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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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

Coulomb Blockade in Quantum Dots

Even $N$  $Odd$ $N$

Coulomb blockade in quantum dots.
Coulomb Blockade in Quantum Dots

Kondo Effect in Quantum Dots

- $T > T_K$: 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 $G$

D. Goldhaber-Gordon et al
Kondo Effect in CB-QDs

\[ 25 \text{ mk} \]

\[ N_{\text{ODD}} \text{ valley: Conductance rises for low } T \text{ (Kondo effect)} \]

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


Kondo Effect in Quantum Dots

Basic mechanism of the Kondo effect in Coulomb Blocked quantum dots

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

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

(c) For arbitrary temperatures ($\leq \Gamma$), the only approach which gives reliable results for $G_{dd'}(E)$ for all $\Gamma, U, \varepsilon_d$ is the numerical renormalization group (NRG)
Theory-Experiment ballgame

Phase Evolution in a Kondo-Correlated System

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

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Kondo effect in Single Molecule Transistors

- 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


- 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).

- Magnetic (Co, Fe) atoms on metallic \textit{surfaces}. Right ingredients for Kondo.
- In this case, Kondo is marked by a \textit{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.

Kondo effect surfaces: STM measurements.

- One extra atom placed in one foci: a peak in the dIdV appears in the other focus although 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.

- Carbon nanotubes deposited on top of metallic 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.

- 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.