  $\Longrightarrow$ strong coupling fixed point is unstable !

Quick status of 2CK : theory and experiment

Some theoretical facts : (NRG, CFT, Bosonization...)

- $S(T=0) = \log(\sqrt{2}) = \log(2)/2$: emergent Majorana !
- $\chi(T) \propto \log(T_K/T)$
- $G(T)/G_0 \simeq 1 - a\sqrt{T/T_K}$: non Fermi liquid

Several experimental studies : (discussion beyond this course)

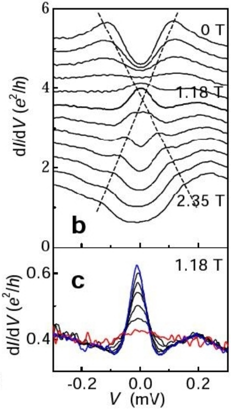
[Potok *et al.* Nature 2007 ; Keller *et al.* Nature 2015] (Stanford)
[Mebrahtu *et al.* Nature 2012 & Nature Physics 2013] (Duke)
[Ifthikar *et al.* Nature 2015] (LPN)

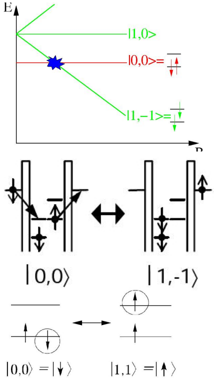
Extra slides

Nice illustration with “real” and “fake” spin 1/2

Even charge CNT quantum dot : [Nygard *et al.*, Nature (2000)]

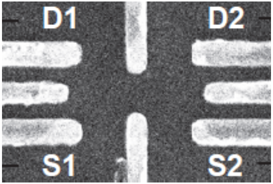
- Magnetic-field induced degeneracy by crossing of singlet and lowest triplet

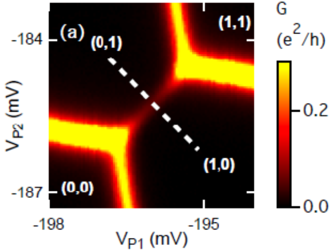




Another illustration with “fake” spin

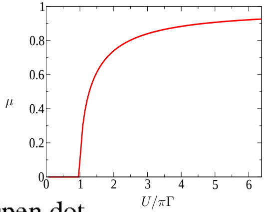
Charge states in double dot setup : [Goldhaber-Gordon group (2012)]





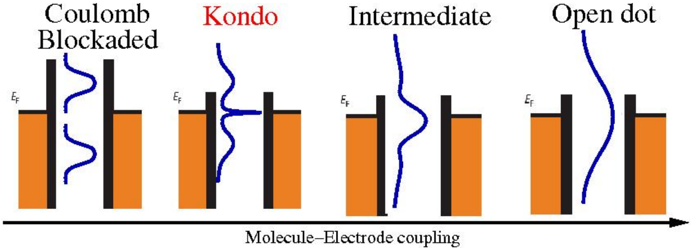
- Pseudospin : (1,0) ⇔↑ and (0,1) ⇔↓
- Kondo process takes place

How to reach the scaling limit ?



Universal (sharp) Kondo resonance requires :

- well-formed local moment i.e. large U/Γ



Consequence : only in the Kondo regime

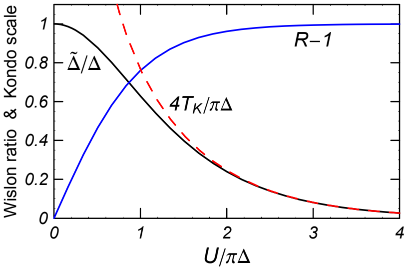
- single parameter scaling of physical quantities
  Zero-bias Conductance : $G(T) = G_0 * f(T/T_K) + G_1$

Question for experiments : how to quantify the universal regime ?

Precise condition to be universal

Wilson ratio : $R = \frac{\chi}{\gamma} * \frac{\gamma}{\chi}_{|U=0}$

- Zero T spin susceptibility (screening) : $\chi(T) \propto \frac{1}{T_K}$
- Low T specific heat (Fermi liquid) : $C(T) = \gamma T \propto \frac{T}{T_K}$



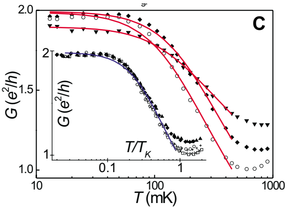
Effective width :
here $\tilde{\Delta} \equiv \tilde{\Gamma}$

Kondo scale :
$T_K \propto e^{-\pi U/8\Gamma}$

- 3% deviation to universality : $U \gtrsim 2\pi\Gamma \Longrightarrow T_K \lesssim U/40$
- Also constraints on level spacing

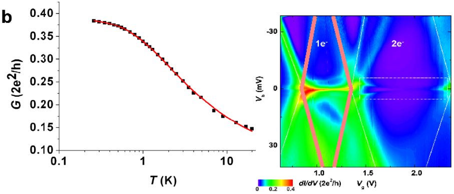
Testing the theory with experiments : $G(T)$

Semiconducting quantum dots : [van der Wiel *et al.* Nature (2000)]



Sizable deviations to scaling due to too small U/T_K

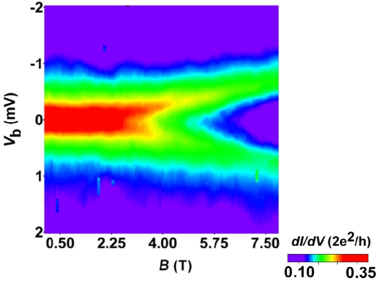
Molecular quantum dots : [Roch *et al.* PRL (2009)]

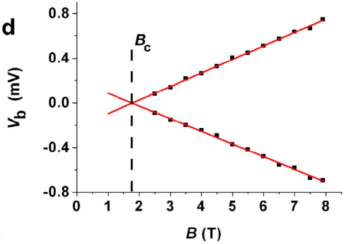


$T_K = 4K, U > 600K$
conditions are met !

Testing the theory with experiments : $G(B)$

Magnetotransport data in molecular quantum dot :



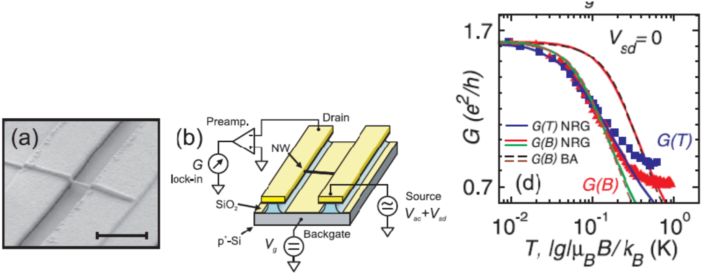


Fit of the Zeeman splitting :

- Kondo peak splits at $B_c = k_B T_K/(2g\mu_B) \Rightarrow T_K = 4.8K$ OK !

Testing the theory with experiments : $G(B)$

Attempt at scaling analysis : (InAs nanowire, Mahalu's group)



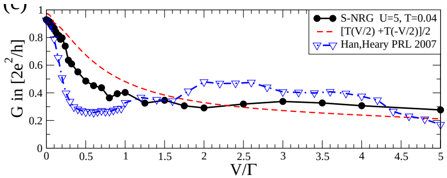
- $G(T)$ and $G(B)$ are different universal scaling functions
- The T_K and B_K scales are not consistent !
- The experiment is quantitatively not fully conclusive...

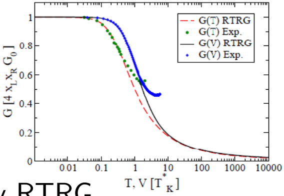
Out of equilibrium scaling

Finite-bias conductance $G(V)$:

- Main physical effect : enhanced scattering from large current density kills the Kondo resonance
- Tough problem for many-body theory
- Reliable experimental data are needed also

Methods : [NRG (Anders 2009), QMC (Han 2007), RTRG (Pletyukhov-Schoeller 2012)]





- T_K and V_K consistently predicted by RTRG
- Deviations to scaling (semiconducting dot)

Checking Fermi Liquid Theory

At low energy : $T \ll T_K$ and $eV/k_B \ll T_K$

$$G(T, V) = G_0 \left[1 - c_T \left(\frac{\pi T}{T_K} \right)^2 - c_V \left(\frac{eV}{k_B T_K} \right)^2 \right]$$

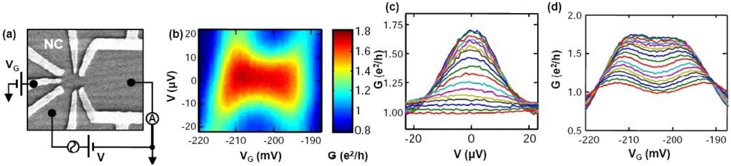
Out of equilibrium Fermi Liquid theory : [Oguri JPS (2004)]

$$\begin{aligned} \alpha \equiv \frac{c_V}{\pi^2 c_T} &= \frac{3}{4\pi^2} \frac{1 + 5(R-1)^2}{1 + 2(R-1)^2} \\ &= \frac{3}{2\pi^2} \simeq 0.16 \, [\text{Kondo regime} \, (R = 2)] \\ &= \frac{3}{4\pi^2} \simeq 0.08 \, [\text{uncorrelated} \, (R = 1)] \end{aligned}$$

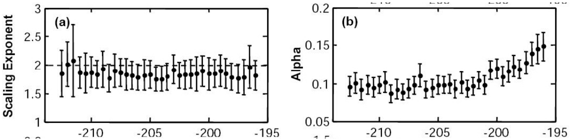
Note : α depends on Γ_L/Γ_R in general
but not any more in the $R = 2$ limit (universality again !)

Hunt for α : 2DEG quantum dot data

Recent experiment : [Grobis *et al.* PRL (2008)]



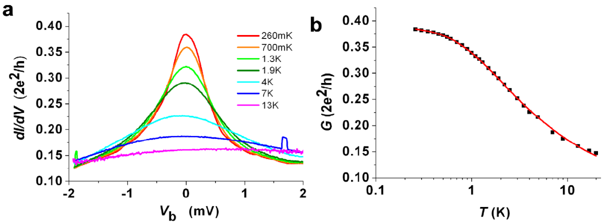
Fermi liquid coefficients :



- Nice systematics !
- $0.1 < \alpha < 0.15$: signature of intermediate correlations ? !

Hunt for α : molecular quantum dot data

Grenoble experiment : [Roch *et al.* PRL (2009)]



- Here $T_K = 4K \implies$ less noise !
- For this only sample :
  we extract $\alpha \simeq 0.15$, OK !
- See recent study by Mahalu's group

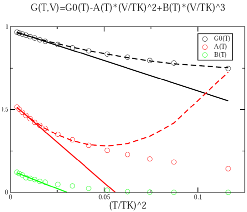
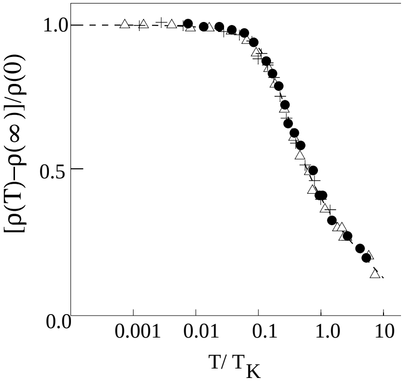


Illustration : whole crossover in diluted alloy

Resistivity of Kondo compound $Mo_x Nb_{1-x}$:

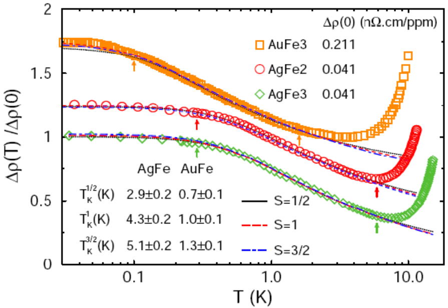


- Scaling on 4 orders of magnitude ! !

Disgression : Kondo anomalies in $Ag_{1-x}Fe_x$ and $Au_{1-x}Fe_x$

Resistance of wires : [Costi *et al.* PRL 2009]

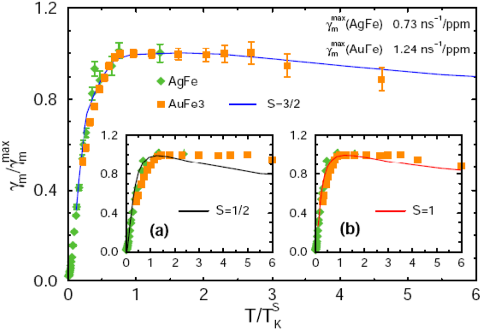
- LDA predicts spin $S = 3/2$ for Fe and 3 orbitals involved in screening process



- Data compatible with full screening (no underscreening !)
- Theory cannot distinguish the spin value S

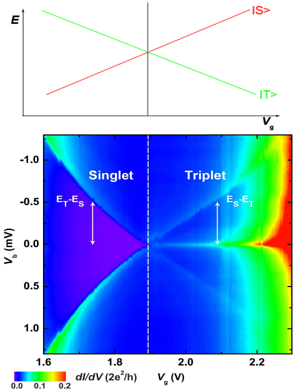
Disgression : Kondo anomalies in wires

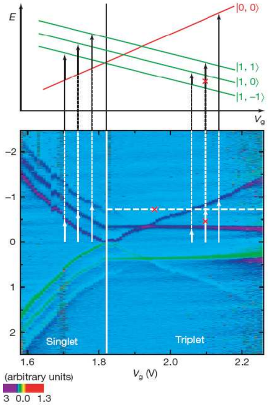
Inelastic contribution to the resistivity :



- This allows to discriminate the spin value :
  $\Longrightarrow S = 3/2$ and 3 orbital involved !
- This systems is thus not underscreened...

Identifying the spin states : gate voltage scan at $B = 3\text{T}$





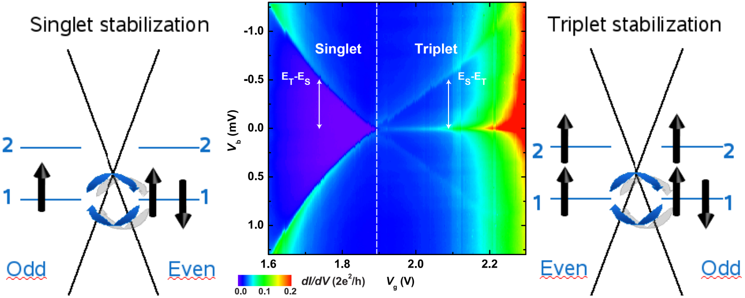
- Zeeman effect agrees with spin 0 or spin 1 ground state
- Gate-induced magnetic splitting (tunable Hund's rule !)

Origin for the gating effect : phenomenology

Role of the leads : energy gain by charge fluctuations

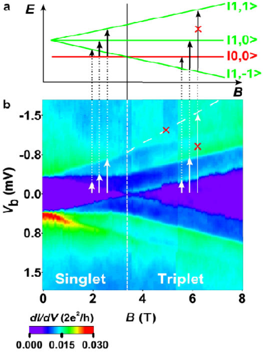
Hopping from level 1 or 2 $\Longrightarrow \delta E_{1,2} = -\frac{t_{1,2}^2}{E_{add}}$

Hypothesis : hopping asymmetry $t_1 \gg t_2$ explains data



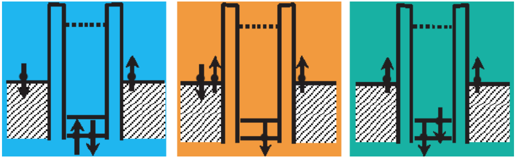
Crucial observation : single screening channel ! !

Second evidence for single screening channel



Magnetic field effect :

- No Kondo anomaly at the singlet-triplet degeneracy point !



- Kondo coupling : $J_K \propto \frac{t_1 t_2}{E_c}$ small as $t_1 \gg t_2$

Modelization the gating effect

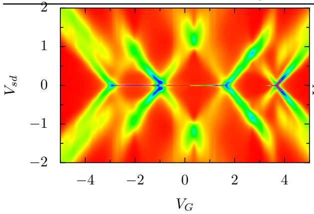
Generalized two-orbital Anderson model :

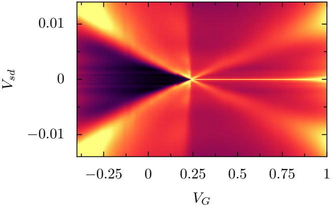
$$H = \sum_{i\sigma} E_i n_{i\sigma} + \sum_i U_i n_{i\uparrow} n_{i\downarrow} + U_{12} n_1 n_2 - J_H \mathbf{s}_1 \mathbf{s}_2 + \sum_{\nu k\sigma} \epsilon_{\nu k} c^\dagger_{\nu k\sigma} c_{\nu k\sigma} + \frac{1}{\sqrt{N_k}} \sum_{i\nu k\sigma} (t_{\nu i} c^\dagger_{\nu k\sigma} d_{i\sigma} + \mathrm{h.c.})$$

with $E_2 - E_1 \simeq J_H/2$ (small bare singlet-triplet gap)

and $t_1 \simeq 2 * t_2$ (moderate hopping asymmetry)

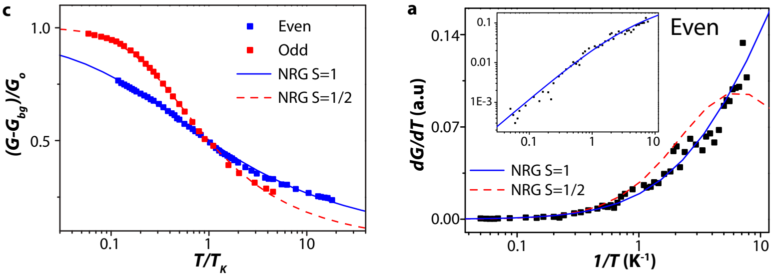
Scenario confirmed by NRG : [Florens *et al.*, JPCM (2011)]





Testing the underscreened Kondo scenario

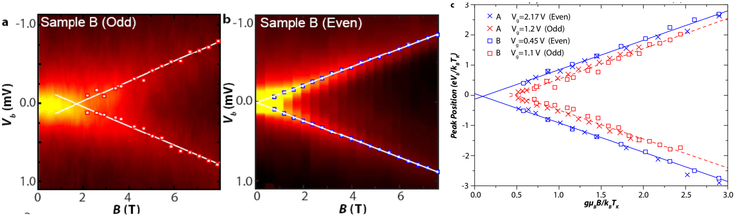
Analysis of the spin $S = 1$ Kondo anomaly : [Roch *et al.*, PRL (2009)]



- Agreement with $S = 1$ NRG clearly better
  ... but tough experiment ! !
- $\frac{dG(T)}{dT}$ shows two logarithmic regimes

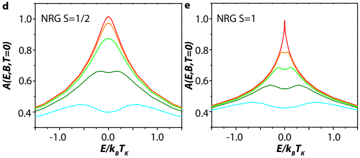
Magnetic field effect : smoking gun !

Comparing $S = 1/2$ and $S = 1$ Kondo anomalies :



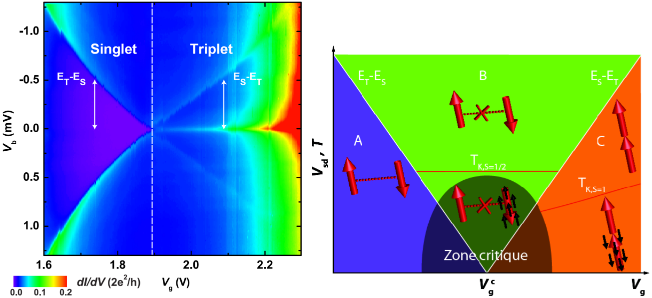
- Splitting occurs at lower magnetic fields for $S = 1$!

NRG calculations : $S = 1$ Kondo resonance very sensitive to field



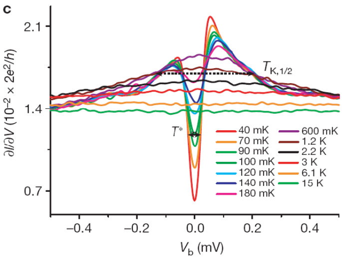
Analysis of the transition

- Far on the singlet side : spin gap
- Far on the triplet side : underscreened Kondo
- Nature of QCP :
  one free spin $S = 1/2 \oplus$ one screened spin $S = 1/2$

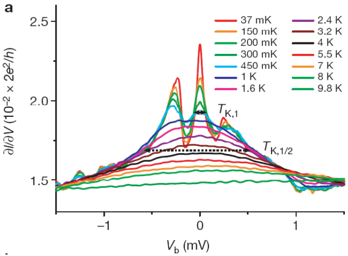


Around the quantum critical point

Singlet side :



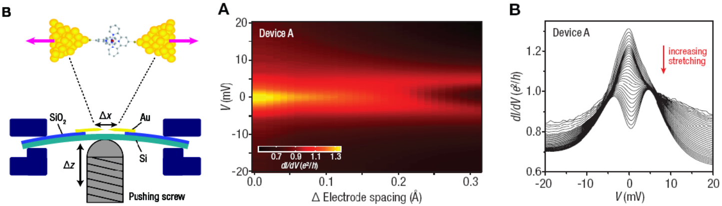
Triplet side :



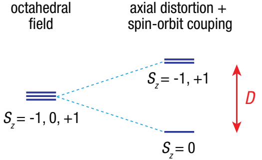
- For $T \gg |E_T - E_S|$ (on both sides) :
  broad spin $S = 1/2$ Kondo anomaly
- Sharp antiresonance (Friedel !) on the singlet side at low T
  $\Longrightarrow$ second-stage of Kondo screening

Unexpected effect

Stretching the molecule : splits the Kondo resonance !



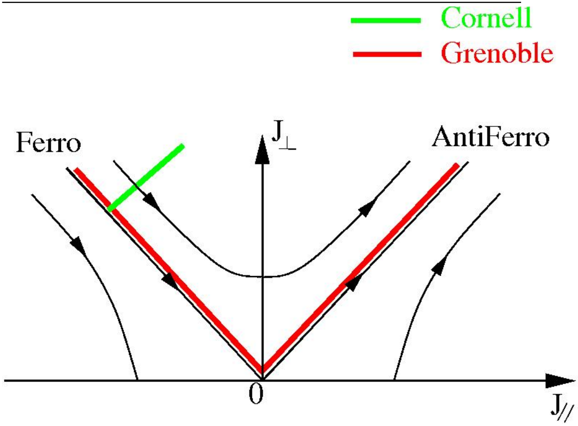
Interpretation : strain induced magnetic anisotropy ?



Putting the $|1,0\rangle$ state down :
kills underscreened Kondo effect

Where are we in parameter space ?

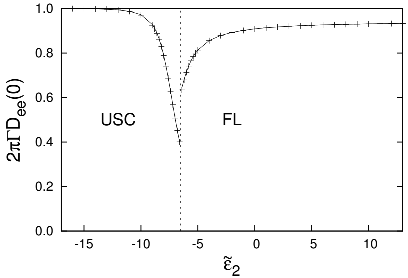
Travelling along Anderson's flow diagram :

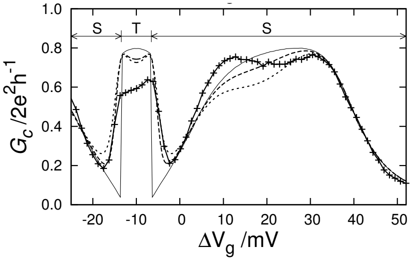


A third experiment : semiconducting dots

Obvious way to tune QPT : just change the charge !

- $S = 1/2$: Fermi liquid, sum rule $\sin^2(\pi Q/2)$
- $S = 1$: non Fermi liquid, sum rule $\cos^2(\pi Q/2)$
  [Pustilnik&Borda PRB 2006 ; Logan et al. PRB 2009 ; Kogan et al. PRB 2003]



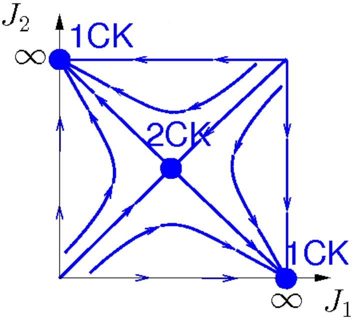


QPT signaled by conductance jump at $T = 0$

Channel anisotropy kills 2CK

Weak coupling RG : with $J_1 \neq J_2$

$$H = H_1 + H_2 + \sum_{\sigma\sigma'} \sum_m J_m \, c^\dagger_{\sigma m} \frac{\vec{\tau}_{\sigma\sigma'}}{2} c_{\sigma' m} \cdot \vec{S}$$

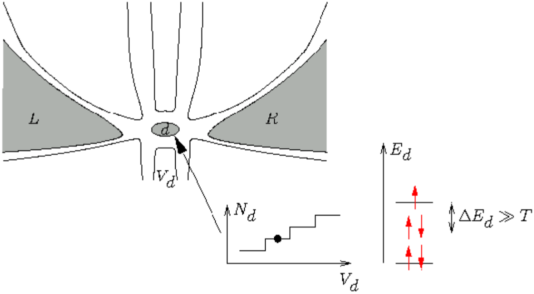


- $\Longrightarrow$ fine tuning needed !
- but can one realize such Hamiltonian with quantum dots ?

Why 2 leads experiments give only 1 channel ?

Kondo Hamiltonian : $\alpha = L, R$

$$H = H_L + H_R + \sum_{\sigma\sigma'} \sum_{\alpha,\alpha'} J_{\alpha,\alpha'} \; c^{\dagger}_{\sigma\alpha} \frac{\vec{\tau}_{\sigma\sigma'}}{2} c_{\sigma'\alpha'} \cdot \vec{S}$$

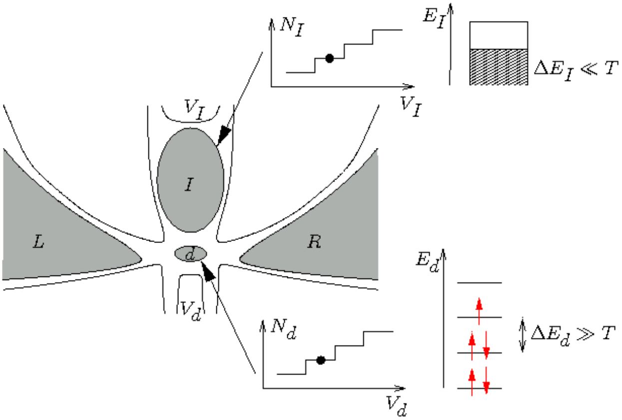


Matrix of couplings : $J_{\alpha,\alpha'} \propto \frac{t_\alpha t'_\alpha}{U}$ has only one non-zero eigenvalue

$$\Longrightarrow H = H_+ + H_- + 8\frac{t_L^2 + t_R^2}{U} \sum_{\sigma\sigma'} c^{\dagger}_{\sigma+} \frac{\vec{\tau}_{\sigma\sigma'}}{2} c_{\sigma'+} \cdot \vec{S}$$

- One channel only

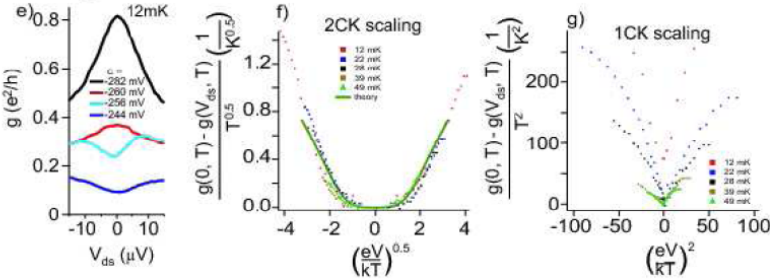
Goldhaber-Gordon/Oreg proposal



- Charge transfert between leads L/R and island I is suppressed below E_c^{I}
- Tough contraint : $\Delta E_{\mathrm{I}} \ll T \ll E_c^{\mathrm{I}}$

Experimental observation

[Potok *et al.* Nature (2007)]



- some evidence for scaling
- issues in the absence of complete quantitative comparison
- is there a better system ?