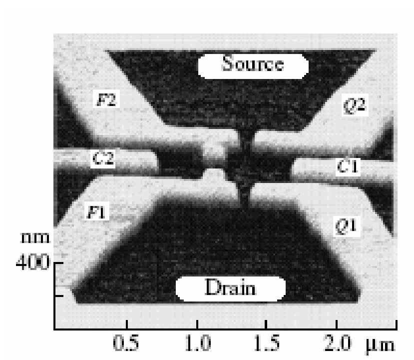
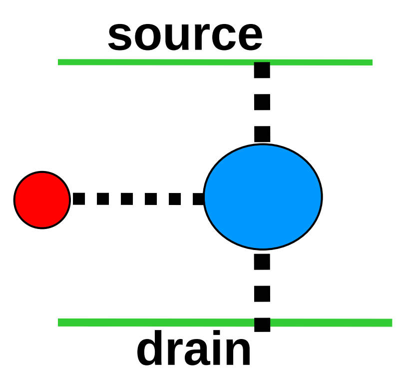
Institut für Theoretische Physik und Astrophysik

Universität Würzburg

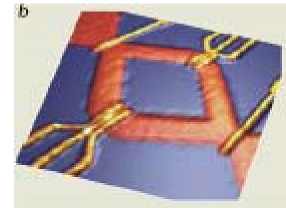
M.N.Kiselev

Dynamical symmetries in nanophysics
(Part I)





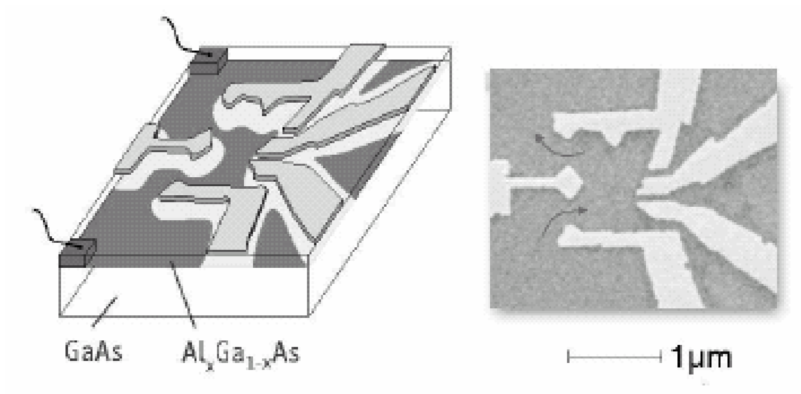
Outline

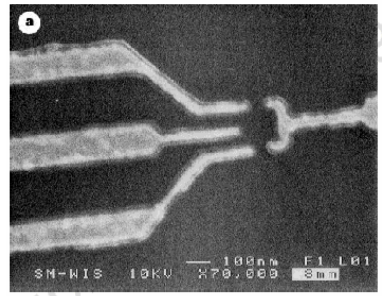


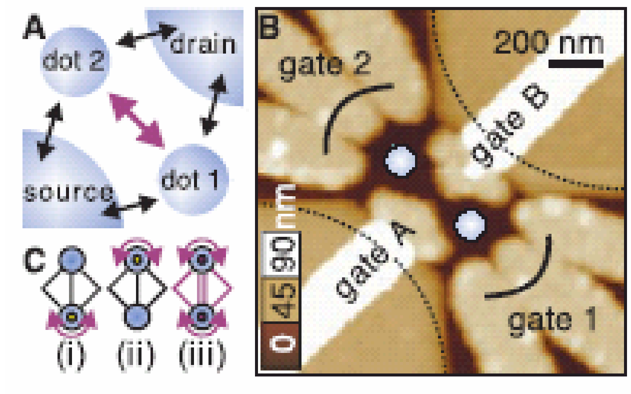
- Quantum Dots with a few electrons
- Equilibrium and Non-Equilibrium Kondo effect
- Coherence and de-coherence
- Hidden dynamical symmetries
- Quantum dots with many electrons
- Stoner instability in isolated dots
- Perspectives

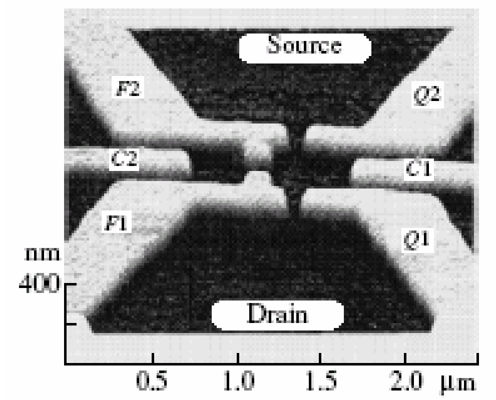
Ref. MK and R.Oppermann, PRL 2000
MK, K.Kikoin and L.W.Molenkamp JETP Lett 2003
MK, K.Kikoin and L.W.Molenkamp, PRB 2003
MK, AHP 2003
K.Kikoin, MK and Y.Avishai, Kuwler 2004, cond-mat/0309606
Y.Avishai, K.Kikoin and MK, NOVA 2005, cond-mat/0407063
MK, D.N.Aristov and K.Kikoin, PRB 2005
MK, Y.Gefen, cond-mat/0504751

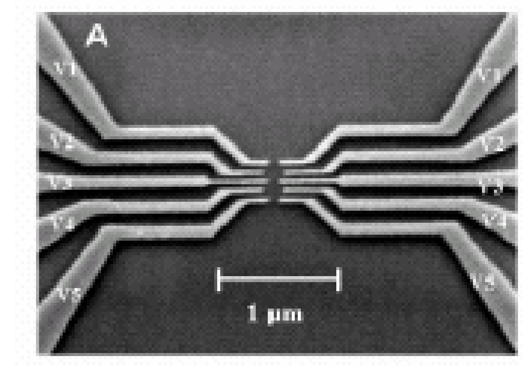
Quantum dots: from simple to complex











D.Goldhaber-Gordon et al (1998)

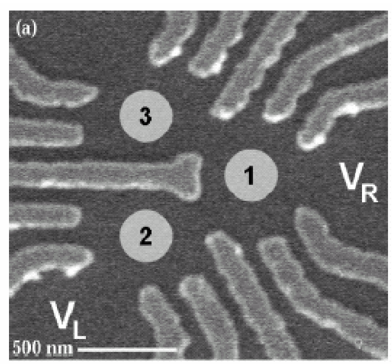
J.P.Kotthaus (1995)

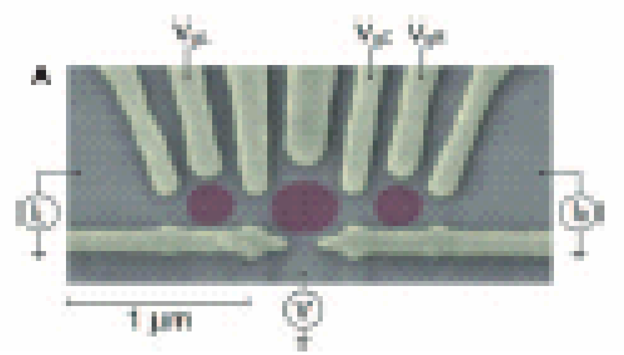
A.Holleitner et al (2002)

L.W.Molenkamp et al (1995)

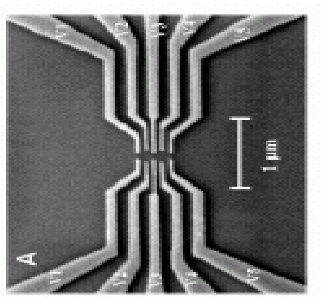
H.Jeong et al (2001)

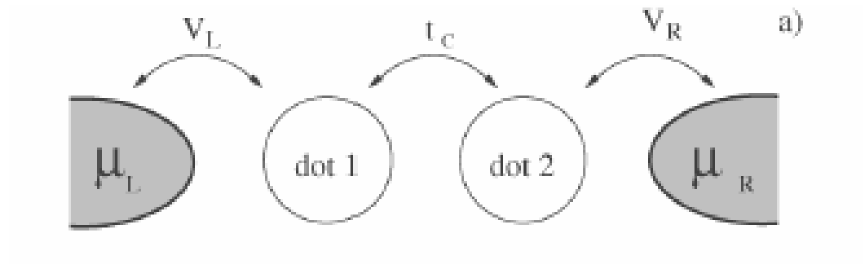
C.Marcus et al (2003)





Examples of dynamical symmetries in QD

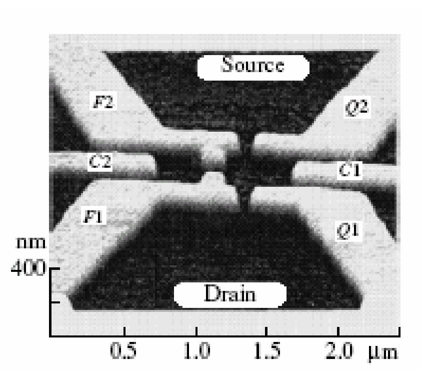


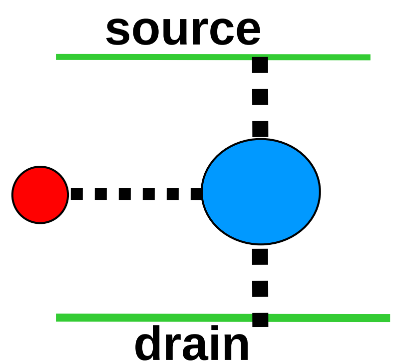


$$SU(4)$$

L.Borda et al (2003)

Spin and iso-spin degrees of freedom

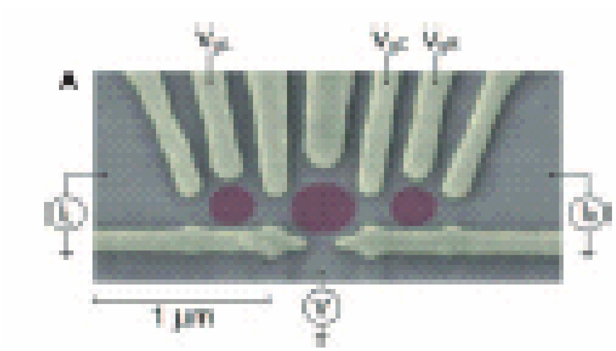




$$SO(4) = SU(2) \otimes SU(2)$$

MK et al (2003)

Interplay between singlet and triplet states in DQD



C.Marcus et al (2003)

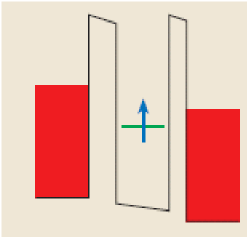
$$SU(3) \qquad SO(5) \qquad SO(7)$$

K.Kikoin et al (2004)

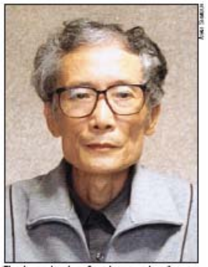
Motivation

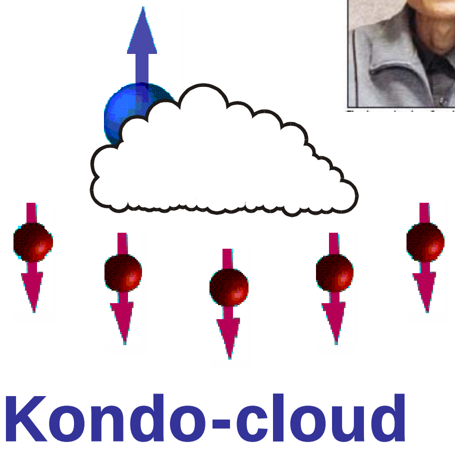
- manifestation of dynamical symmetries in quantum dots
- how dynamical symmetries affect transport through nano-particles
- dynamical symmetries in systems out of equilibrium

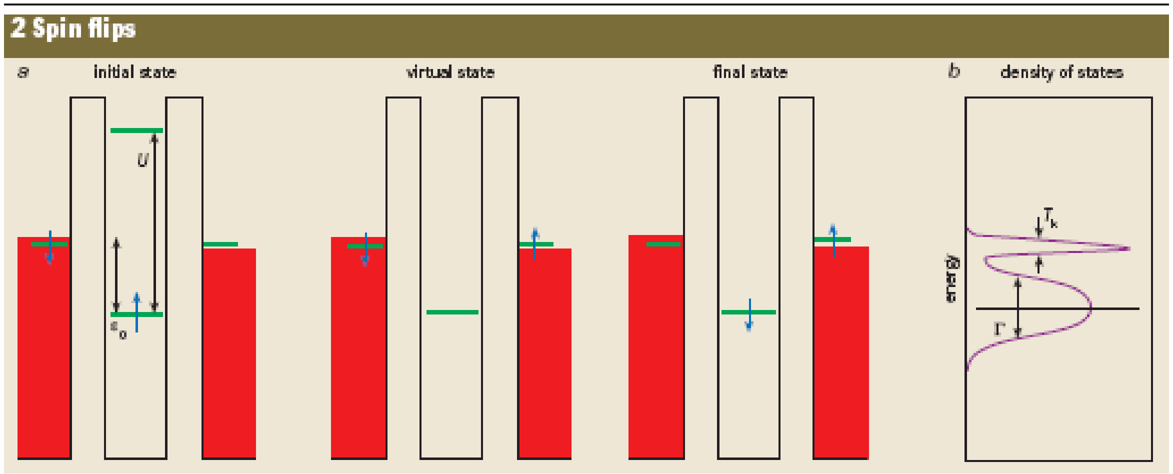
Kondo effect as a tool to test dynamical symmetries



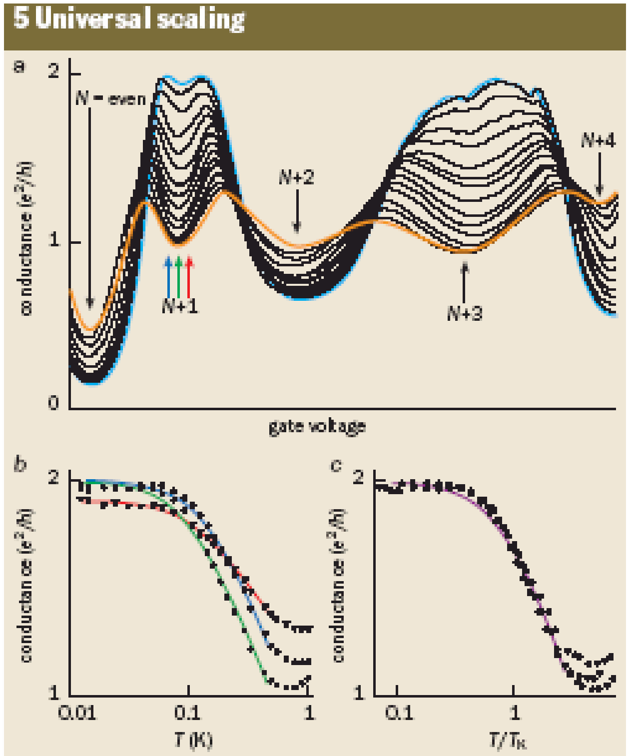
Kondo Effect in Quantum Dots

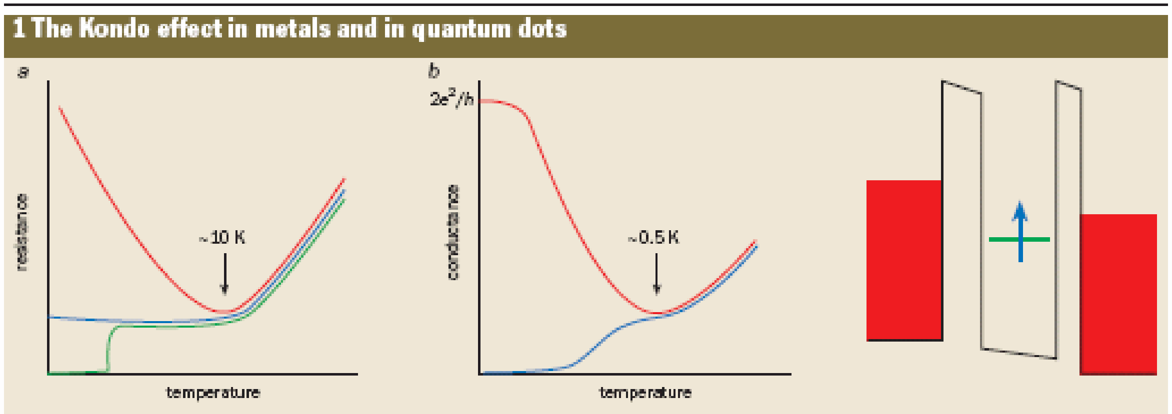




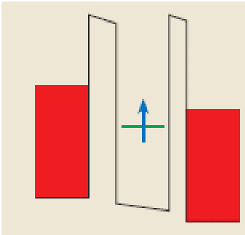


$$G/G_0 \propto \ln^{-2}\left(T/T_K\right)$$

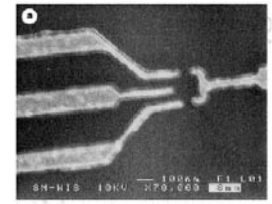


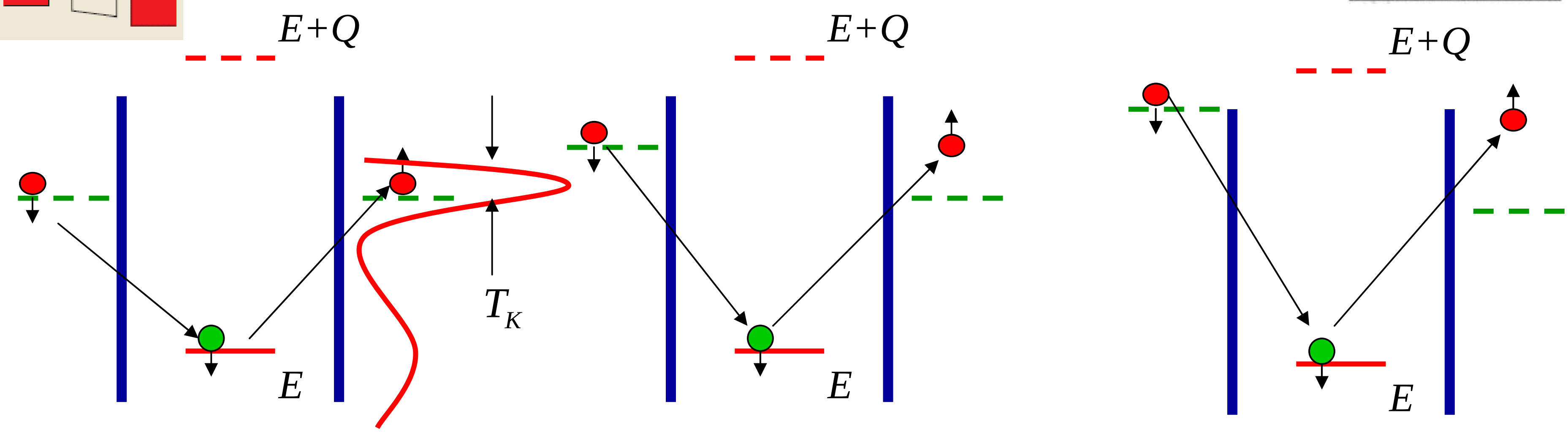


L.Kouwenhoven and L.Glazman (2001)



Non-equilibrium Kondo effect





Zero-bias (equilibrium)

$$T_K$$

Small bias (quasi-equilibrium)

$$eV \ll T_K$$

Large bias (out of equilibrium)

$$eV \gg T_K$$

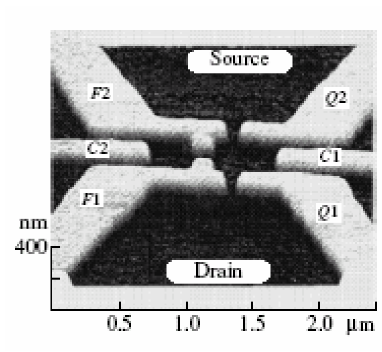
Effects of decoherence

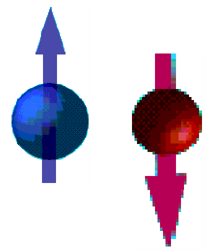
$$\Gamma_{rel} \sim eV$$

$$\Gamma_{rel} \sim eV / \ln^2 \left(eV / T_K \right)$$

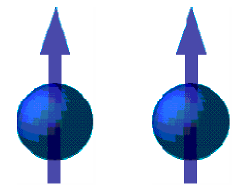
There is no strong coupling (Kondo) regime at low T in out of equilibrium

From Single Quantum Dot to Double Quantum Dot

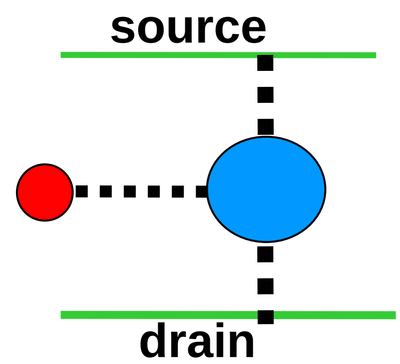




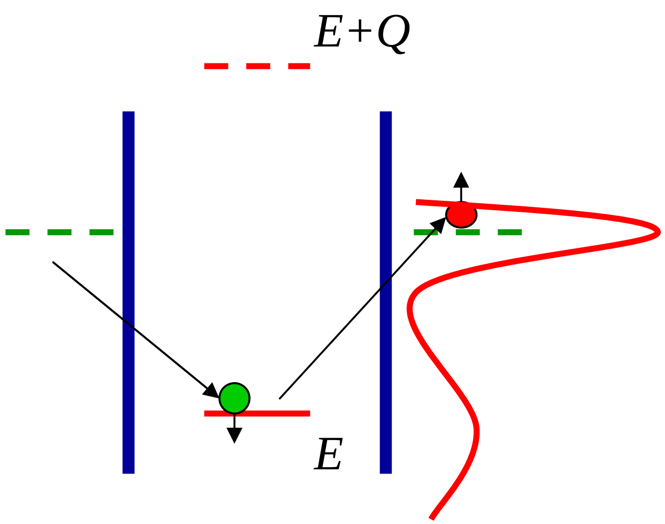
Singlet



Triplet



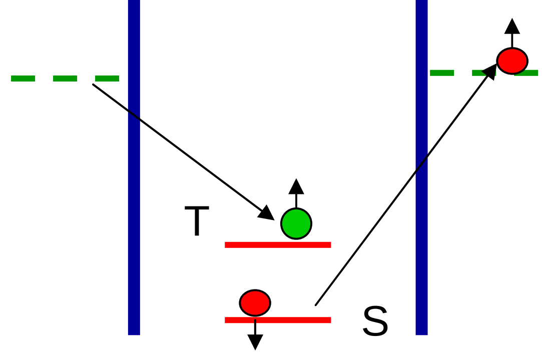
- Kondo co-tunneling through QD: N=1
- Kondo co-tunneling through DQD: N=2



Kondo Hamiltonian

$H = J\,(\mathbf{S}\ \mathbf{s})$

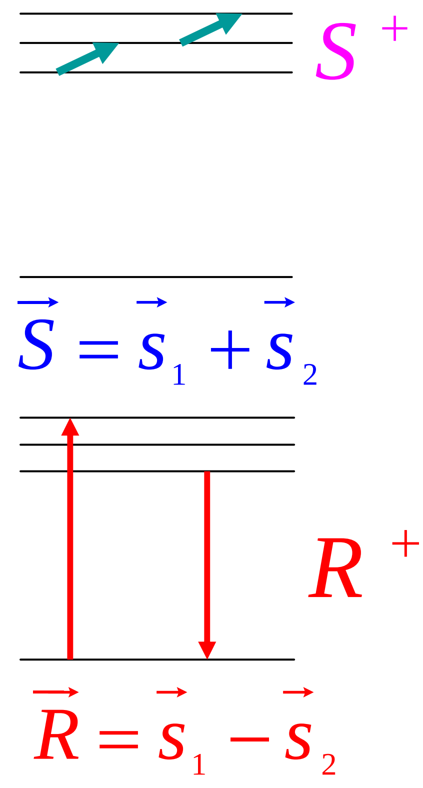
$S=1/2$



Generalized Kondo Hamiltonian

$H = J_1\,(\mathbf{S}\ \mathbf{s}) + J_2\,(\mathbf{R}\ \mathbf{s})$

$S=1$ (triplet) plus $S=0$ (singlet)



Non-universal Kondo temperature

$$\Delta_{TS} \sim T_K(\Delta_{TS})$$

"Simple" knowledge about Kondo Effect

• Kondo effect exists if the total number of electrons in a dot is odd

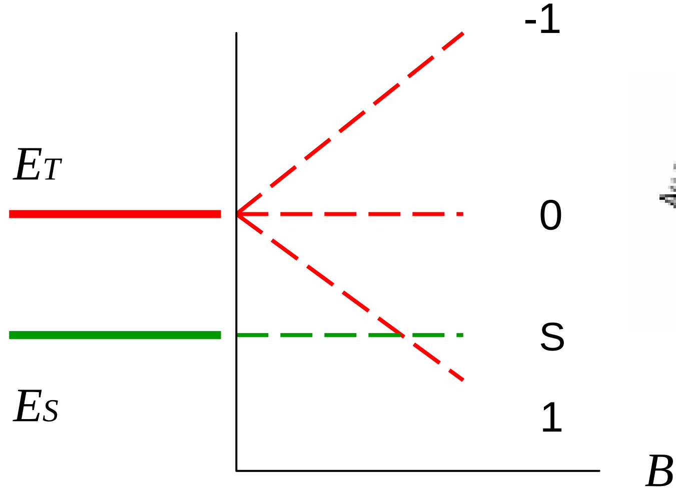
• Kondo effect is destroyed by external magnetic field

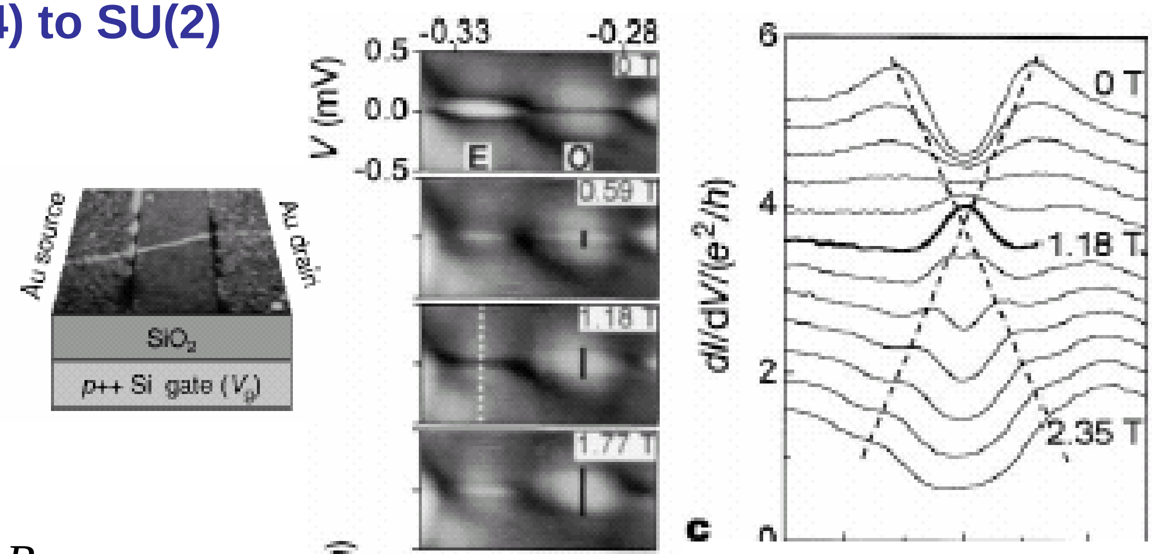
• Relaxation effects associated with the non-equilibrium conditions eliminate the Kondo peak

Is it always true?

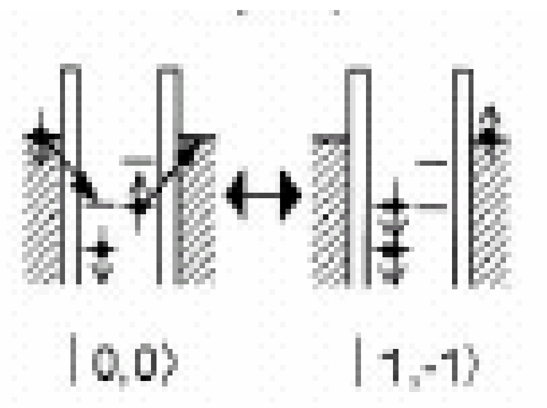
S/T transition: *Magnetic field induced Kondo effect*

Symmetry reduction from SO(4) to SU(2)





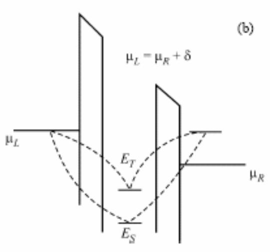
$$H_{Kondo} = J\left(\vec{R}\bullet\vec{s}\right)$$



Kondo effect due to the dynamical symmetry of DQD

M. Pustilnik, Y. Avishai & K.Kikoin (2000)

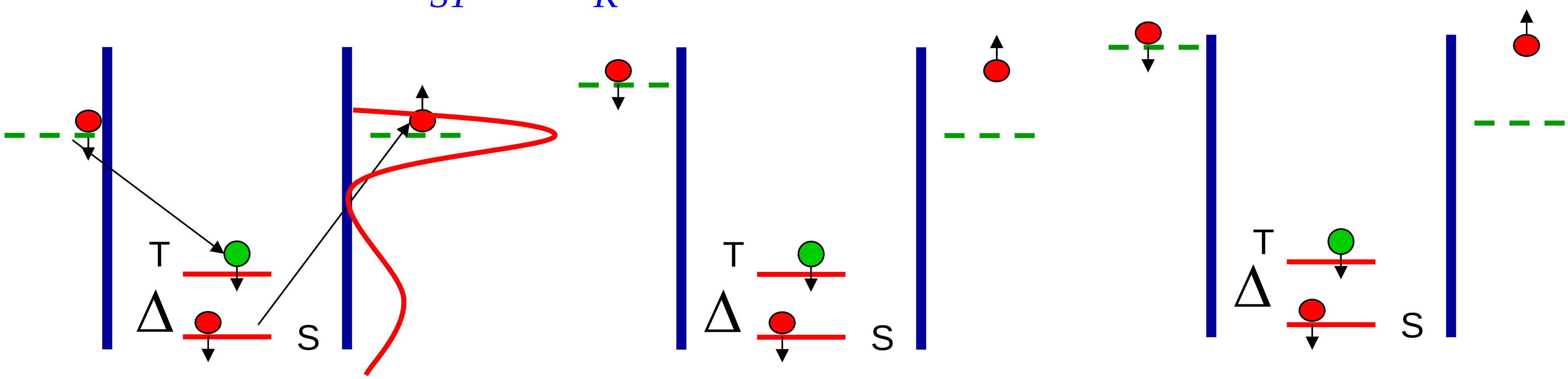
D. Kobden et al (2000)



Non-equilibrium Kondo effect in DQD

$\Delta_{ST} \ll T_K^{EQ}$ **Underscreened S=1 NEK**

$\Delta_{ST} \gg T_K^{EQ}$ **Is Kondo effect possible?**

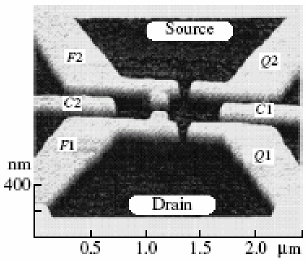


Zero-bias (equilibrium)	**Small bias (quasi-equilibrium)**	**Large bias (out of equilibrium)**
T_K^{EQ}	$eV \ll T_K^{EQ}$	$eV \gg T_K^{EQ}$
Effects of decoherence	$\Gamma_{rel} \sim eV$	**?**

What happens if $eV \sim \Delta_{ST}$ **?**

$$\Delta_{ST} \gg T_K^{EQ}$$

Non-equilibrium Kondo effect in DQD



Basic equations and differential conductance

$$\frac{dJ_{LL}^{T}}{d\ln D} = -\nu\left(J_{LL}^{T}\right)^2, \frac{dJ_{LL}^{ST}}{d\ln D} = -\nu J_{LL}^{ST} J_{LL}^{T},$$

$$\frac{dJ_{LR}^{T}}{d\ln D} = -\nu J_{LL}^{T} J_{LR}^{T}, \frac{dJ_{LR}^{ST}}{d\ln D} = -\nu J_{LL}^{ST} J_{LR}^{T},$$

$$\frac{dJ_{LR}^{S}}{d\ln D} = -\frac{1}{2}\nu\left(J_{LL,+}^{ST} J_{LR,-}^{TS} + \frac{1}{2} J_{LL,z}^{ST} J_{LR,z}^{TS}\right)$$

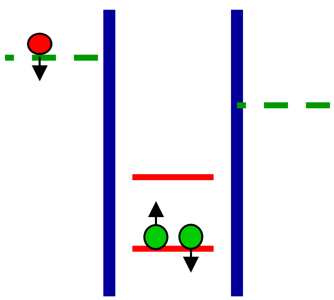
$$J_{\Lambda\Lambda'}^{ST} = \frac{J_0^{S}}{1-\nu J_0^T \ln(D/T)}$$

$$J_{\Lambda\Lambda'}^{T} = \frac{J_0^{T}}{1-\nu J_0^T \ln(D/T)}$$

$$G(eV,T) \propto |J_{LR}^{ST}|^2$$

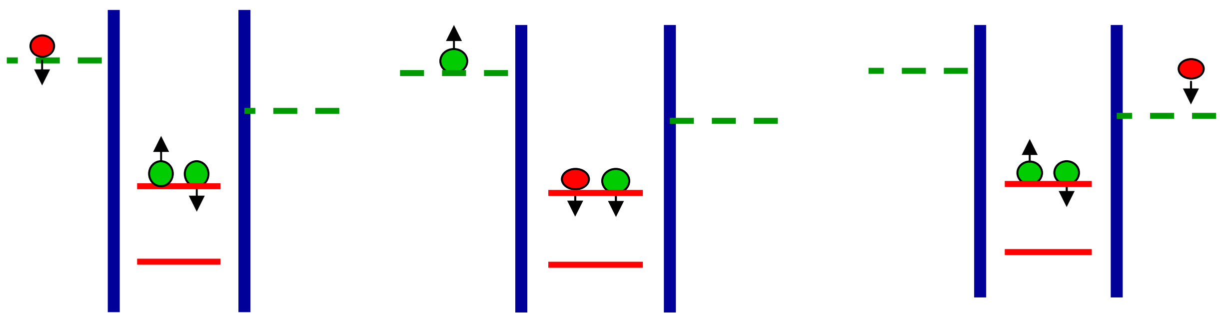
$$T_K^{NEQ} = D\exp\left(-\frac{1}{\nu J_0^T}\right) = \left(T_K^{EQ}\right)^2 / D$$

initial

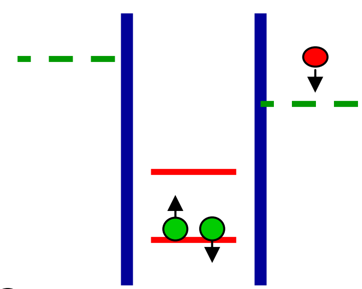


$$G/G_0 \propto \ln^{-2}\left(\max\left[\left(eV-\Delta\right),T\right]/T_K\right)$$

Virtual Kondo Processes

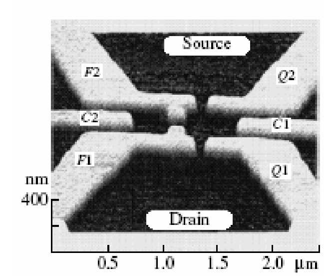


final



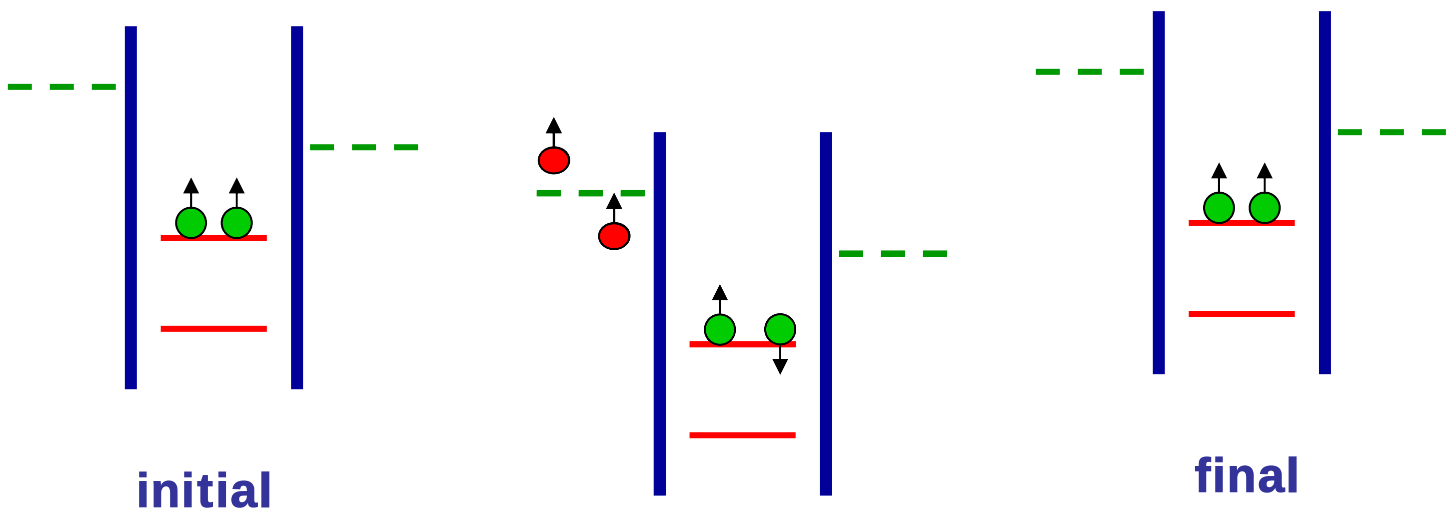
$$\Delta \gg T_K^{EQ}$$

Non-equilibrium Kondo effect in DQD



Effects of decoherence and repopulation

Triplet / Triplet Relaxation



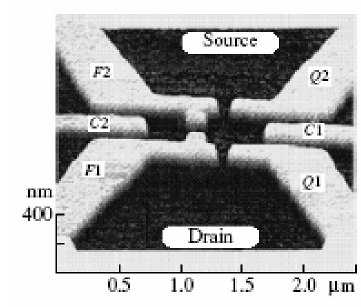
$$\hbar/\tau_d \sim eV\left(J^{ST}/D\right)^2\left[1+O\left(J/D\ln\left\{D/eV\right\}\right)\right]$$

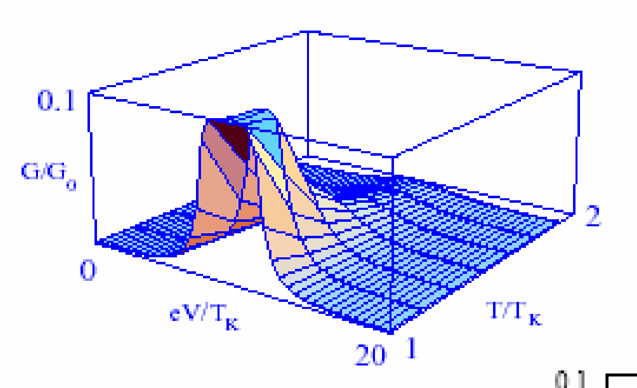
$$P_t\left(eV\right) \propto \exp\left(-\Delta^*\left(eV\right)/T\right)$$

$$\Delta^*\left(eV\right)-\Delta = O\left(J/D\ln\left[\frac{D}{\max\left\{\omega, eV, T\right\}}\right]\right)$$

Non-equilibrium Kondo effect in Double Quantum Dot

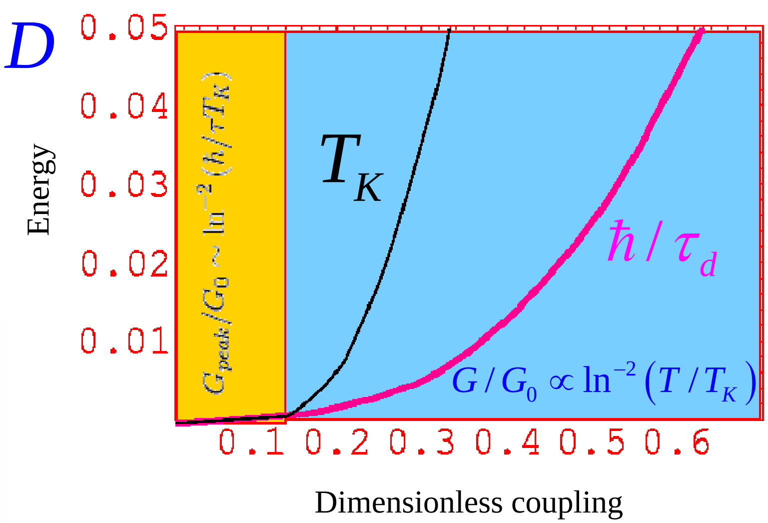
$$H_{\text{int}} = \sum[(J^{TT}_{\alpha\alpha'}\vec{S} + J^{ST}_{\alpha\alpha'}\vec{P})\cdot\vec{s}_{\alpha\alpha'} + J^{S}_{\alpha\alpha'}X^{SS}n_{\alpha\alpha'}]$$





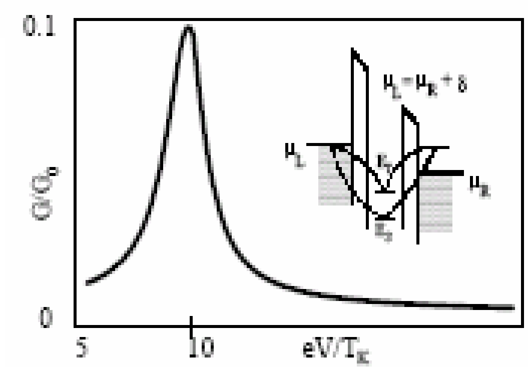
$$T_K^{NEQ} \sim \left(T_K^{EQ}\right)^2 / D$$

$$T_K^{NEQ} \ll T_K^{EQ}$$



$$G(eV,T) \propto |J^{ST}_{LR}|^2$$

$$G_0 = 2e^2/h$$



AC Voltage

DC Voltage

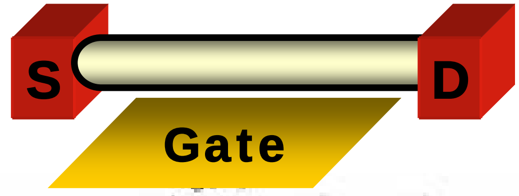
$$G/G_0 \propto \ln^{-2}\left(\max\left[(eV-\Delta),T\right]/T_K\right)$$

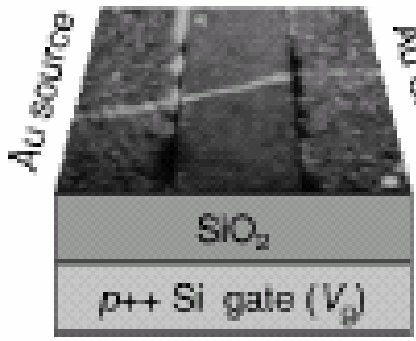
$$G_{peak} \propto \overline{G\left(V_{ac}\cos(\omega t)\right)}$$

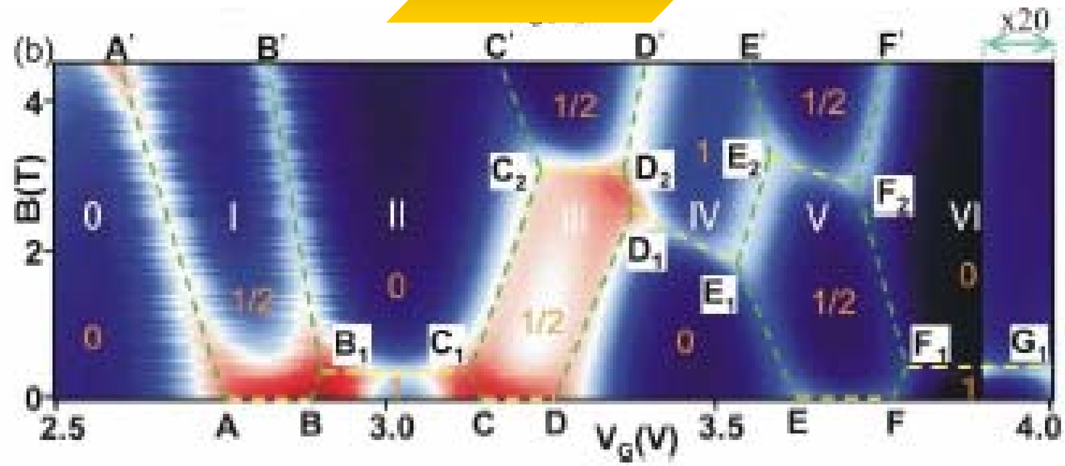
$$G_{peak}/G_0 \propto \ln^{-2}\left(\frac{\hbar}{\tau T_K}\right)$$

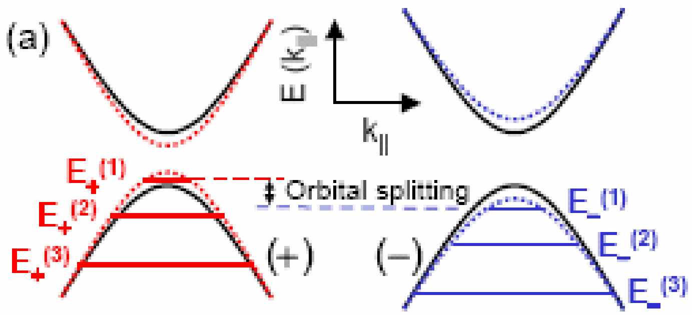
MNK, K.Kikoin and L.W.Molenkamp, (2003)

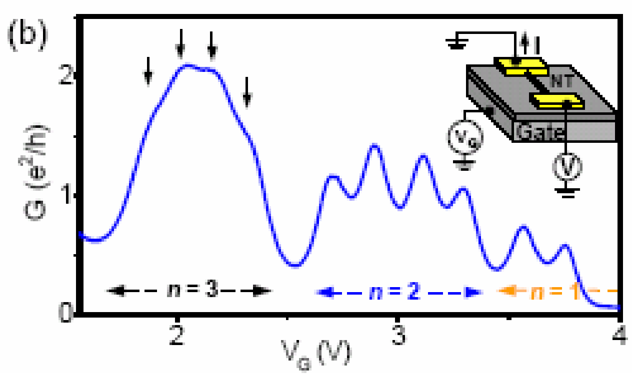
Experiment in carbon nanotubes

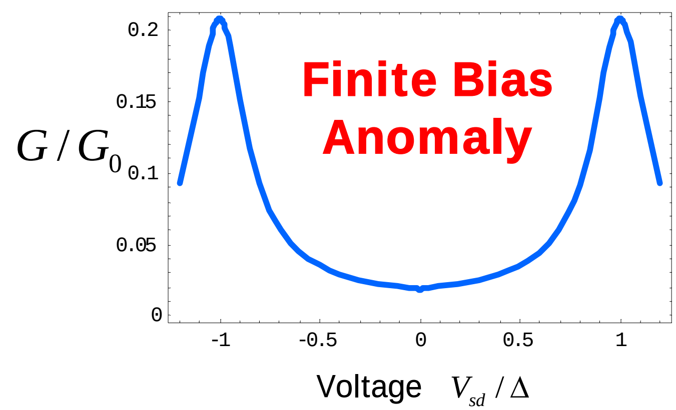


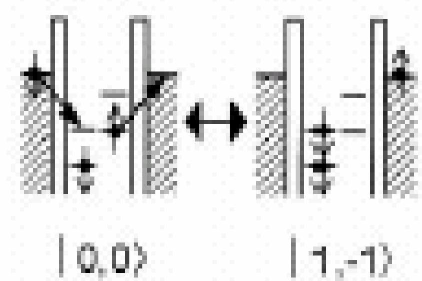






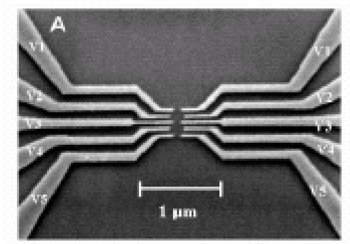


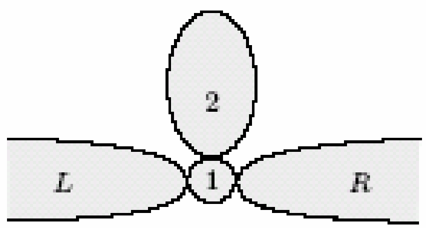




P.Jarillo-Herrero, cond-mat/0411440

Double Quantum Dot: SU(4) physics and quantum criticality





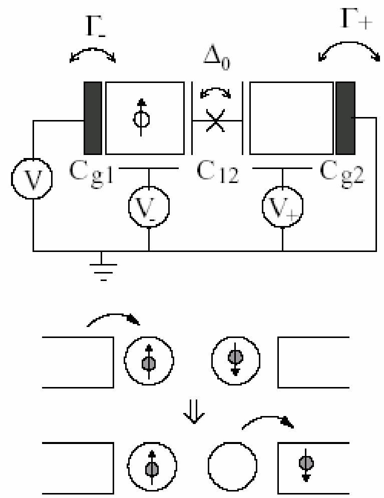
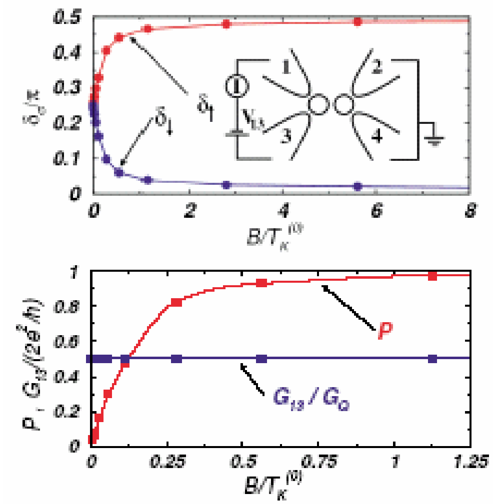


FIG. 1. Upper part: Schematics of the DD device. Lower part: Virtual process leading to 'spin-flip assisted tunneling' as described in Eq. (4)

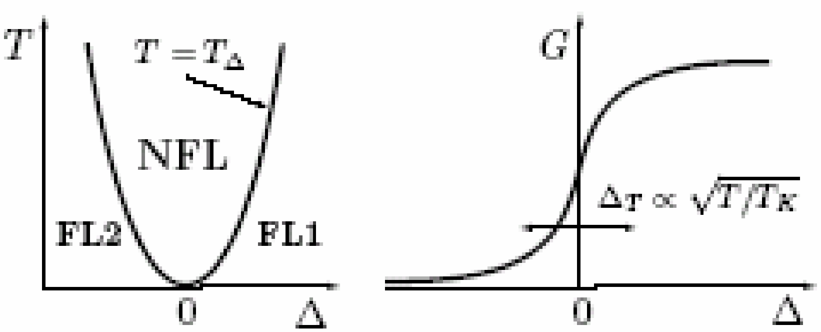


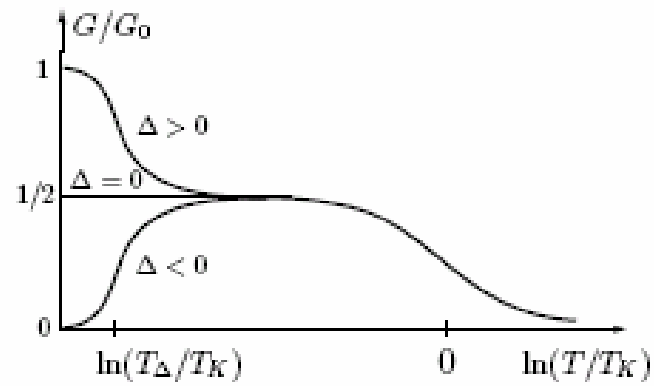
SU(4) symmetry

L.Borda et al (2003)

$$\Delta = \nu(J_1 - J_2)$$

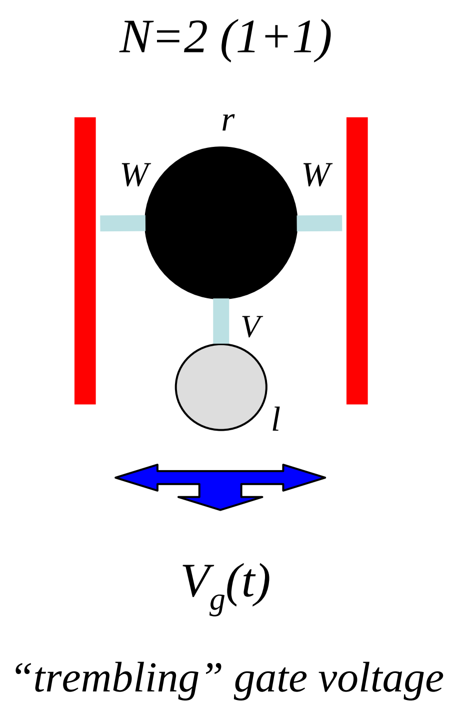
Electrons in large dot provide an additional channel for Kondo effect

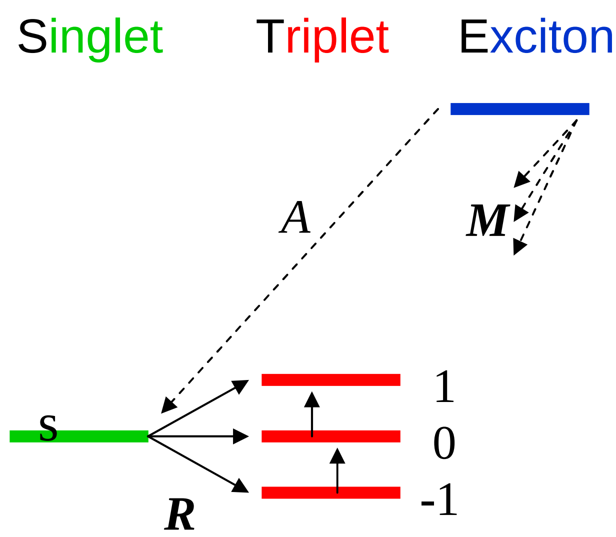




M.Pustilnik et al (2004)

Perspectives:
Double Quantum Dot as Charge-Spin Transformer





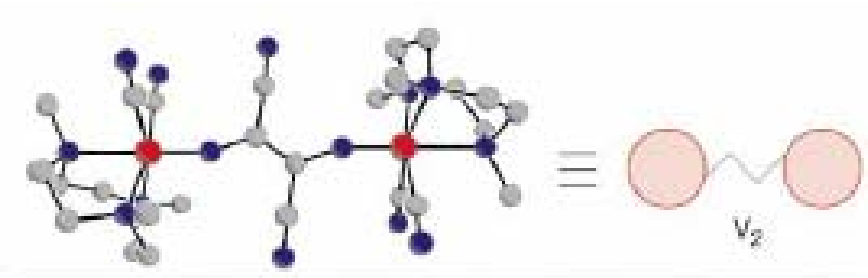
SO(5) algebra

Transformation of charge fluctuations (noise) to spin fluctuations

Relaxation, dephasing, decoherence…

MK, K.Kikoin, Y.Avishai, and J.Richert (in progress)

Perspectives:
Phonon-induced Kondo effect in real and artificial molecules



- How may a distortion excite magnetic degrees of freedom?
- Is it possible to achieve Kondo regime by inelastic processes?
- Single-phonon assisted processes vs multiphonon processes.

MK, K.Kikoin, Y.Avishai, and M.Wegewijs (in progress)

Messages

Kondo tunneling in QD with few electrons is more rich effect than Kondo scattering in metals

The effects of dynamical symmetries are directly observable in transport experiments

Singlet/Triplet mixing can be controlled by the gate voltage and results in peculiar non-equilibrium effects