Kondo Effect in Quantum Dots

Based on the Papers:

Kondo effect in a single-electron transistor

D. Goldhaber-Gordon et al.

NATURE, VOL 391, 8 JANUARY 1998

A Tunable Kondo Effect in Quantum Dots

Sara M. Cronenwett et al.

24 JULY, VOL 281, SCIENCE

Overview

- Introduction:
  - The Kondo Effect
  - Electron transport in a Quantum Dot
- First measurements of Kondo effect in QD
  - Zero-bias differential conductance
  - Differential conductance out of equilibrium ($V_{ds} \neq 0$, $B \neq 0$)
  - Stability diagram
- Summary

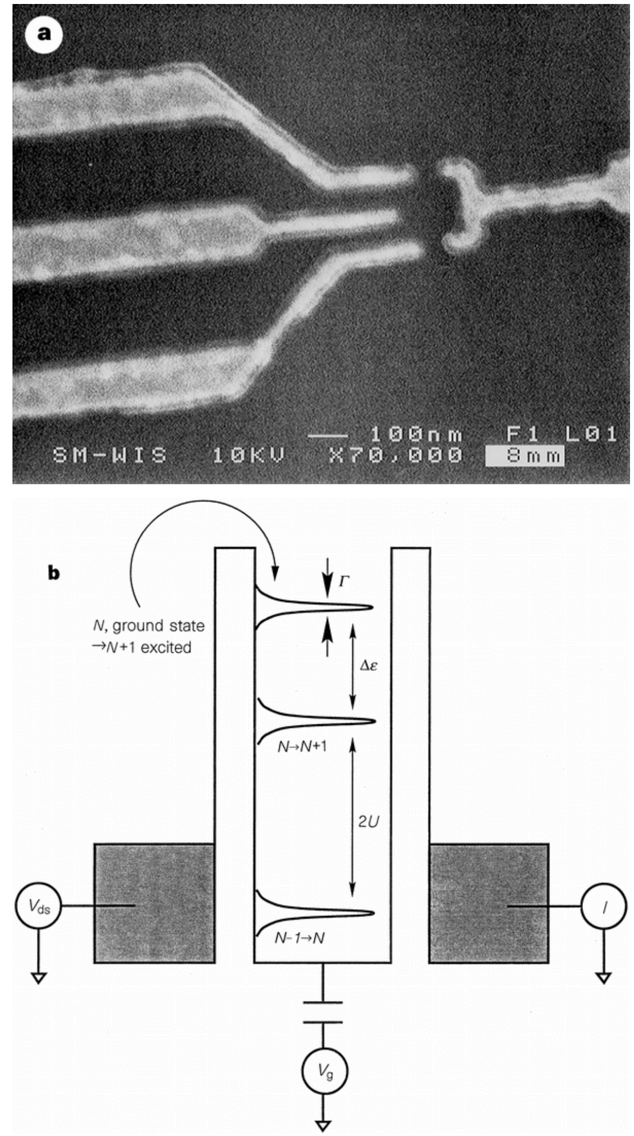
Introduction:

The Kondo Effect

- Interaction between localized and delocalized electrons
- Originally found in metals with impurity atoms with an unpaired electron
- At low temperatures, the spin of an unpaired localized electron forms a singlet state with surrounding delocalized electrons at the Fermi energy
- Interaction due to scattering between localized and delocalized electrons combined with a spin-flip of the localized electron

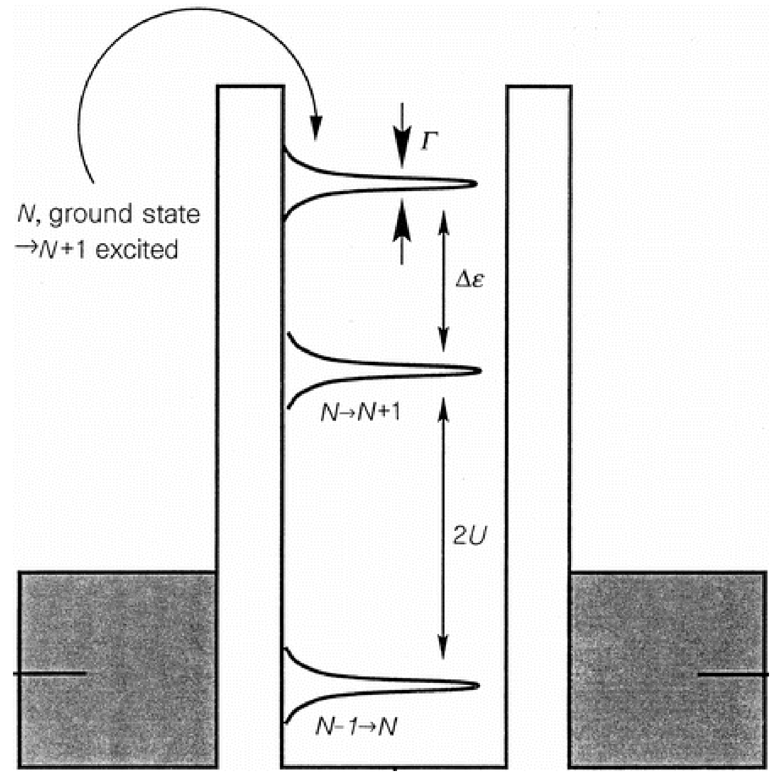
Realization of a QD

- 2DEG in a GaAs/AlGaAs heterostructure
- Further restrictions by applying negative voltage to metal gates on top of the 2DEG
- Dot diameter of ~100 nm
- Importance of small dots, as we will see...



Important energy scales of a QD

- Charging energy: $\boldsymbol{U=e^2/2C}$
- Energy difference between spatial electronic states $\boldsymbol{\Delta\varepsilon}$
- Coupling to leads $\boldsymbol{\Gamma}$ and represents width of spectral density of dot energy levels
- Kondo temperature $\boldsymbol{k_B T_K}$ $= [U\Gamma/4]^{1/2} exp[\pi\varepsilon_0(\varepsilon_0+U)/\Gamma U] < \Gamma$

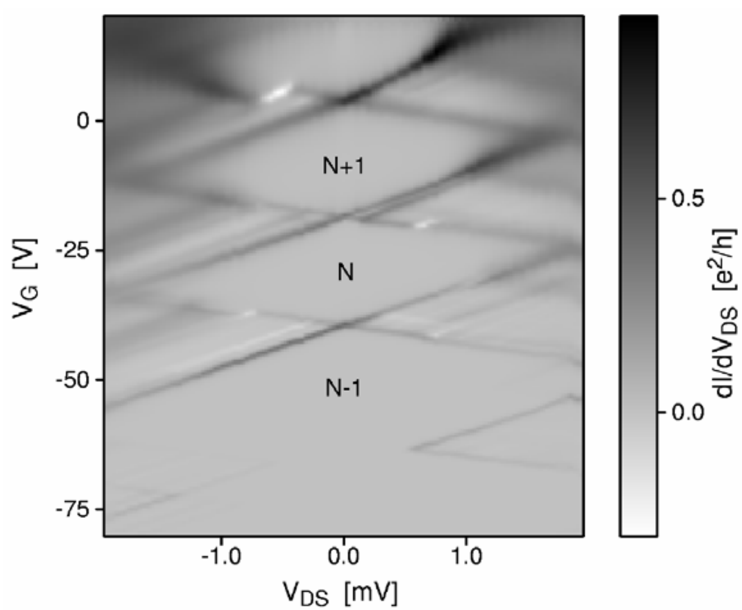


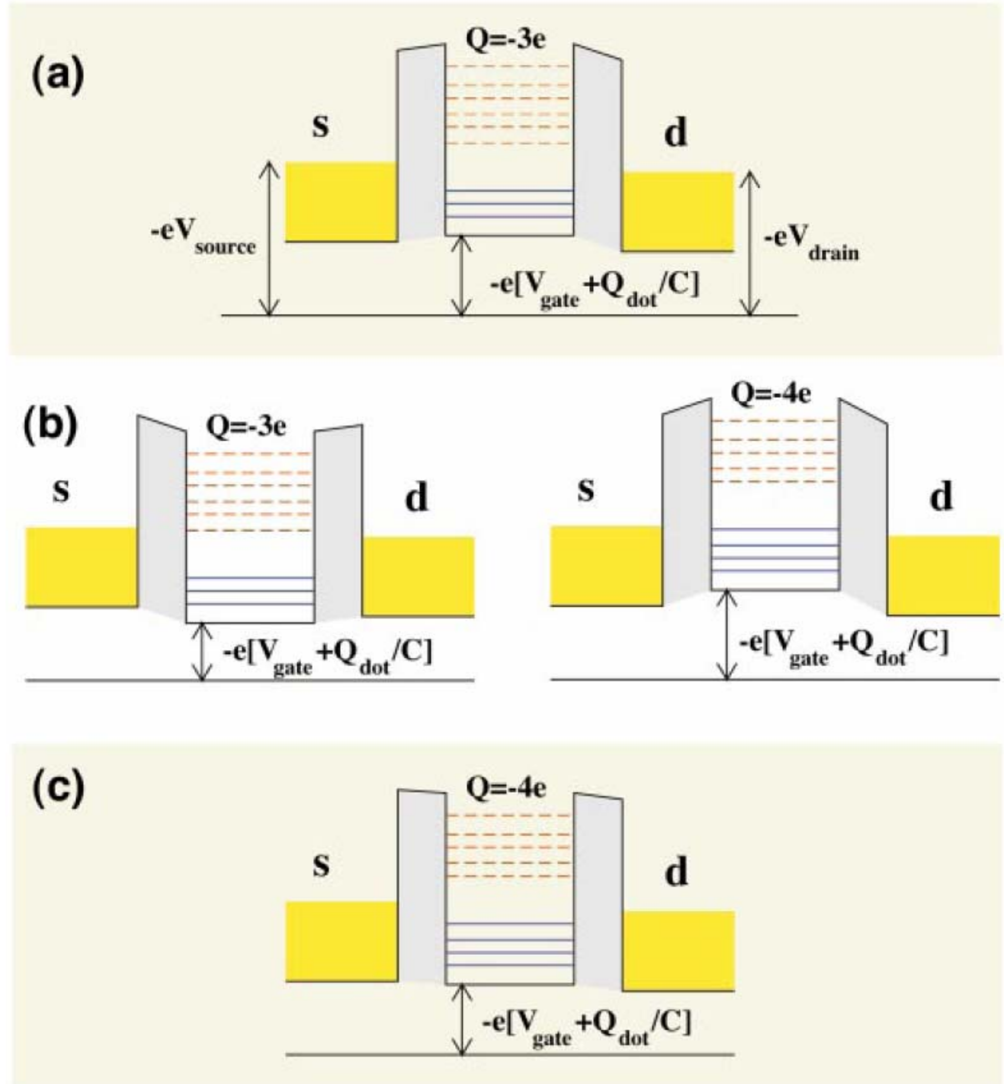
- By producing smaller dots $\Delta\varepsilon$ is increased, so Γ can be made larger to get higher Kondo temperatures
- Γ can be tuned by changing the gate voltages of the tunnel barriers

First-order tunneling

- Explanation of Coulomb blockade (CB) and stability diagram

- In CB only second-order tunneling possible



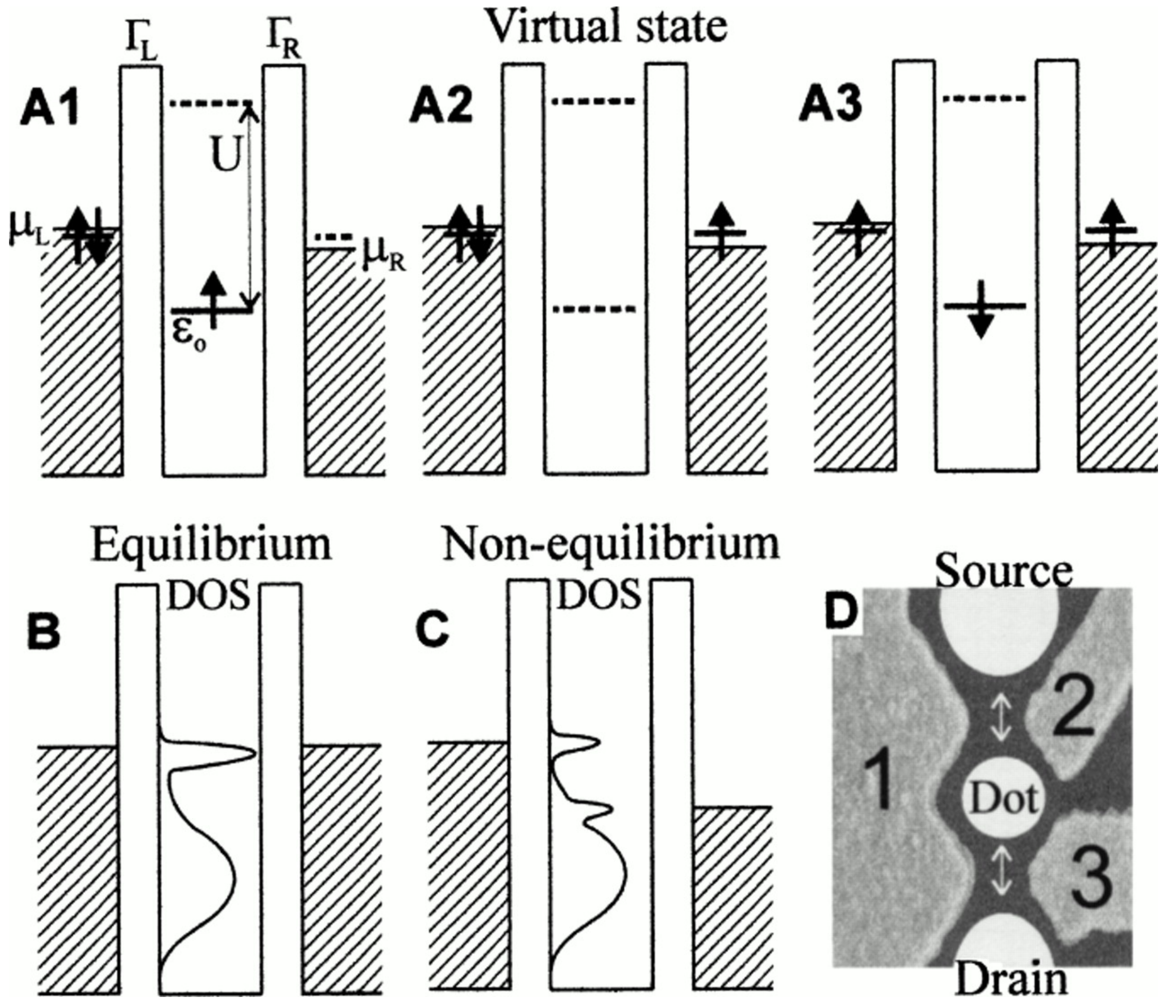


Second-order tunneling

Here: Kondo Effect

•Virtual tunneling events, which involve **spin-flips**, build up a **macroscopically correlated state** with properties known as the **Kondo effect**

•Narrow Kondo resonances in DOS with lead-electrons at the Fermi-energy



Second-order tunneling

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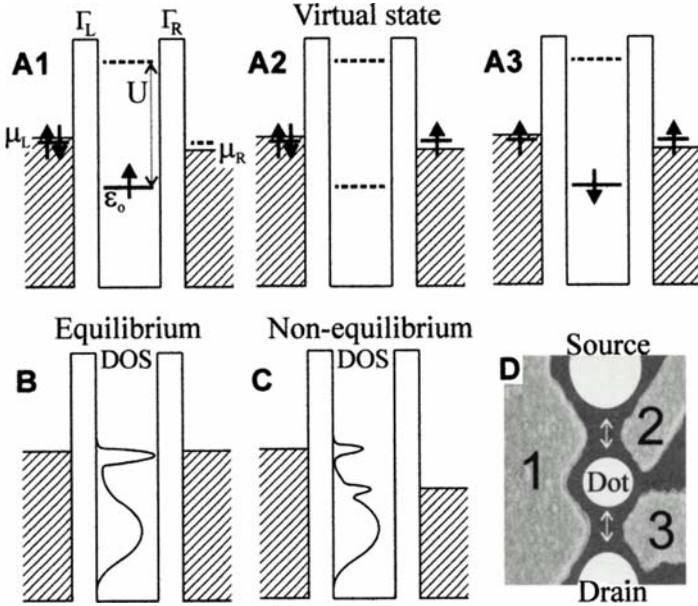


•The spatial state with the highest energy (ε_0) should be **singly occupied** i.e. the electron number on the dot has to be odd

•A finite coupling to the leads necessary (good coupling vs. defined dot)

•Then the spin of the „unpaired“ electron in the dot forms singlet with the delocalized electrons in the leads

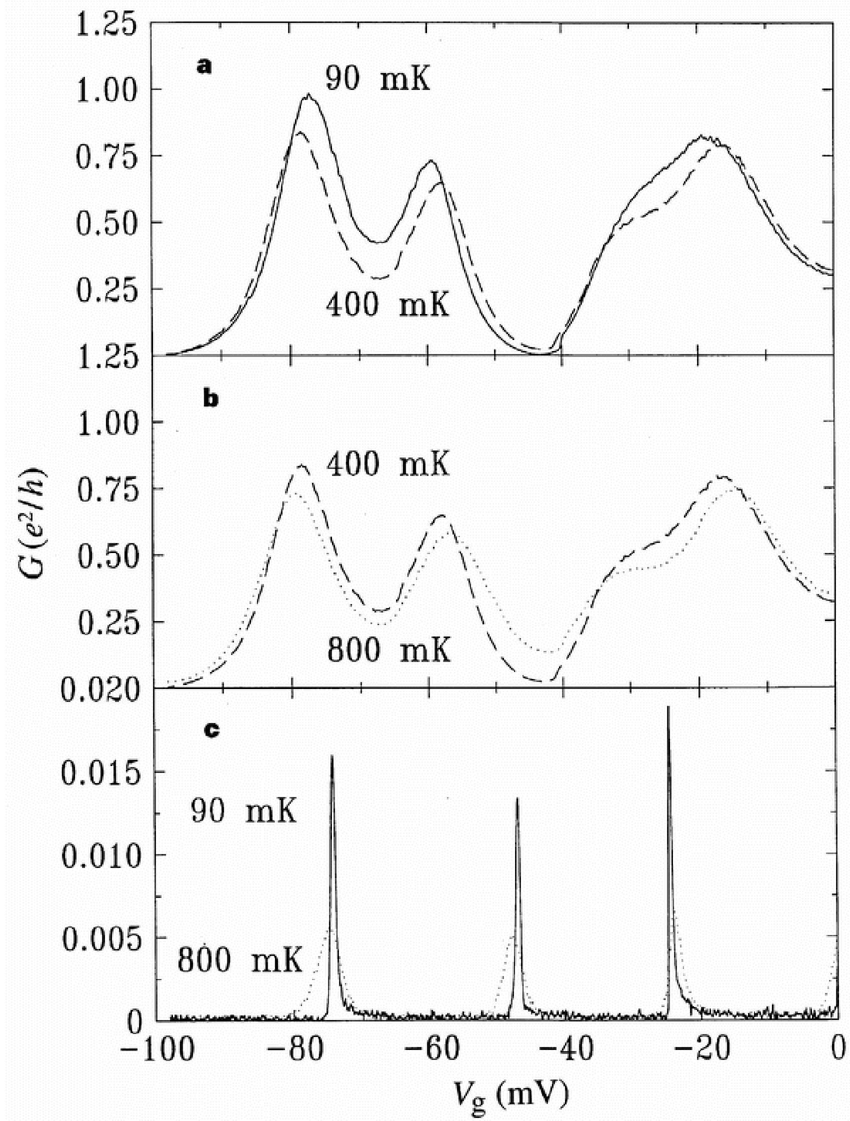
•A magnetic field splits this singlet state into a Zeeman doublet separated by the energy $g\mu_B B$

Zero-bias diff. conductance G

- With large Γ the conductance peaks form pairs for every spatial state

- With decreasing T the peaks get narrower and larger but...

- Increase of linear conductance in the intra-pair space (i.e. for odd numbers of electrons in the dot) due to **Kondo effect** as T is decreased further



Measurements:

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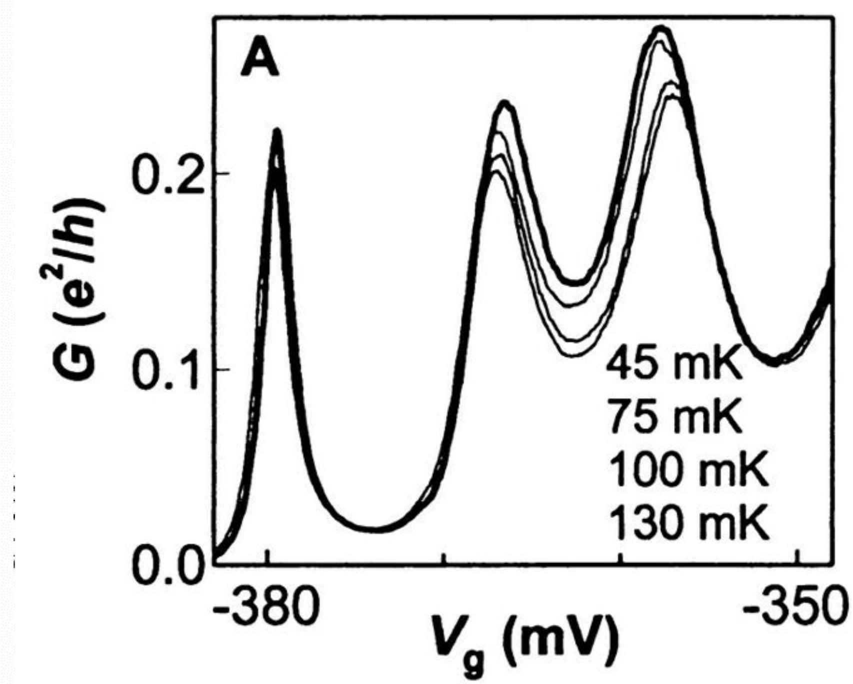

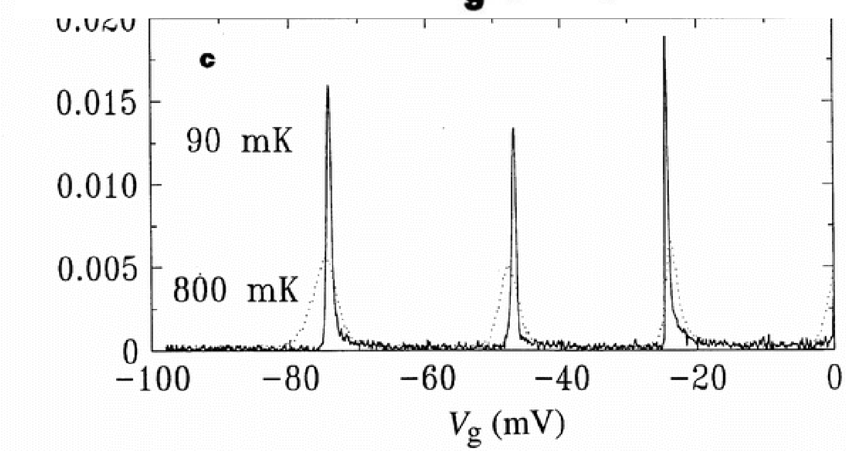

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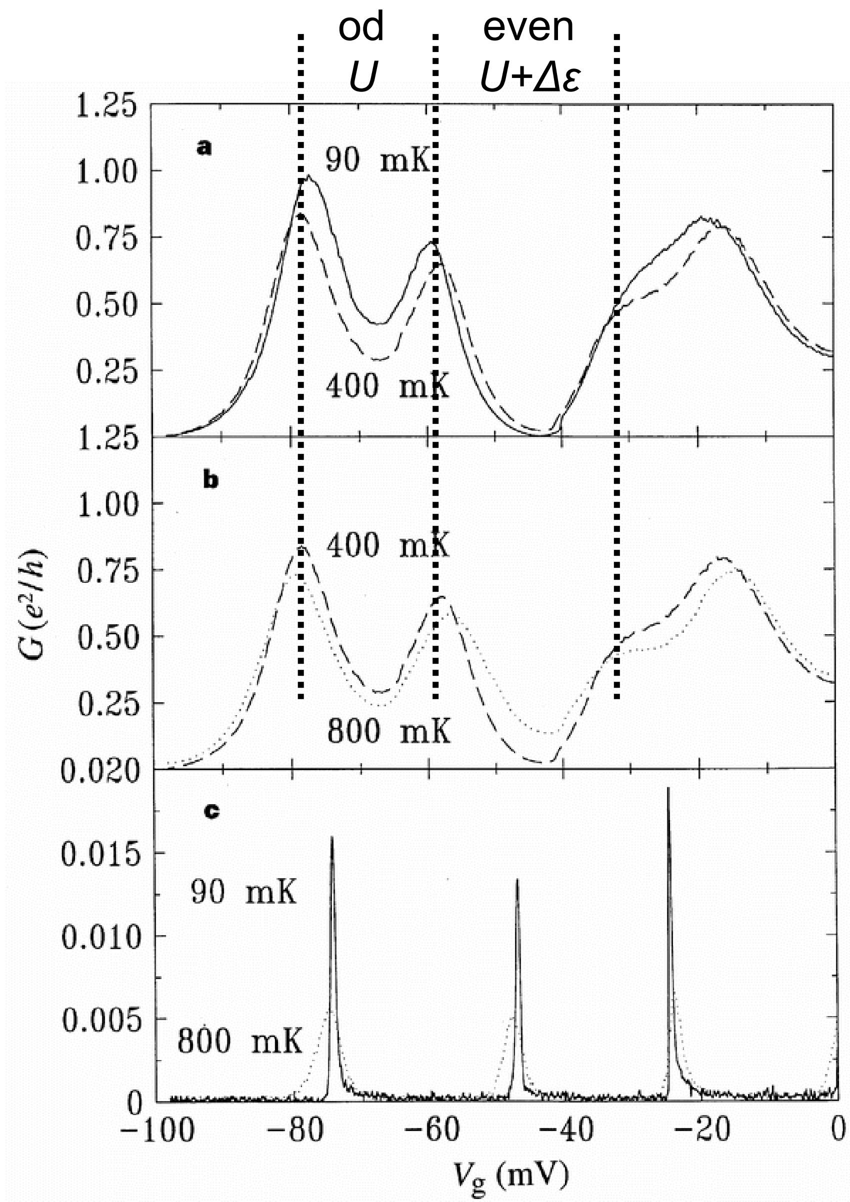

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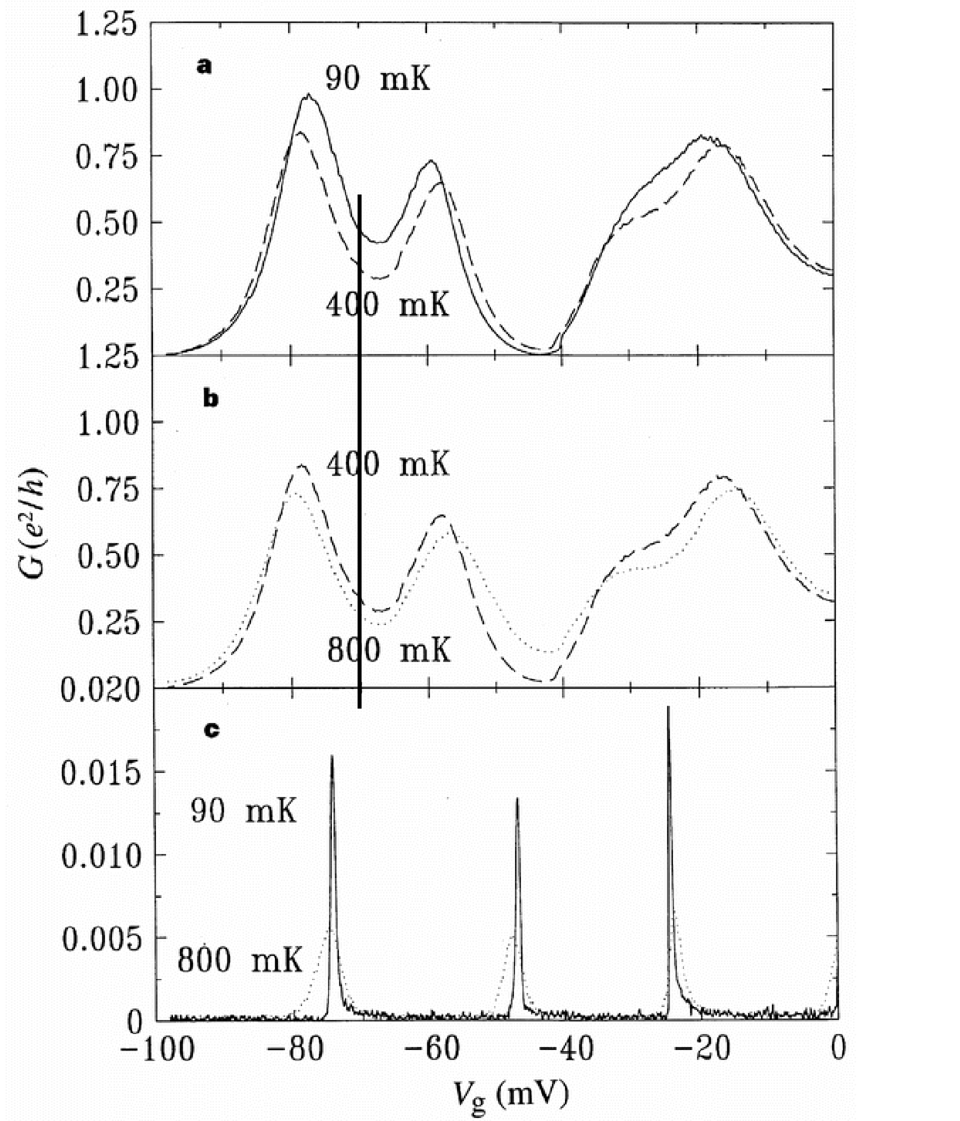
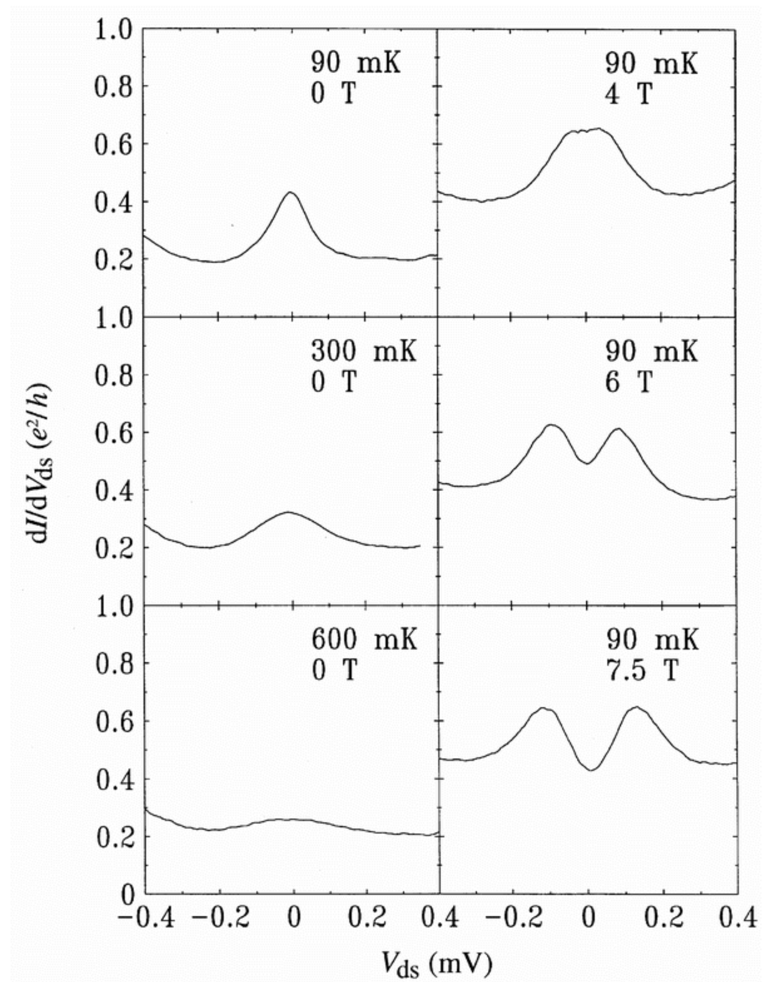


Measurements:

Differential conductance out of equilibrium

- Sensitivity to V_{ds}
- Temperature dependence of zero-bias Kondo resonance
- With a magnetic field the Zeeman splitting leads to peaks at $\pm g\mu_B B/e$ (correct value of Zeeman splitting found for magnetic field parallel to sample surface)



Differential conductance out of equilibrium

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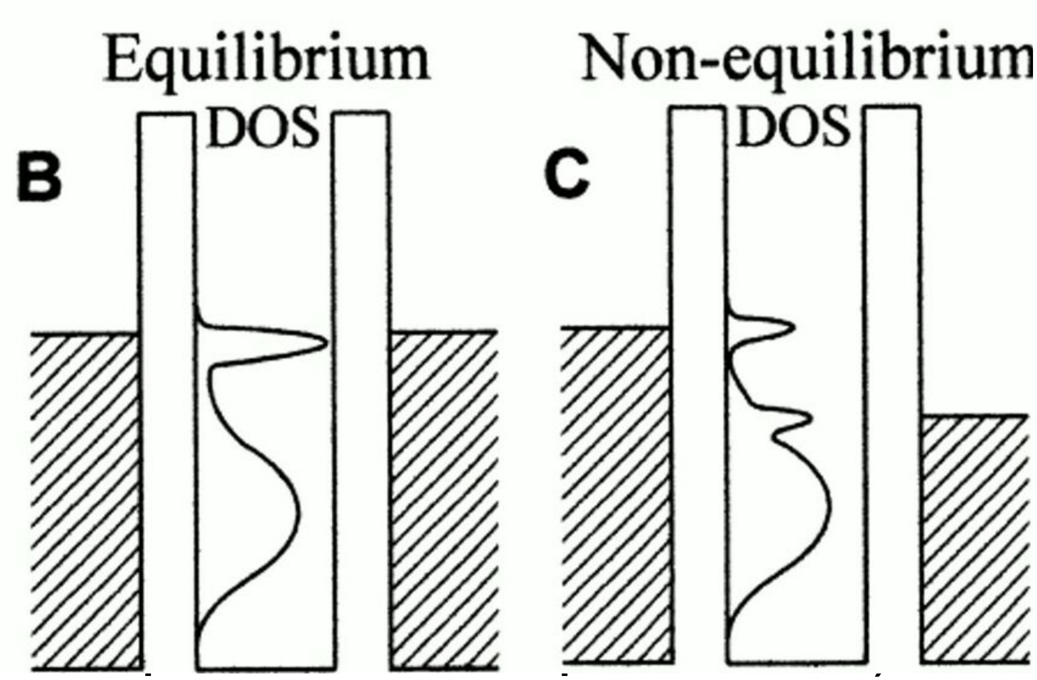
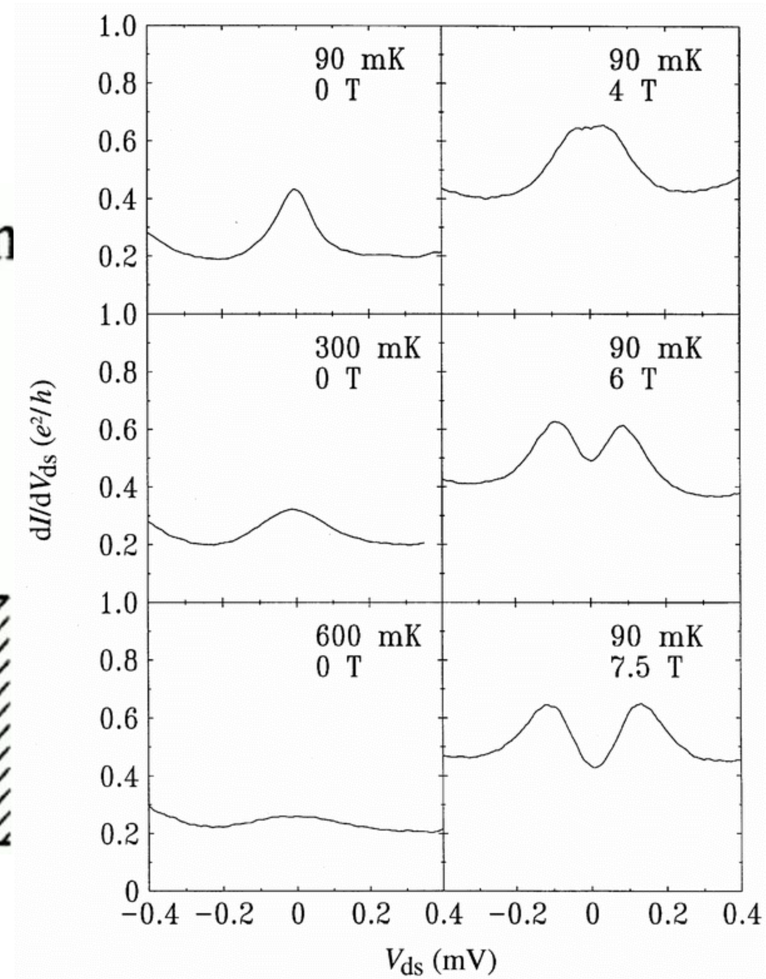




Measurements:

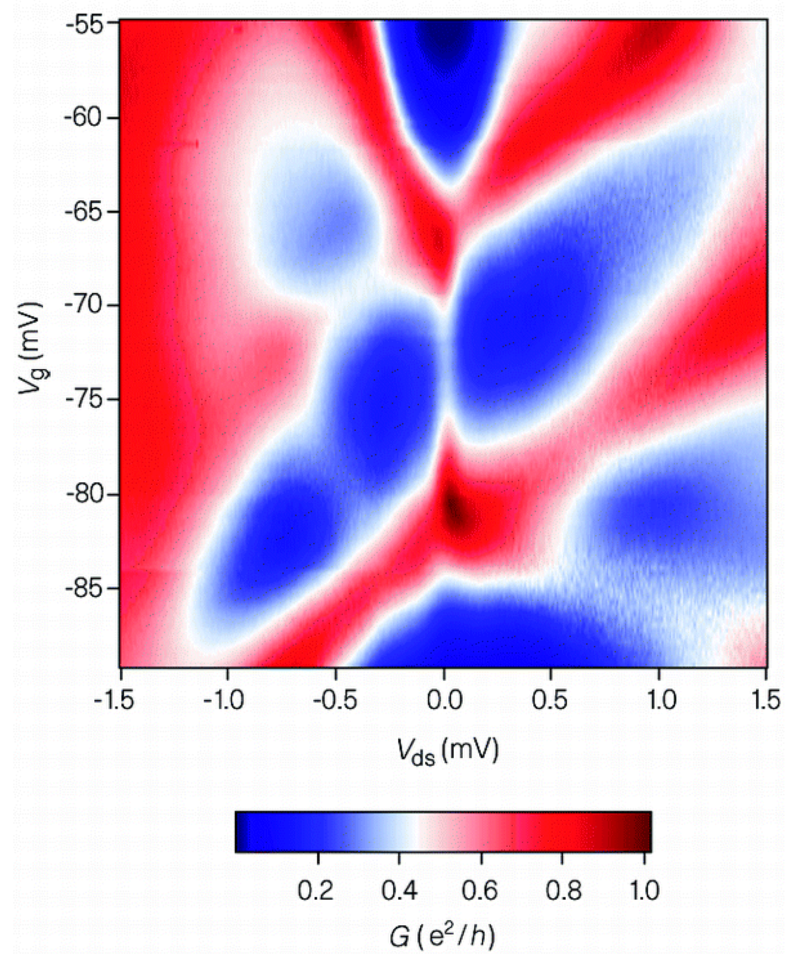
Stability diagram

- Differential conductance as a function of V_{ds} and V_g

- White vertical line at $V_{ds} = 0$ is Kondo resonance

- Bright diagonal lines are conductance outside the CB

- Measured quantities:
  - $U \approx 0.6$ meV ($\Gamma/\Delta\varepsilon \sim 1$)
  - $\Delta\varepsilon \approx U$
  - $\Gamma \approx 0.2$ meV



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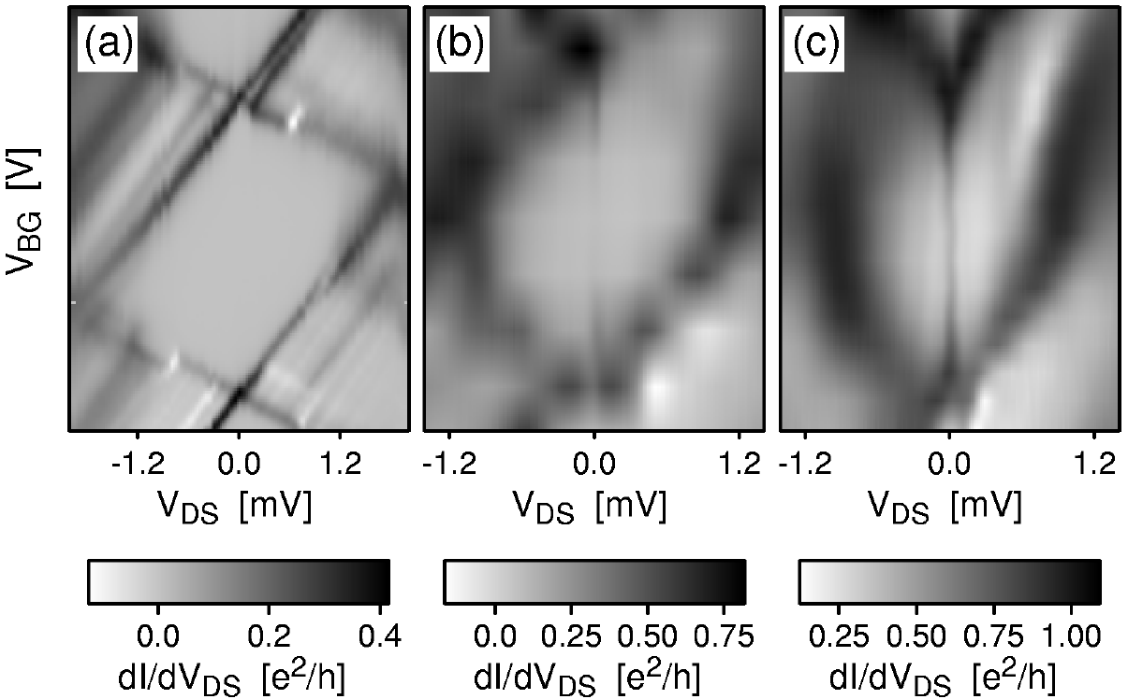

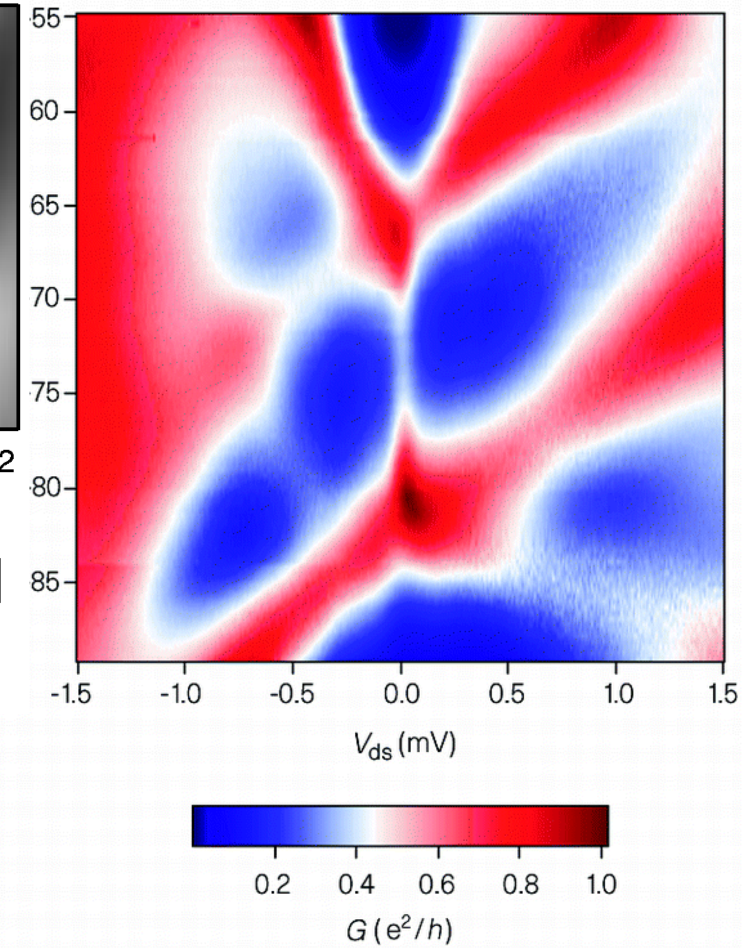

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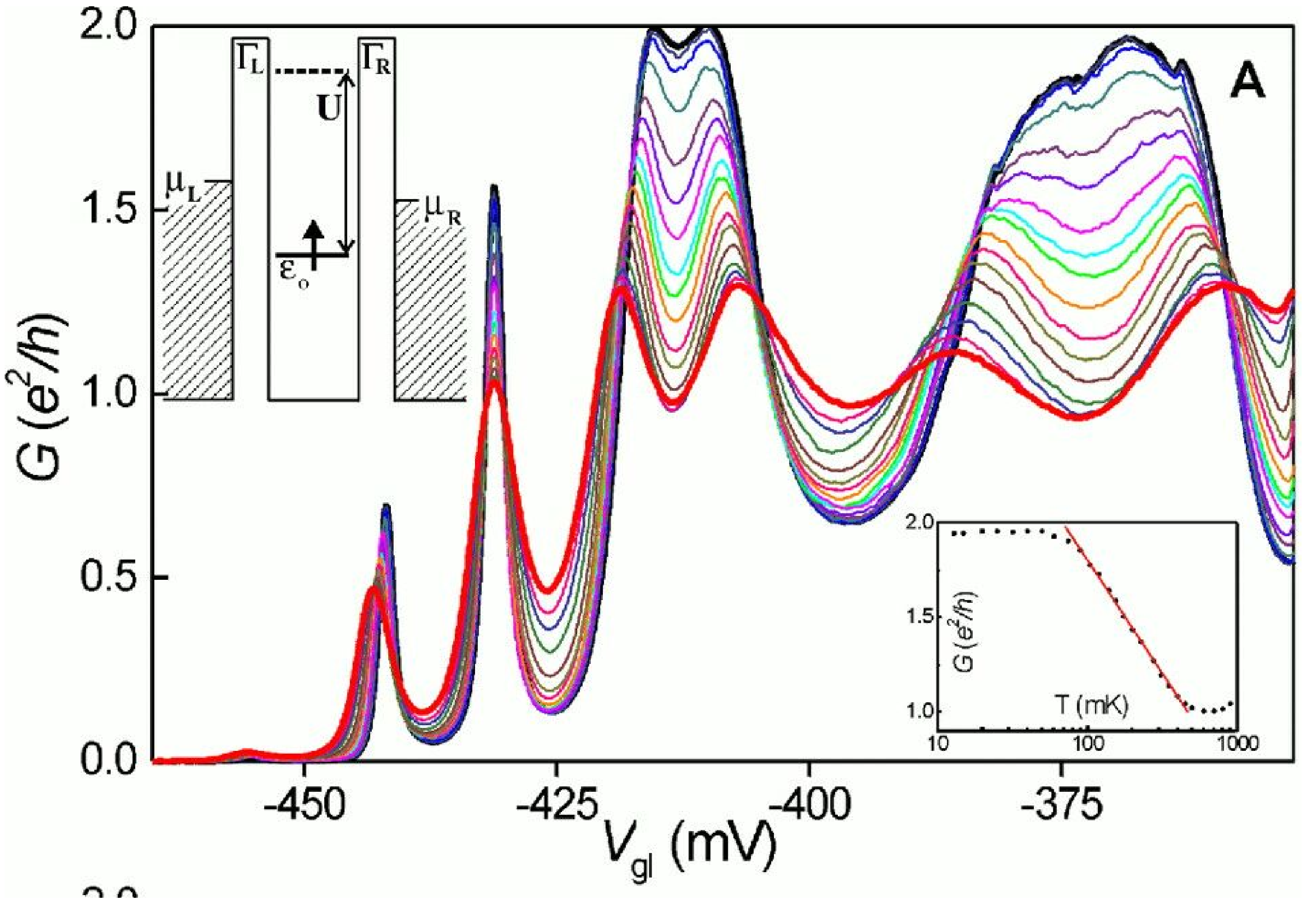
The Kondo Effect in the Unitary Limit



Summary

- Localized spin forms singlet with delocalized electrons: **Kondo Effect**
- Realization in small QD with odd number of electrons in the dot and a good coupling to the leads
- Verification with measurements of:
  - Enhanced zero-bias conductance
  - Zeeman splitting in magnetic field as expected