Lectures: Condensed Matter II

1 – Quantum dots

2 – Kondo effect: Intro/theory.

3 – Kondo effect in nanostructures

Luis Dias – UT/ORNL

Lecture 3: Outline

- Quantum Dots: brief review.
- Kondo effect: Review.
- Kondo effect in quantum dots.
- Kondo effect in Single Molecule Transistors.
- Kondo effect in Surfaces (STM, “quantum mirage”).
- Kondo effect in carbon nanotubes.

History of Kondo Phenomena

- Observed in the ‘30s
- Explained in the ‘60s
- Numerically Calculated in the ‘70s (NRG)
- Exactly solved in the ‘80s (Bethe-Ansatz)

So, what’s new about it?

Kondo correlations observed in many different set ups:

- Transport in quantum dots, quantum wires, etc
- STM measurements of magnetic structures on metallic surfaces (e.g., single atoms, molecules. “Quantum mirage”)
- ...

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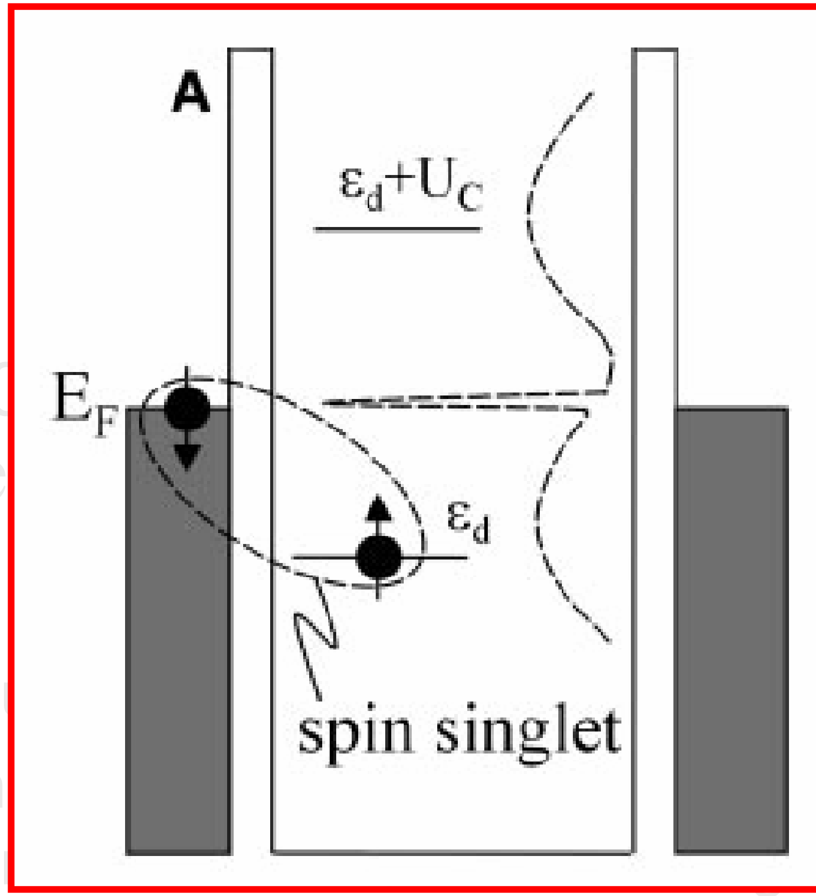
So, what's ne



Kondo correlations observed

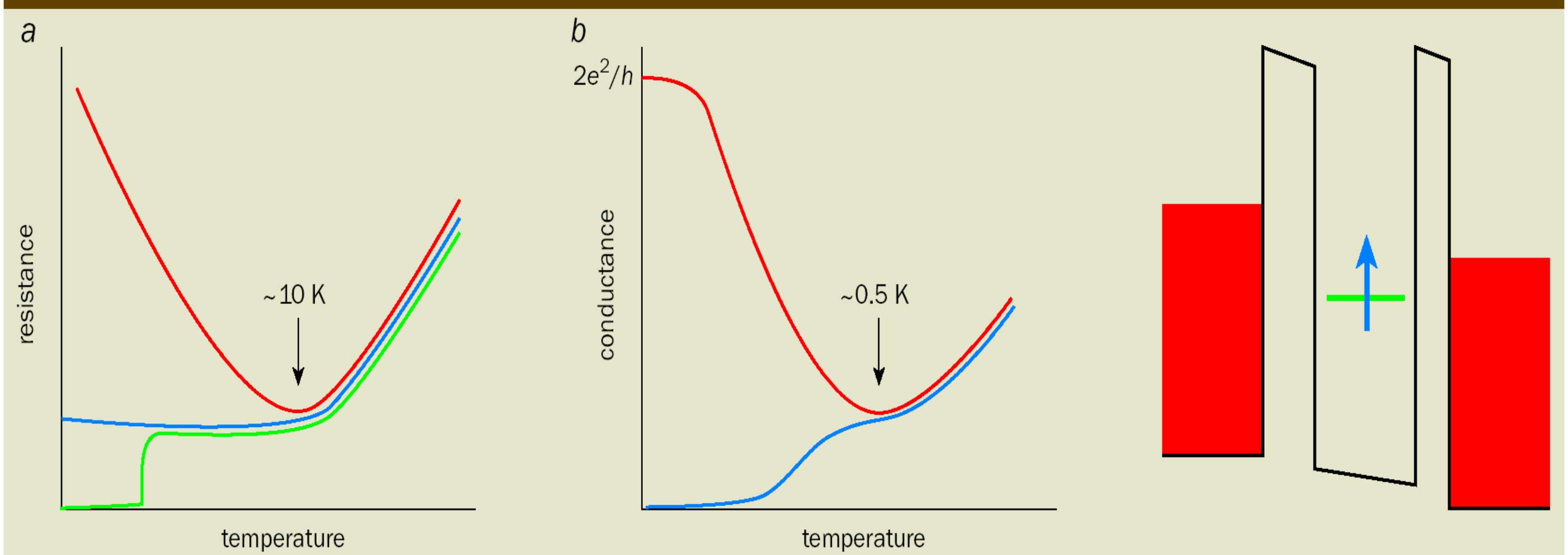
- <u>Transport in quantum dots</u>, q
- STM measurements of magn surfaces (e.g., single atoms, ')
- ...

Kondo Effect in Quantum Dots

Revival of the Kondo effect

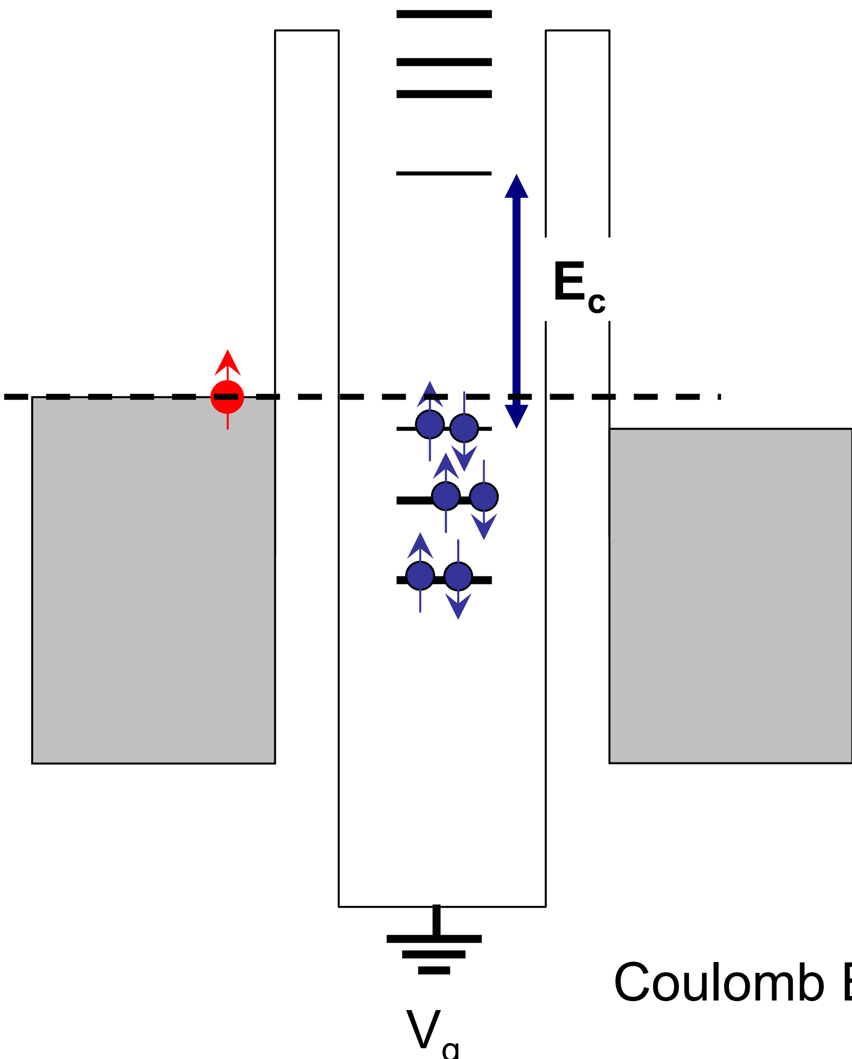
Leo Kouwenhoven and Leonid Glazman

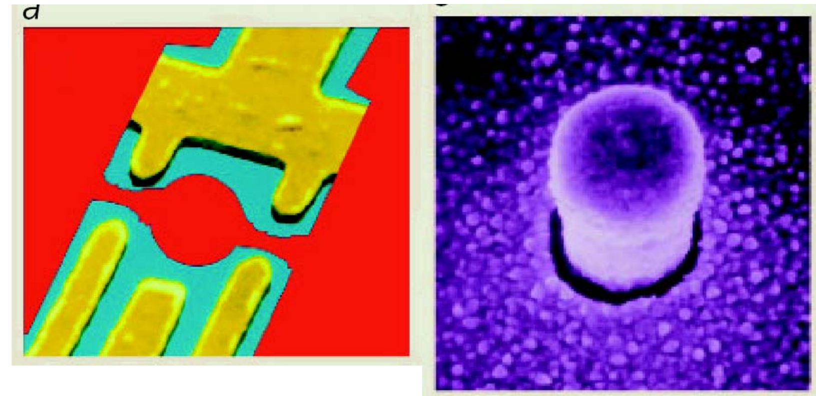
1 The Kondo effect in metals and in quantum dots

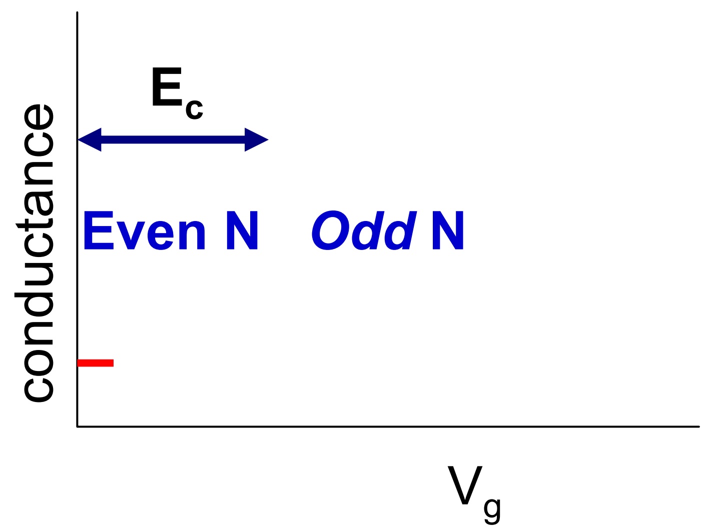


Kowenhoven and Glazman *Physics World* – Jan. 2001.

Coulomb Blockade in Quantum Dots

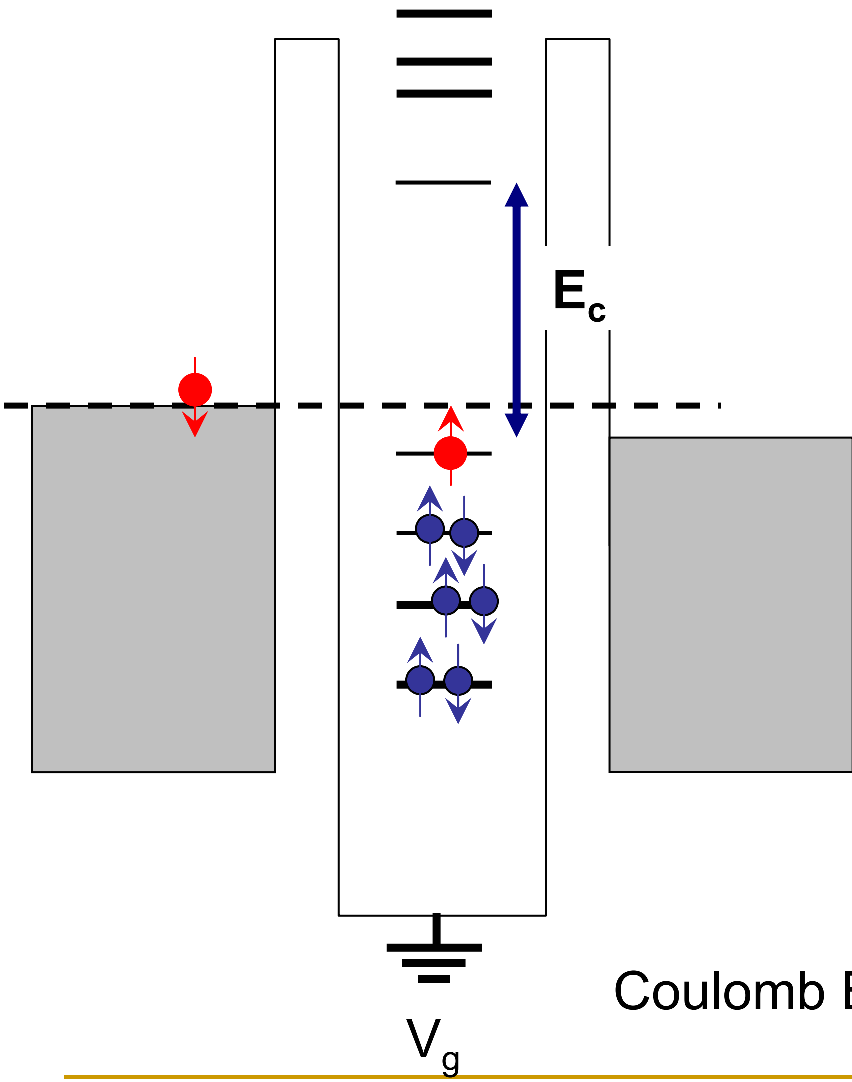


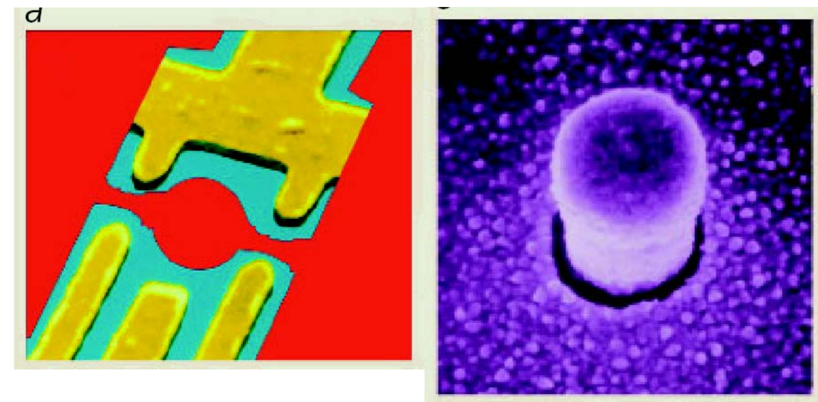


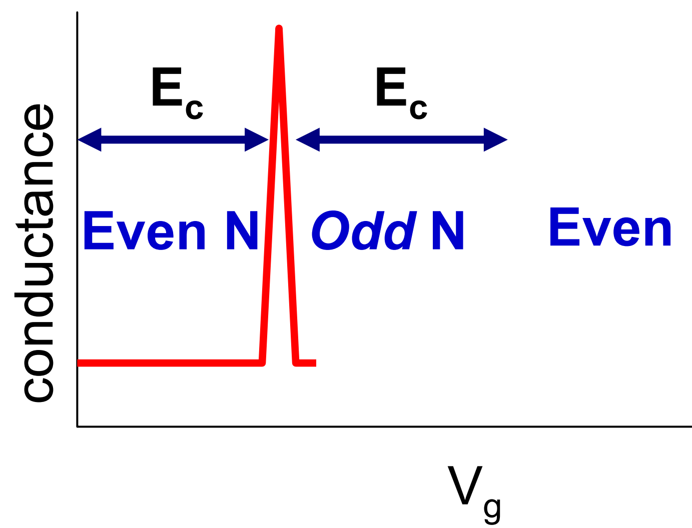


Coulomb Blockade in Quantum Dots

Coulomb Blockade in Quantum Dots



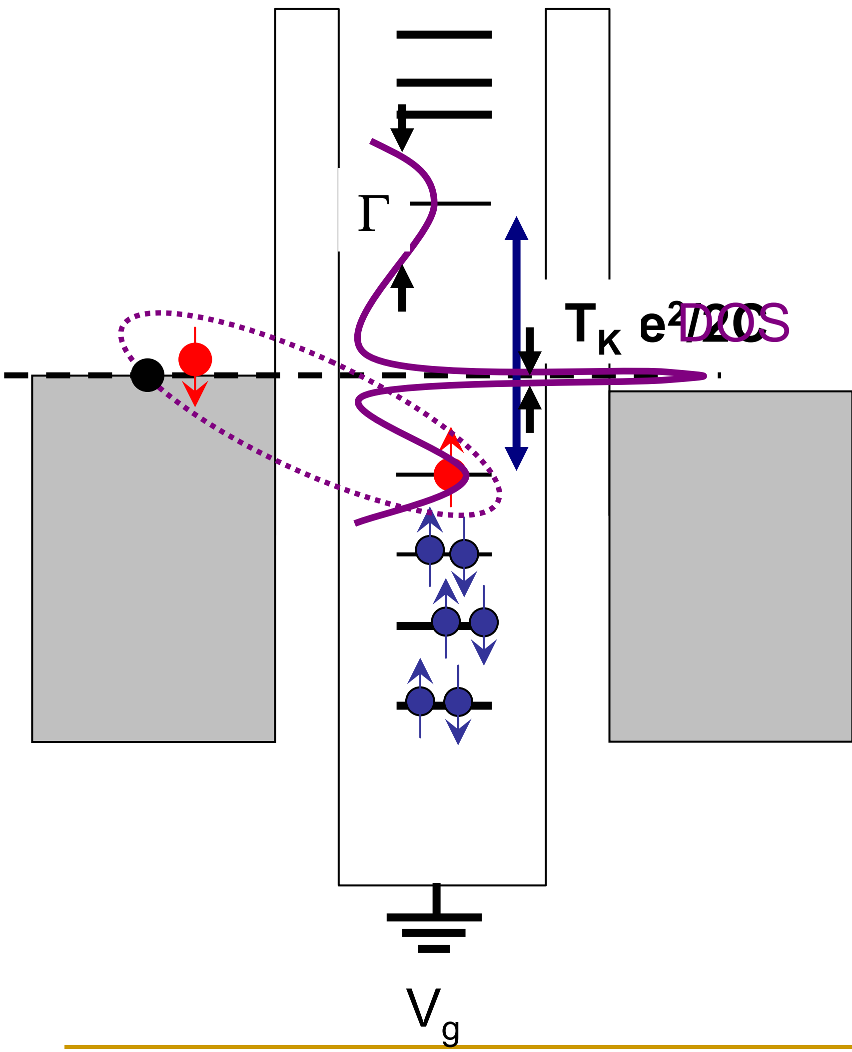


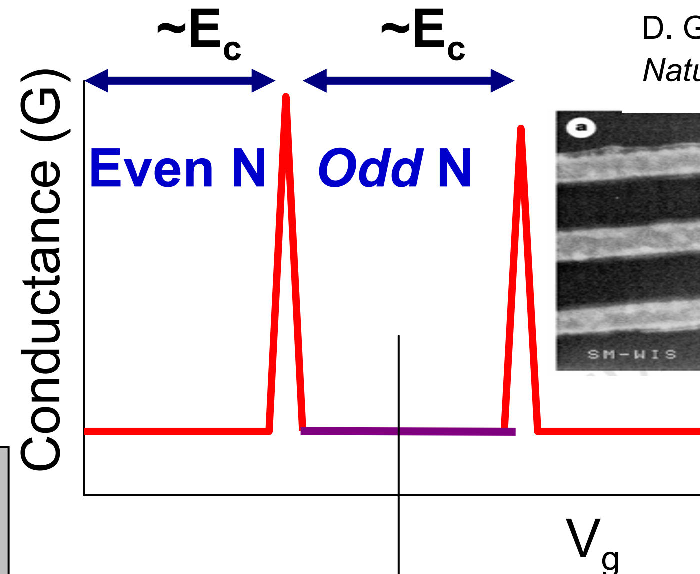


Coulomb Blockade in Quantum Dots

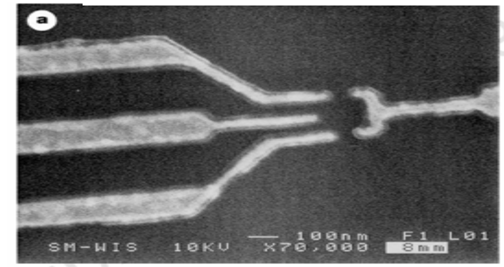
Y. Alhassid *Rev. Mod. Phys.* **72** 895 (2000).

Kondo Effect in Quantum Dots





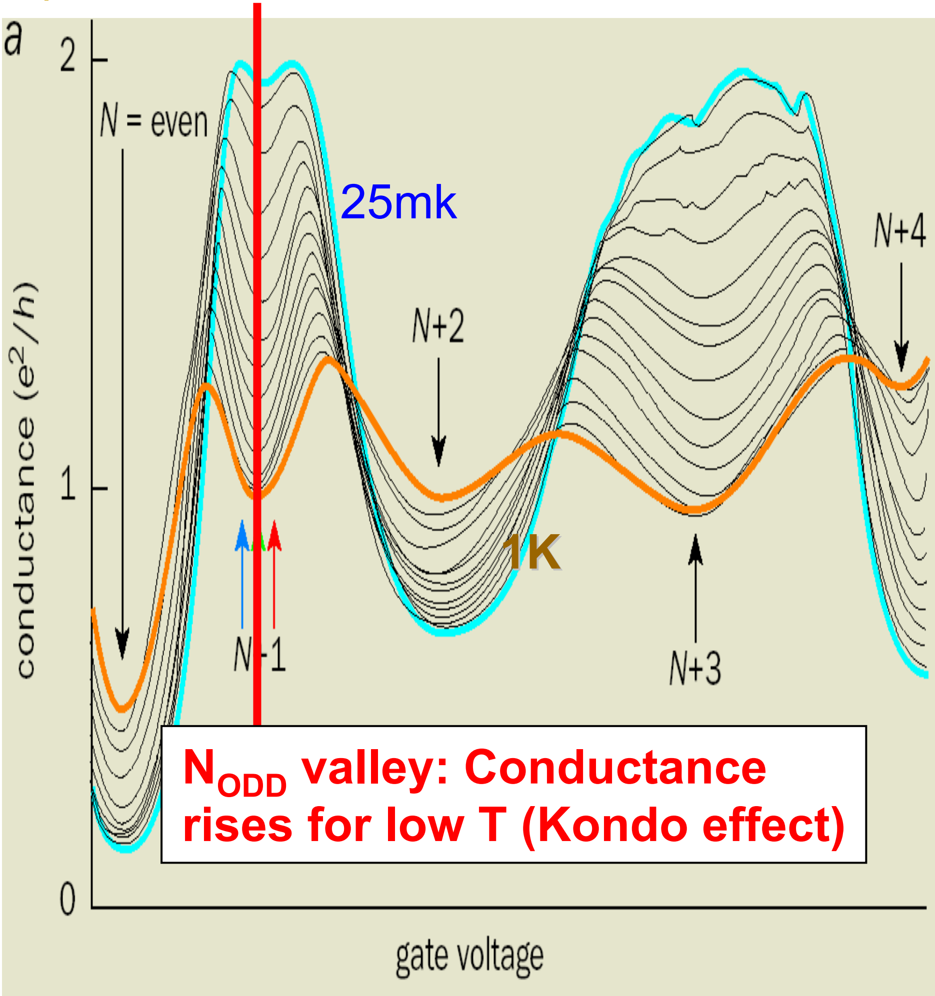
D. Goldhaber-Gordon et al
Nature **391** 156 (1998)

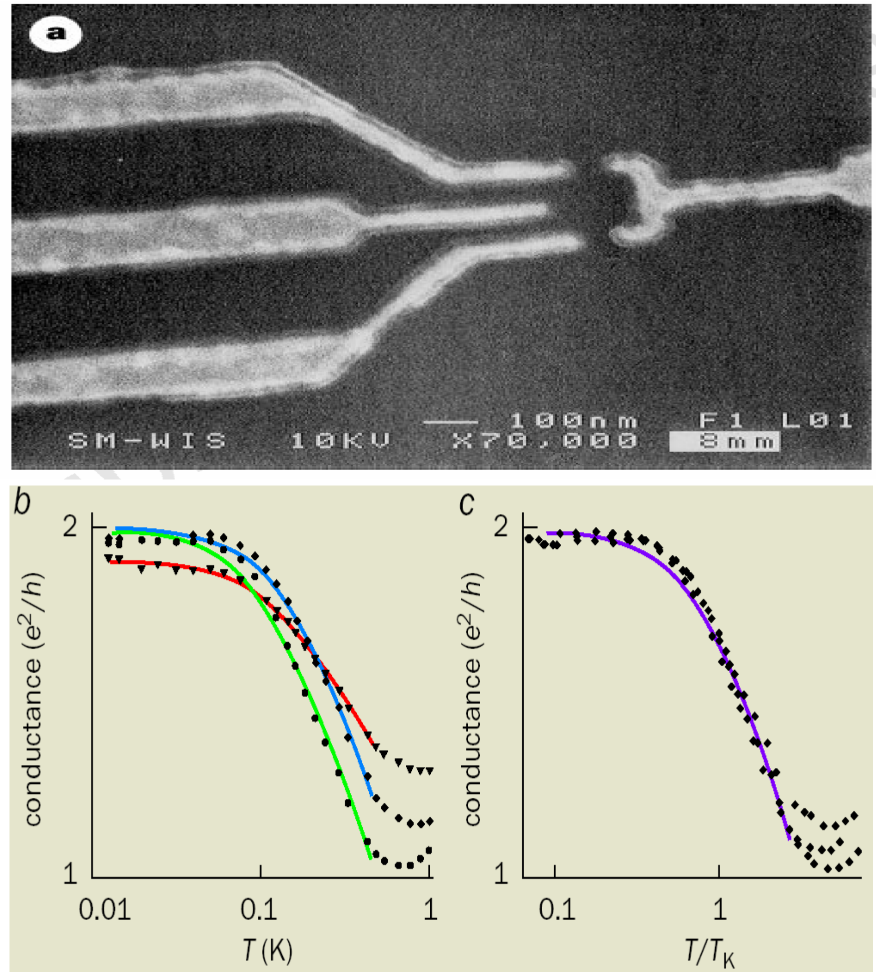


- $T>T_K$: Coulomb blockade (low G)
- $T<T_K$: Kondo singlet formation
- Kondo resonance at E_F (width T_K).
- New conduction channel at E_F:

Zero-bias enhancement of G

Kondo Effect in CB-QDs



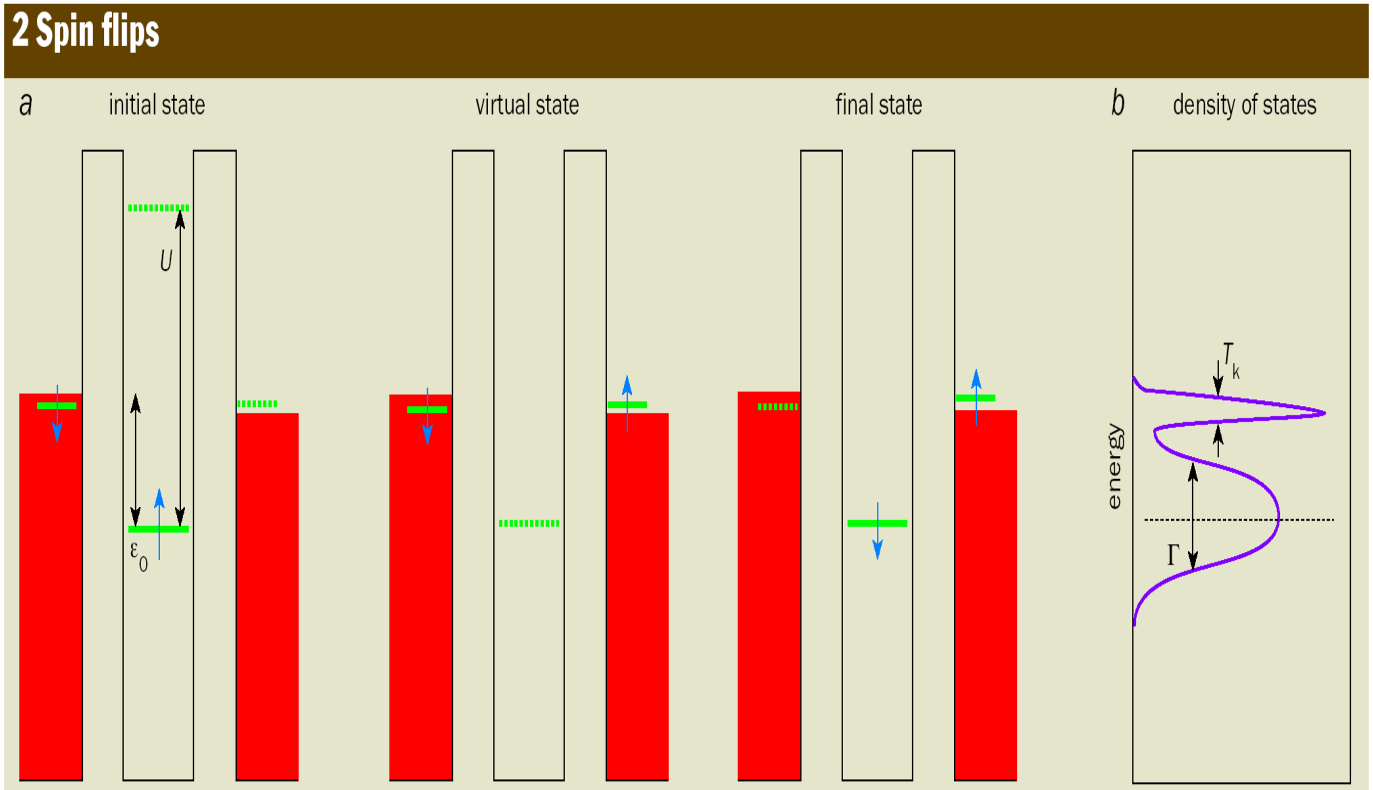


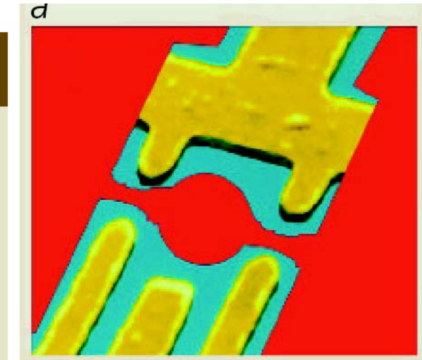
Kondo Temperature T_k : only scaling parameter (~0.5K, depends on V_g)

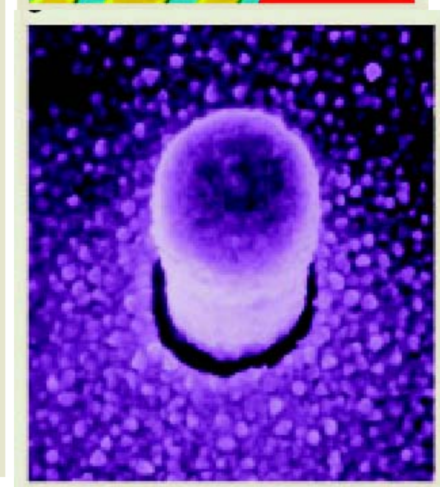
Kowenhoven and Glazman *Physics World* – Jan. 2001.

From: Goldhaber-Gordon *et al. Nature* **391** 156 (1998)

Kondo Effect in Quantum Dots





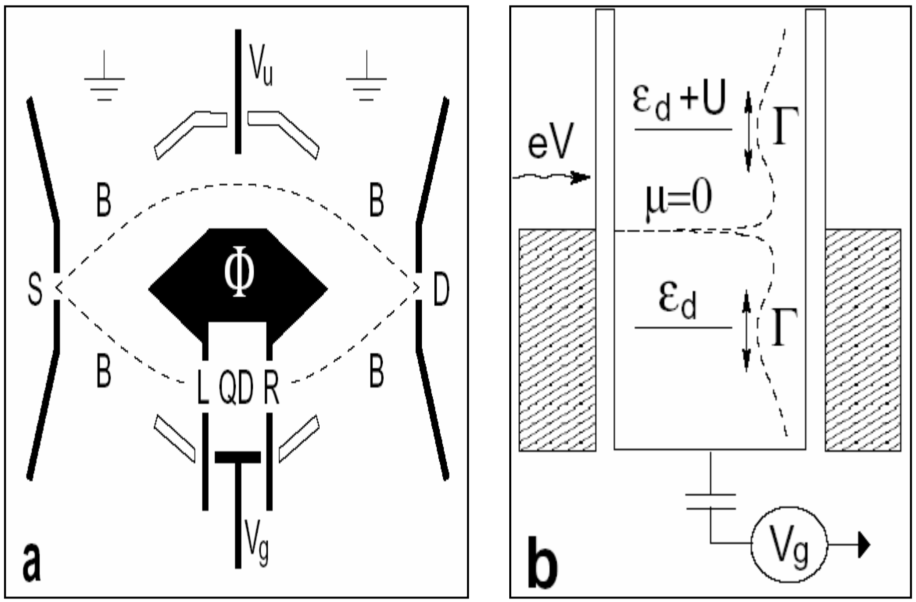


Basic mechanism of the Kondo effect in Coulomb Blocked quantum dots

Kowenhoven and Glazman *Physics World* – Jan. 2001.

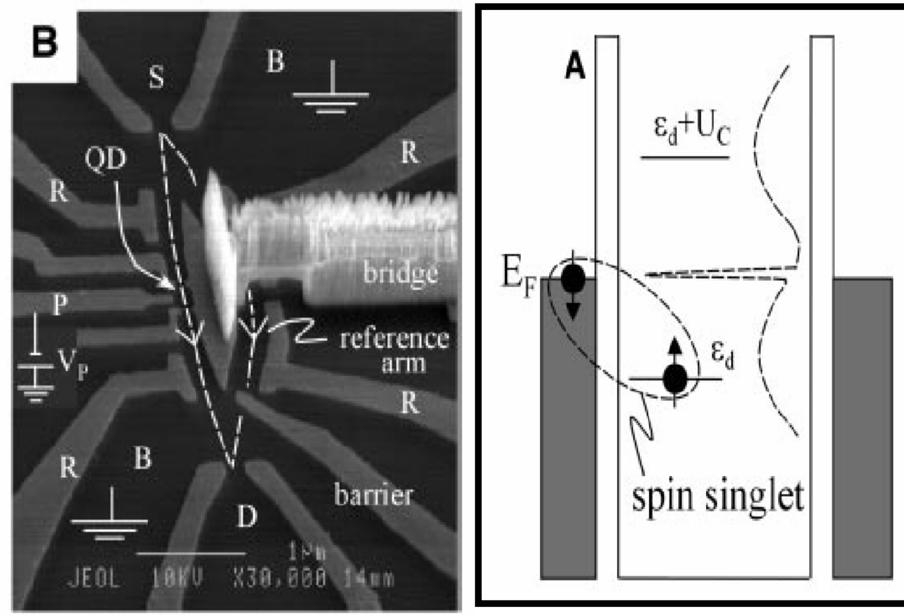
Theory-Experiment ballgame

Transmission Phase Shift of a Quantum Dot with Kondo Correlations



Theory
(Gerland et al.
PRL **84** 3710 (2000))

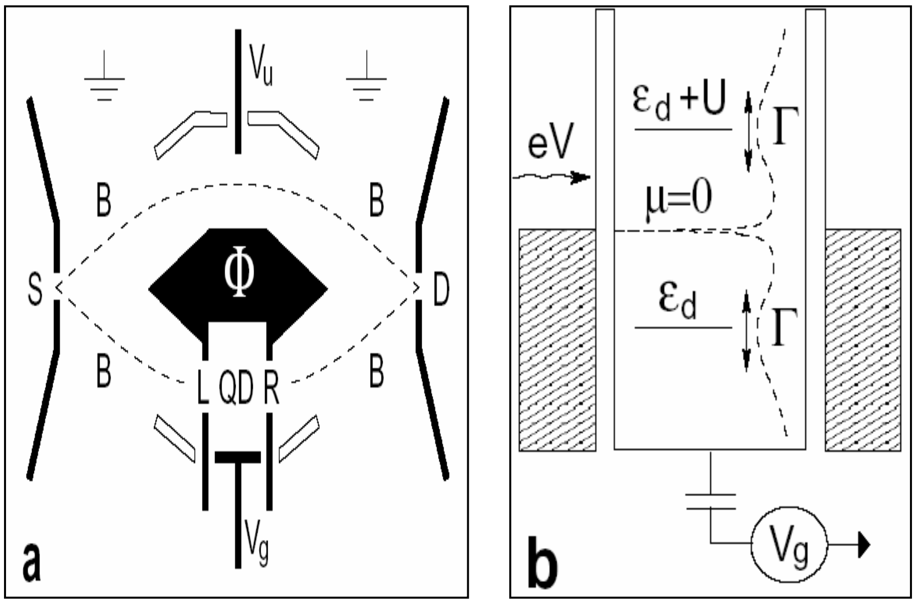
Phase Evolution in a Kondo-Correlated System



Experiment
(Ji, Heiblum et al.
Science **290** 779 (2000))

Theory-Experiment ballgame

Transmission Phase Shift of a Quantum Dot with Kondo Correlations



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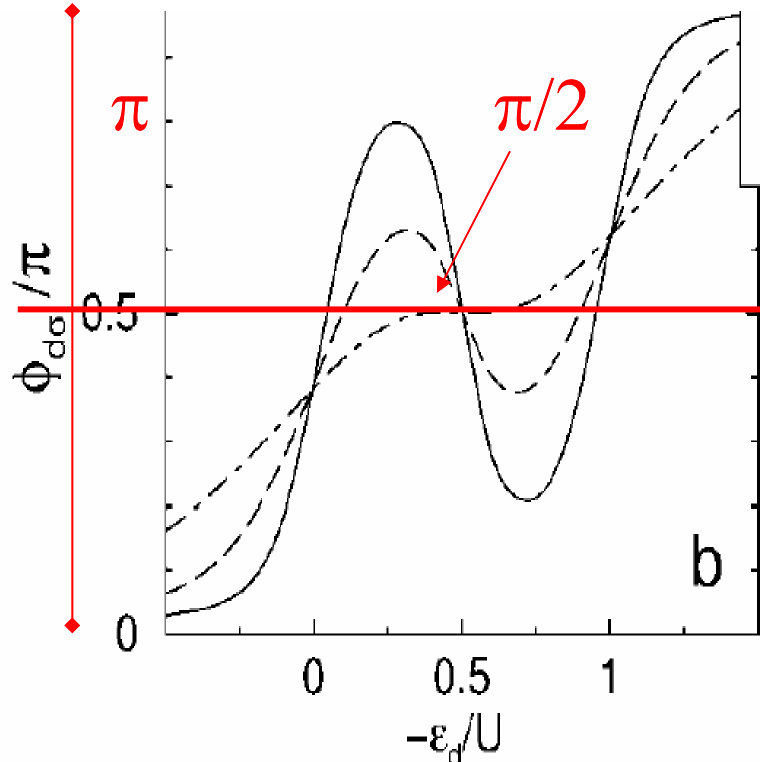
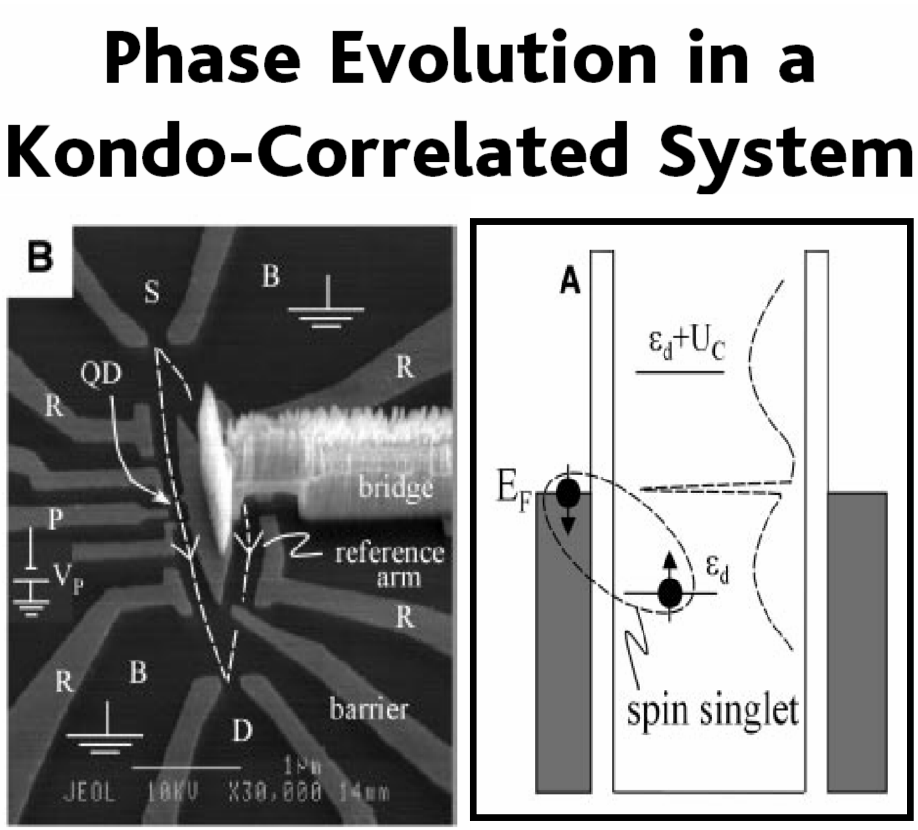


(c) For arbitrary temperatures ($\lesssim\Gamma$), the only approach which gives reliable results for $\mathcal{G}_{d\sigma}(E)$ for all Γ, U, ε_d is the *numerical renormalization group* (NRG)

Theory (Gerland et al. PRL **84** 3710 (2000))

Theory-Experiment ballgame



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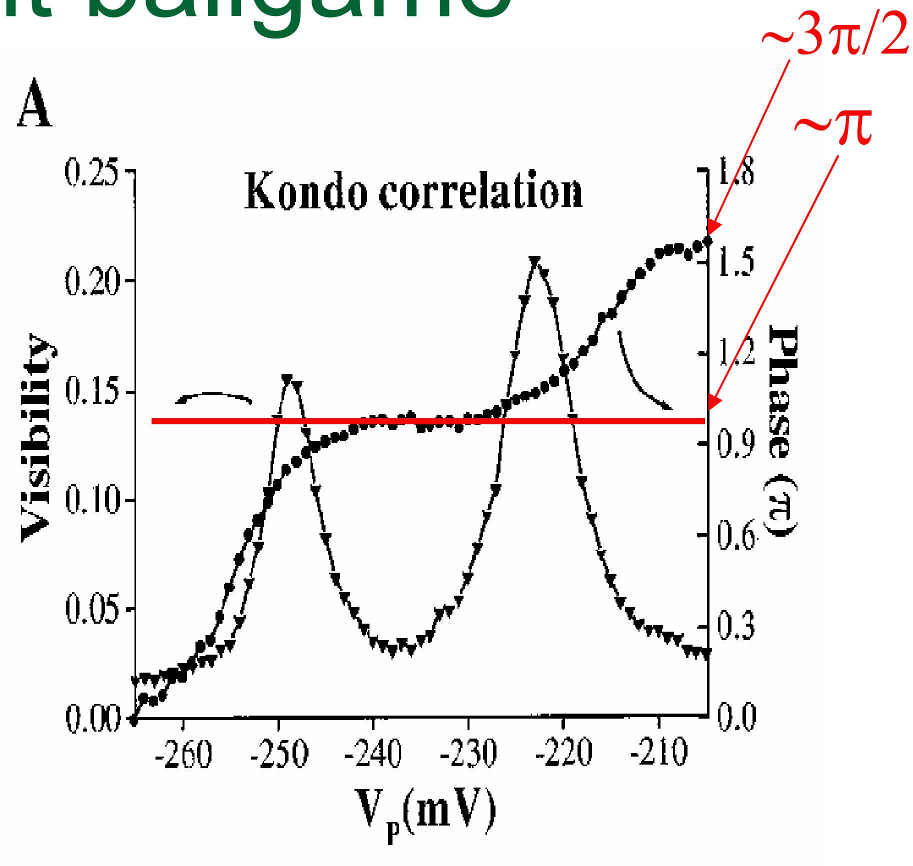
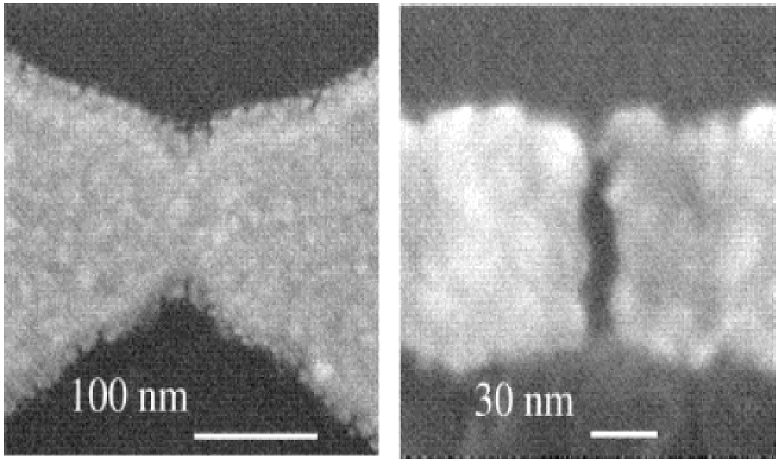
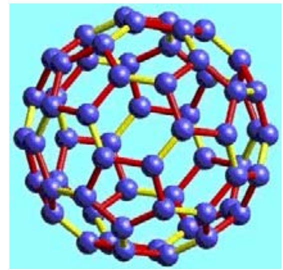


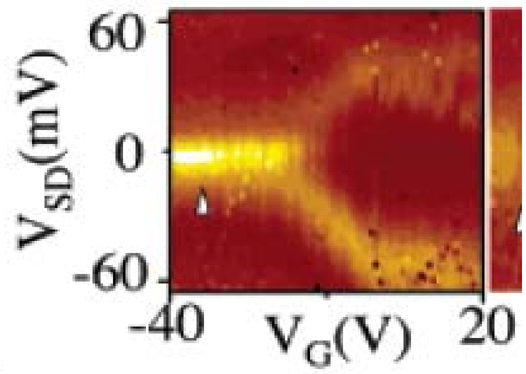
Experiment (Ji et al. *Science* **290** 779 (2000))

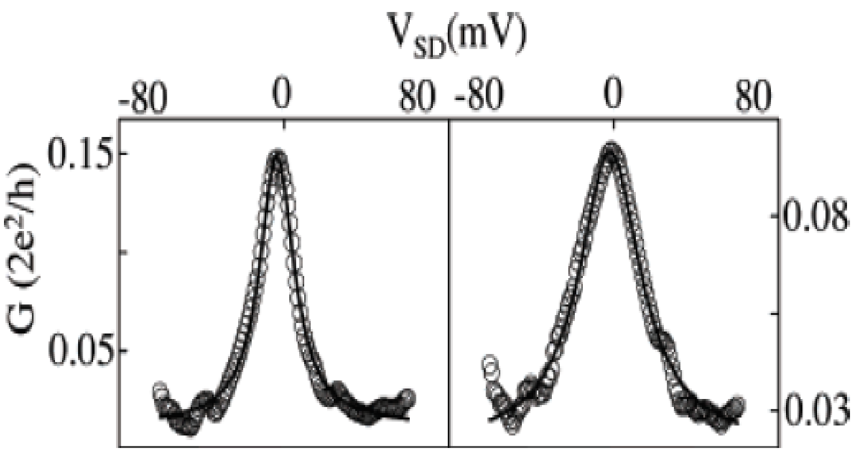
Kondo effect in Single Molecule Transistors





C_{60}



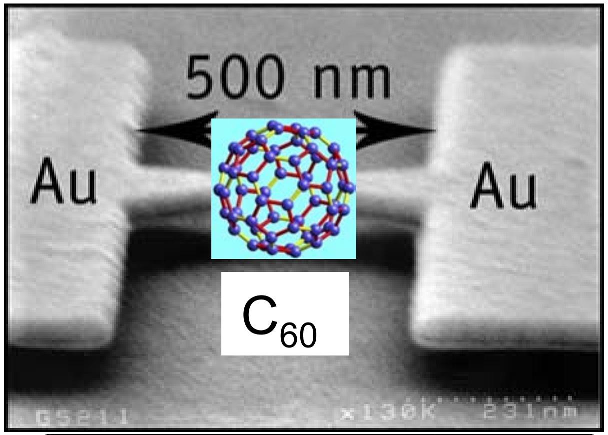


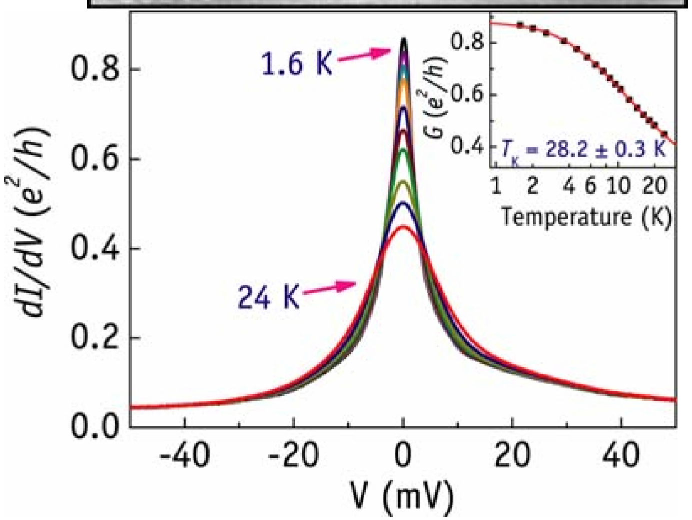
T=18K T=50K

Yu, Natelson, *NanoLett.* **4** 79 (2004).

- Single molecule transistors: C_{60} molecules “caught” between electrodes (break junction).
- Zero-bias peak as a function of gate voltage: correct Kondo scaling.
- Correct behavior vs. Bias.
- T_K>50K .

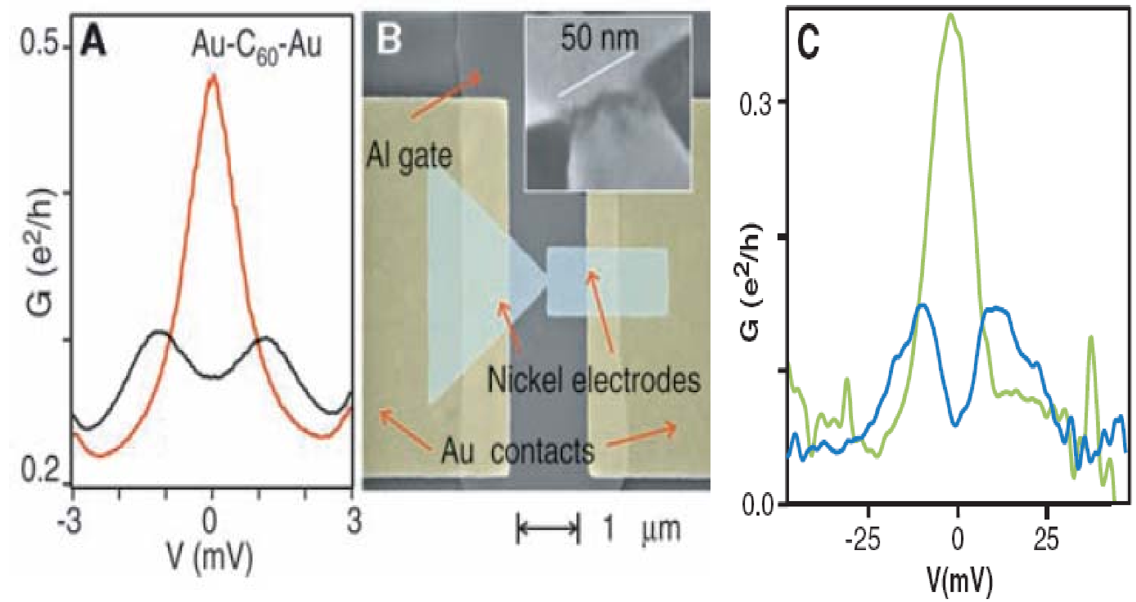
Kondo effect in Single Molecule Transistors





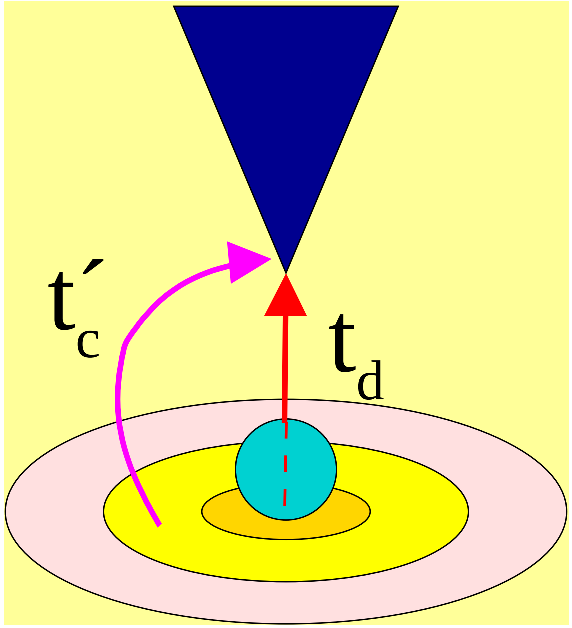
From Dan Ralph's webpage:
http://people.ccmr.cornell.edu/~ralph/

Pasupathy et al., *Science* **306** 86 (2004)

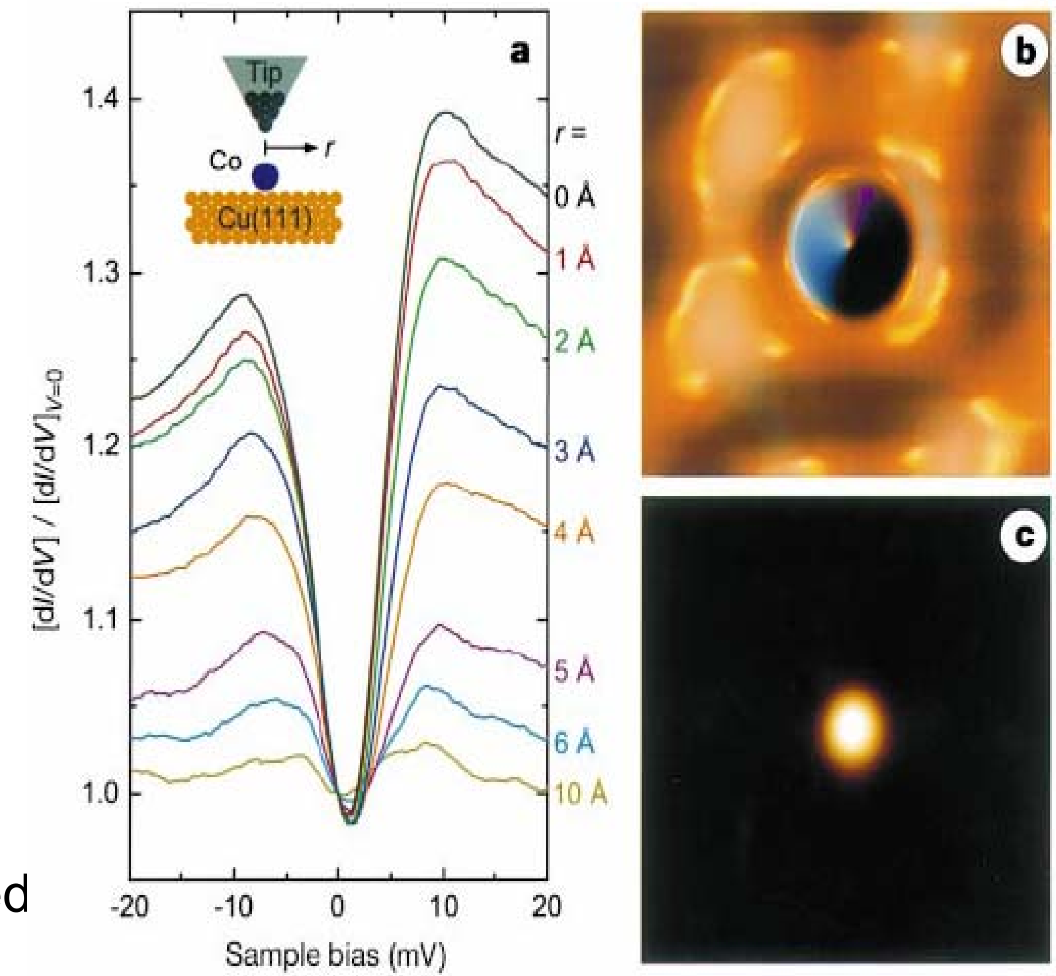


- Similar expts (D. Ralph's group).
- Supression of the Kondo resonance in the presence of a magnetic field (top left, black curve, B=10T) and *magnetic* leads (top right, parallel [green] and antiparallel [blue] magnetizations).

Kondo effect in surfaces (STM images).

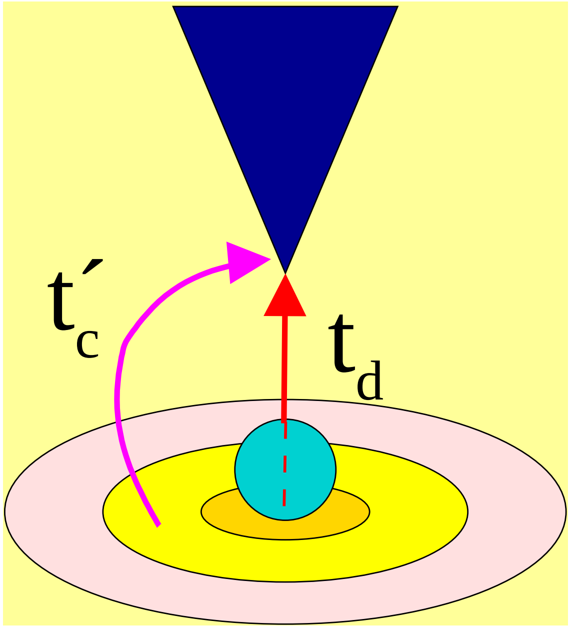


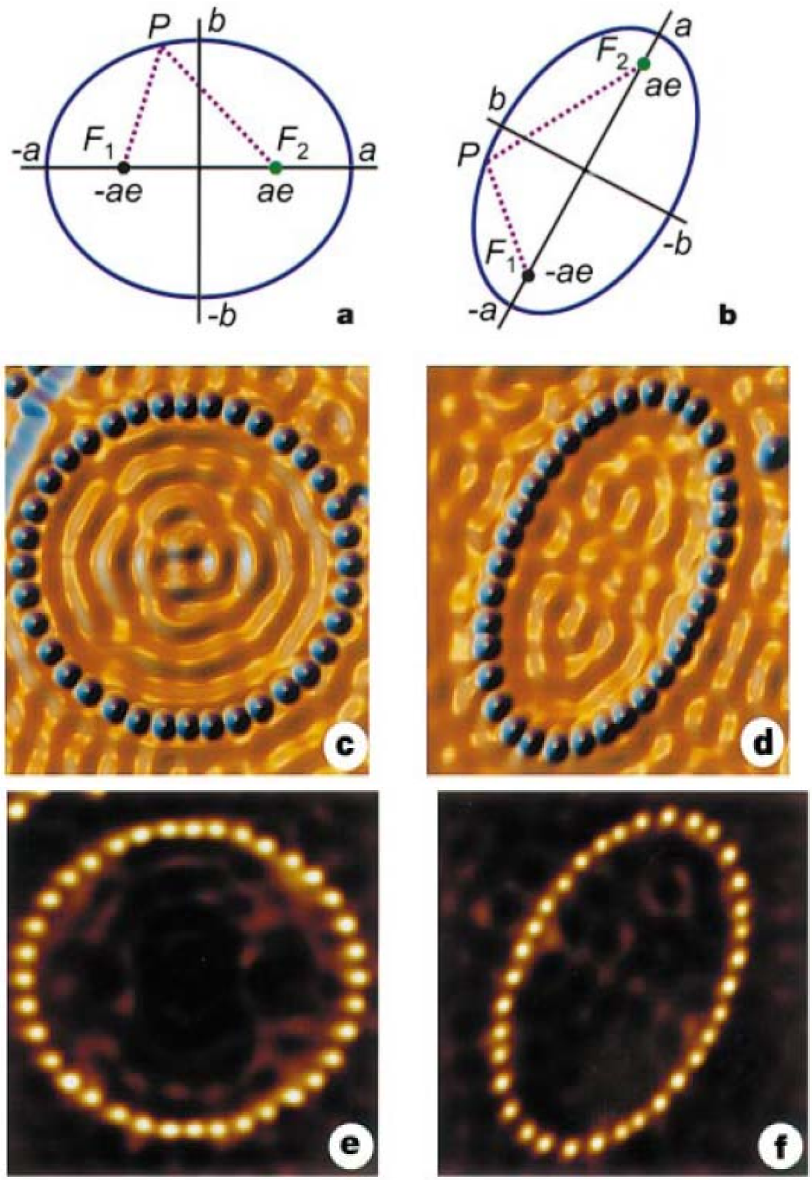
Manoharan et al., *Nature* **403** 512 (2000).



- Magnetic (Co, Fe) atoms on metallic *surfaces!* Right ingredients for Kondo.
- In this case, Kondo is marked by a *dip* at zero-bias conductance (dI/dV at V=0).

Kondo effect surfaces: STM measurements.

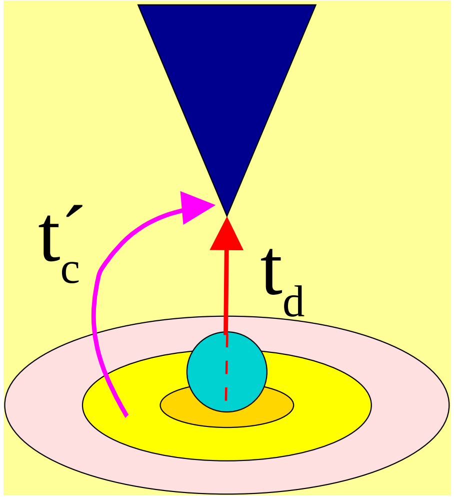




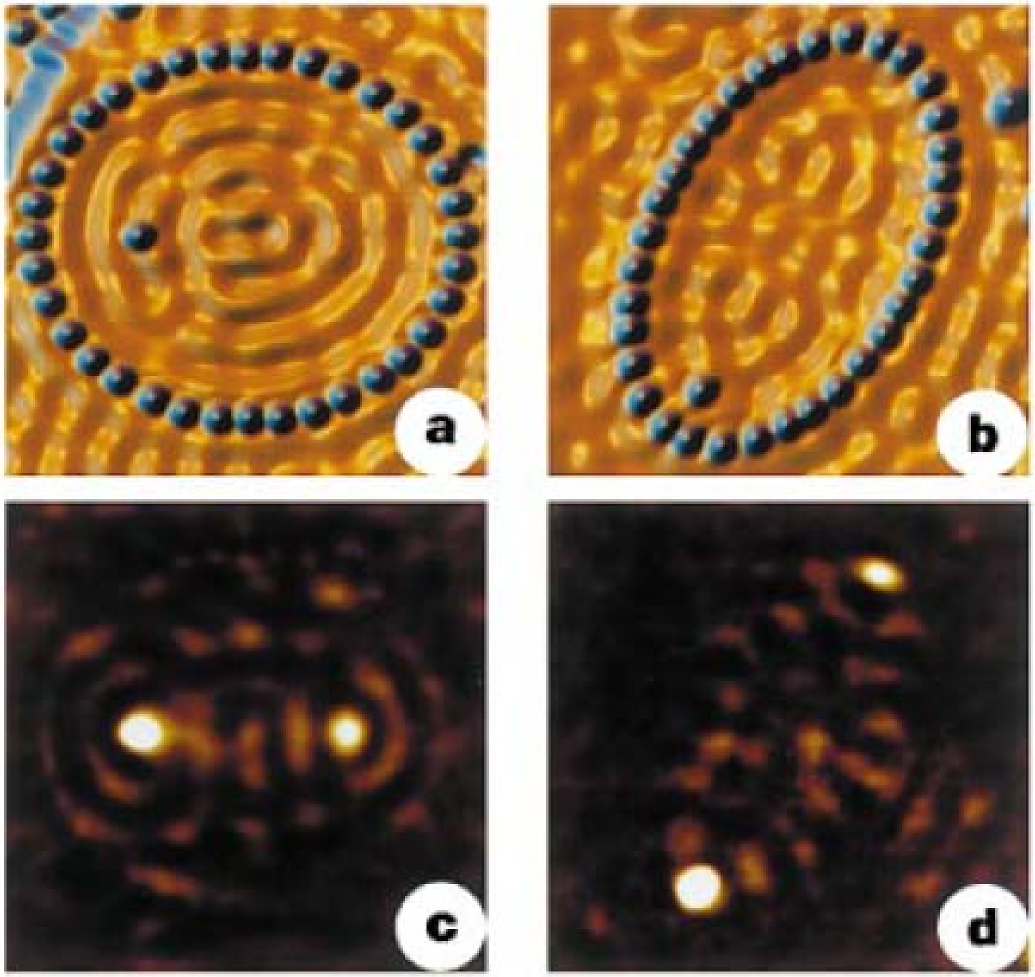
- STM atomic manipulation: can build local structures ("quantum corrals").
- Elliptical shape: imaging (top) and dI/dV measurements (bottom).
- Cobalt atoms on Cu(111) shown.

Manoharan et al., *Nature* **403** 512 (2000).

Kondo effect surfaces: STM measurements.



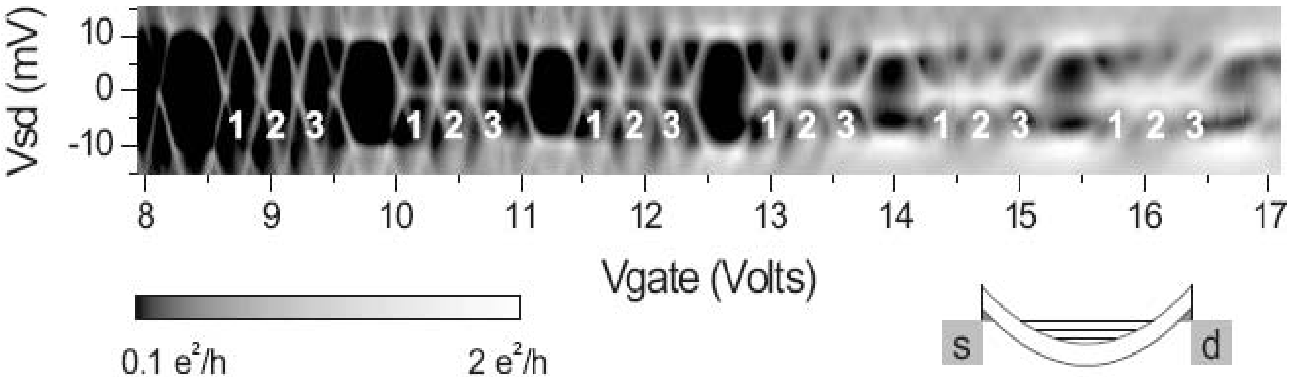
Manoharan et al., *Nature* **403** 512 (2000).

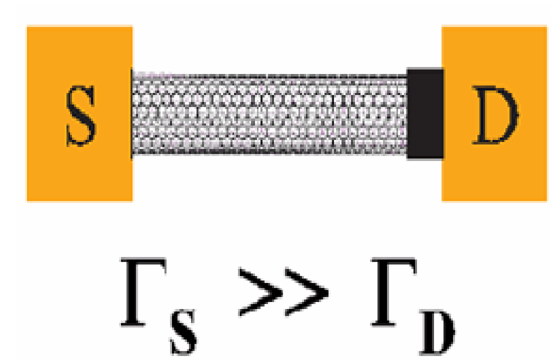


- One extra atom placed in one foci: a peak in the dIdV appears in the other focus athough NO ATOM is there! ("quantum mirage").
- Theory: "focusing" of Kondo-scattered surface electrons*.

*Schiller and Agam, *PRL* **86** 484 (2001)..

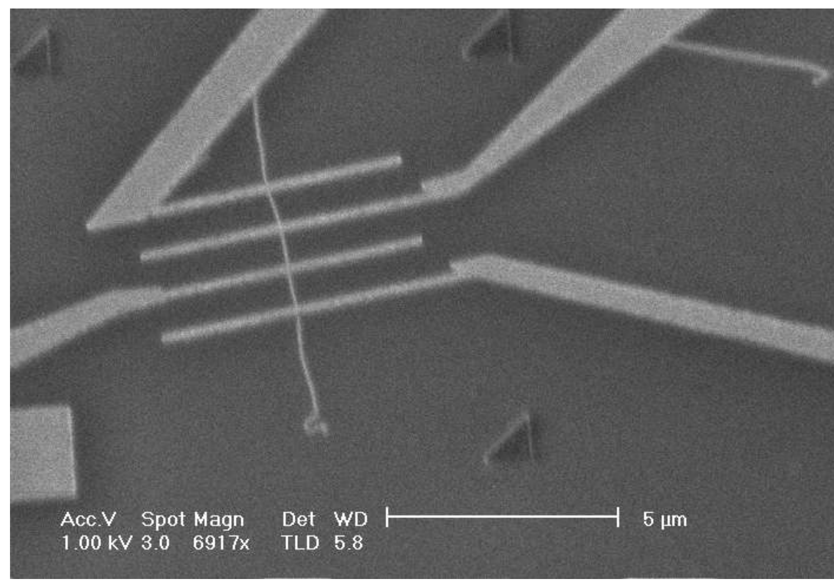
Kondo effect In Carbon nanotubes.





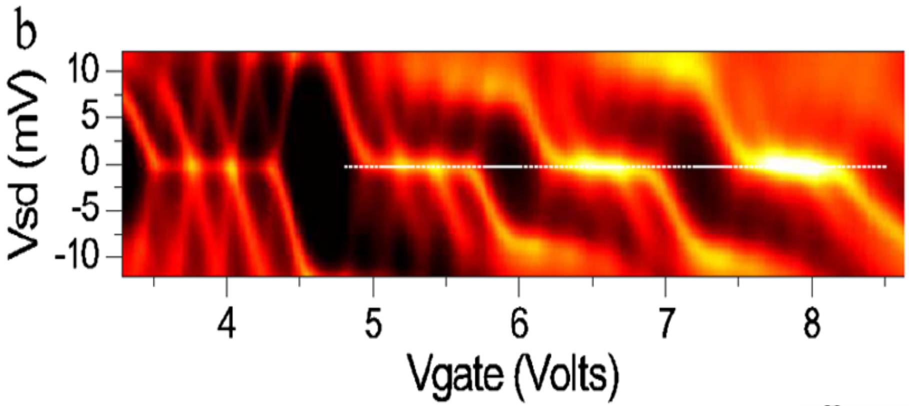
Makarovski, Zhukov, Liu, Filkenstein *PRB* **75** 241407R (2007).

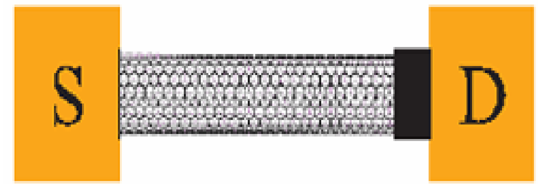
- Carbon nanotubes depsited on top of mettalic electrodes.
- Quantum dots defined *within* the carbon nanotubes.
- More structure than in quantum dots: “shell structure” due to *orbital* degeneracy.



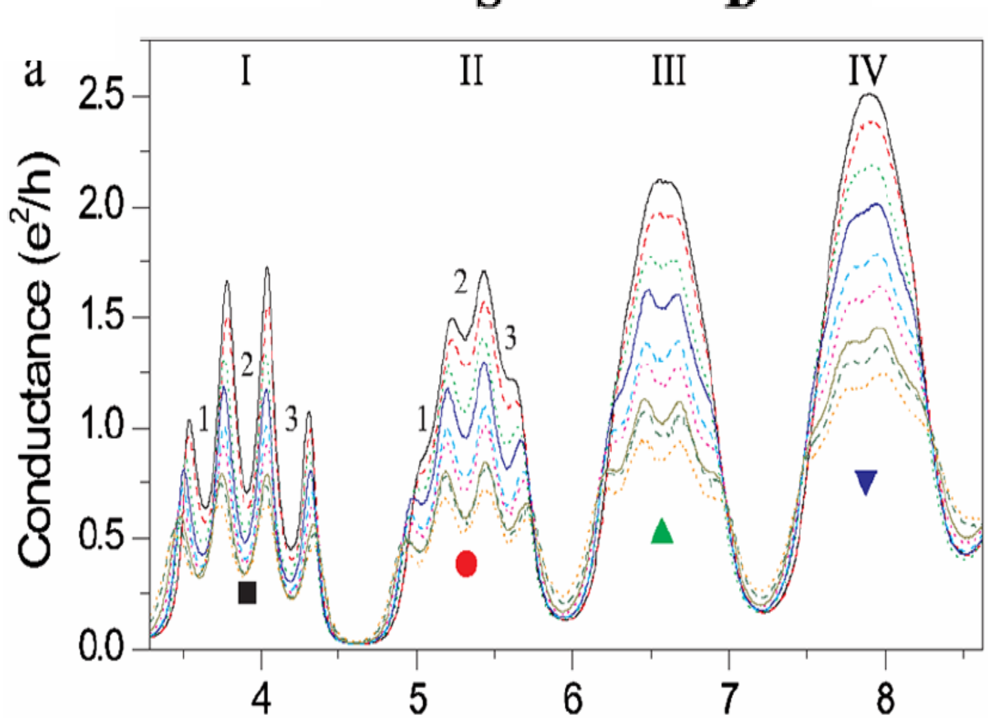
Gleb Filkenstein’s webpage: http://www.phy.duke.edu/~gleb/

Kondo effect In Carbon nanotubes.





$$\Gamma_S \gg \Gamma_D$$



Makarovski, Liu, Filkenstein *PRL* **99** 066801 (2007).

- Temperature behavior is Kondo-like.
- Interesting *merging of the four shells* at high V_g ("SU(4)" Kondo instead of the usual SU(2) Kondo).
- NRG calculations* support that picture.

* Anders, Logan, Galpin, Filkenstein *PRL* **100** 086809 (2008).