

### Spin-Polarized Tunneling Microscopy and the Kondo Effect



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# Acknowledgments

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Overview of the Kondo Effect

Kondo Systems: Quantum Dots and STM

Spin-Polarzied STM and the Kondo effect

*|*+! *|*−"





(Anderson model)

 $2E_d+U$ 

 $\overline{E_d}$ 

 $\epsilon_{\text{F}}$ 





 $2E_d+U$ 

 $E_d$ 

 $\epsilon_F$ 











# Kondo Effect: Quantum Dots

![](_page_11_Figure_1.jpeg)

**Exetence In Goldhaber-Gordon** Set used in the top surface of the top surface of the SET used in the experiments of the experiments of the SET used in the experiments of the surface of the SET used in the experiments of th Nature **39**, (1998)

#### Kondo Effect: Quantum Dots Fig. 2 Sketch of the electrostatic potential energy experienced by an electron moving at the  $H = \sum \sum$  $\sqrt{ }$  $d^{\dagger}_{\sigma}d_{\sigma} + U\hat{n}_{\uparrow}\hat{n}_{\downarrow} + \sum_{\Delta} \sum_{\Delta}$  $\epsilon_{k}c_{\alpha k\sigma}^{\dagger}c_{\alpha k\sigma}+E_{d}$  $V_{\alpha k d} c_{\alpha k \sigma}^{\dagger} d_{\sigma} + \text{H.c.}$  $H = \sum_{\ell} \sum_{\ell}$ σ α∈L*,*R *k,*σ α∈L*,*R *k,*σ *<i>{*}\set\_{}}}}}}}\right] *<i>{*}</del> *<i>{*}\\$P\${\mathematics}}} dot tunneling Leads source *U* dot  $\boldsymbol{V}$  source  $\boldsymbol{E_d}$ source  $E_{\rm d}$  drain dotdrain 00nm **Exetence In Goldhaber-Gordon** Set used in the top surface of the top surface of the SET used in the experiments of the experiments of the SET used in the experiments of the surface of the SET used in the experiments of th

Nature **39**, (1998)

#### Kondo Effect: Quantum Dots  $H = \sum$ α∈L*,*R  $\blacktriangledown$ *k,*σ  $\epsilon_{k}c_{\alpha k\sigma}^{\dagger}c_{\alpha k\sigma}+E_{d}$  $\sqrt{ }$ σ  $d^{\dagger}_{\sigma}d_{\sigma} + U\hat{n}_{\uparrow}\hat{n}_{\downarrow} + \sum_{\Delta} \sum_{\Delta}$ α∈L*,*R *k,*σ  $V_{\alpha k d} c_{\alpha k \sigma}^{\dagger} d_{\sigma} + \text{H.c.}$ Leads *<i>{*}\set\_{}}}}}}}\right] dot *<i>{*}</del> tunneling *<i>{*}\\$P\${\mathematics}}}  $\rho_{\text{dot}}(\omega)$ = density of states *dI* D. Goldhaber-Gordon $\frac{\stackrel{\omega}{dV}}{dV} \propto \rho_{\mathrm{dot}}(\omega)$ Nature **39**, (1998) Fig. 2 Sketch of the electrostatic potential energy experienced by an electron moving at the  $H = \sum_{\ell} \sum_{\ell}$ D. Goldhaber-Gordon source drain dot  $\boldsymbol{V}$  source  $\boldsymbol{E_d}$ *U* source  $E_{\rm d}$  drain dot

![](_page_14_Figure_0.jpeg)

# Kondo Effect in the Presence of Ferromagnetism

![](_page_15_Figure_1.jpeg)

![](_page_15_Figure_2.jpeg)

#### Kondo Effect in the Presence of Ferromagnetism VOLUME 91, NUMBER 12 19 SEPTEMBER 12 19 SEPTEMBER 12 19 SEPTEMBER 2003 AND THE SEPTEMBER 2003 AND THE SEPTEMBER 2003

![](_page_16_Figure_1.jpeg)

#### the G(V,B) plots exhibit magnetic hysteresis, witching fields reversed about B 0 0.00 minutes reversed about B 0 0.00 minutes reversed about B 0 0.00 minute WE CAN THE CHANGE CHANGE with the relative orientation of the moments of the moments De acampa af E PIESEIILE UI I  $\mathbb{F}_{\mathbb{F}_{q^2}}$  the splittings between the conductance the conductance of  $\mathbb{F}_{q^2}$ pet in the Kondo Effect in the propondence magnetic field of 70 T. An upper limit on the local magnetic field that can be generated Presence of Ferromagnetism

![](_page_17_Figure_1.jpeg)

A. N. Pasupathy Science **306** (2004)

#### the G(V,B) plots exhibit magnetic hysteresis, witching fields reversed about B 0 0.00 minutes reversed about B 0 0.00 minutes reversed about B 0 0.00 minute WE CAN THE CHANGE CHANGE with the relative orientation of the moments of the moments De acampa af E PIESEIILE UI I  $\mathbb{F}_{\mathbb{F}_{q^2}}$  the splittings between the conductance the conductance of  $\mathbb{F}_{q^2}$ pet in the Kondo Effect in the propondence magnetic field of 70 T. An upper limit on the local magnetic field that can be generated Presence of Ferromagnetism are sandwiched between two ferromagnetic nickel electrodes (see the figure). These new spintronic devices combined and compiled the spintronic devices combined and combined and combined o two fundamental electron-electron interac- $\theta$  to condense matter physics: Presence a first sight, the effects seem to exclude the seeing seems seems to exclude the seeing second  $\sim$  most prominent many-body effects in  $\sim$ condensed matter physics (*6*, *7*). If the tunneling barriers defining the quantum dot are the single electron can leak out of the dot and hybridize with the delocalized electrons in the contacts. The Coulomb repulsion on the dot leads to an anti-

by the magnetic electrodes in the small gap

is given by their magnetization, 0.6 T for Ni.

peaks is in excellent agreement with some

recent predictions that the interaction of a

quantum dot with spin-polarized electrodes electrodes and

can produce a splitting of the Kondo resonance and

(12–14). In this model, the conductance of a

single-level quantum dot is determined by

the tunneling spin polarizations PL,P<sup>R</sup> and

![](_page_18_Figure_1.jpeg)

A. N. Pasupathy Science **306** (2004)

#### the G(V,B) plots exhibit magnetic hysteresis, witching fields reversed about B 0 0.00 minutes reversed about B 0 0.00 minutes reversed about B 0 0.00 minute WE CAN THE CHANGE CHANGE with the relative orientation of the moments of the moments De acampa af E PIESEIILE UI I  $\mathbb{F}_{\mathbb{F}_{q^2}}$  the splittings between the conductance the conductance of  $\mathbb{F}_{q^2}$ pet in the Kondo Effect in the propondence magnetic field of 70 T. An upper limit on the Presence of Ferromagnetism are sandwiched between two ferromagnetic nickel electrodes (see the figure). These new spintronic devices combined and compiled the spintronic devices combined and combined and combined o two fundamental electron-electron interac- $\theta$  to condense matter physics: Presence a first sight, the effects seem to exclude the seeing  $\sim$  most prominent many-body effects in  $\sim$ condensed matter physics (*6*, *7*). If the tunneling barriers defining the quantum dot are the single electron can leak out of the dot and hybridize with the delocalized electrons in the contacts. The Coulomb repulsion on the dot leads to an anti-2.6 -40 -20 0 20 40 400 **(e2/h x 10-2 )**  $\mathbf{V}$  and  $\mathbf{V}$  are different from  $\mathbf{V}$ Coulomb blockade conductance per The split peaksin Figure 2 display a strong  $\mathcal{C}$  and  $\mathcal{C}$  and  $\mathcal{C}$  and  $\mathcal{C}$ in the two magnetic electrodes. For negative B in Fig. 2 B, the moments are parallel and the moments are parallel and the moments are parallel and the moments by the magnetic electrodes in the small gap is given by their magnetization, 0.6 T for Ni. The magnetic field dependence of our  $55511$ nal for C60 with Australia

![](_page_19_Figure_1.jpeg)

 $V(\Gamma)$  -1.0 -0.5 0.0 0.0 0.5 1.0

 $-1.0$   $-0.5$   $0.0$   $0.5$   $1.0$ <br> $V(\Gamma)$ 

(A) Sample 1: (blue) electrode

![](_page_20_Figure_1.jpeg)

Kondo Effect: STM *tdk*  $w_{kk'}$  $V_{dk}$  $H = \sum$  $k\sigma$  $\epsilon_k^{\phantom{\dag}} c_k^{\dag}$  $\frac{1}{k\sigma}c_{k\sigma} + \sum$  $k\sigma$  $\epsilon_{k}a_{k\sigma}^{\dagger}a_{k\sigma} + E_{d}$ 1 σ  $d^{\dagger}_{\sigma}d_{\sigma} + U\hat{n}_{\uparrow}\hat{n}_{\downarrow} + \sum$  $k\sigma$  $V_{kd}c_{k\sigma}^{\dagger}d_{\sigma} + \text{H.c}$  $+$  $\blacktriangledown$  $k\sigma$  $t_{kd}a_{k\sigma}^{\dagger}d_{\sigma} + \text{H.c} + \sum w_{kk'}c_{k\sigma}^{\dagger}a_{k'\sigma} + \text{H.c}$  $k, k', \sigma$ 

$$
\frac{dI}{d(eV)} \propto |w|^2 \rho_{\rm sub}(\omega) + |t|^2 \rho_d(\omega) - \frac{1}{\pi} {\rm Im}\, \left\{2twVG_0^{\rm R}(\omega)G^d(\omega)\right\}
$$

![](_page_22_Picture_2.jpeg)

$$
\frac{dI}{d(eV)} \propto |w|^2 \rho_{\rm sub}(\omega) + |t|^2 \rho_d(\omega) - \frac{1}{\pi} {\rm Im}\, \left\{2twVG_0^{\rm R}(\omega) G^d(\omega) \right\}
$$

![](_page_23_Figure_2.jpeg)

$$
\frac{dI}{d(eV)} \propto |w|^2 \rho_{\rm sub}(\omega) + |t|^2 \rho_d(\omega) - \frac{1}{\pi} {\rm Im}\, \left\{2twVG_0^{\rm R}(\omega)G^d(\omega)\right\}
$$

![](_page_24_Figure_2.jpeg)

![](_page_25_Figure_1.jpeg)

![](_page_26_Figure_1.jpeg)

![](_page_27_Figure_1.jpeg)

 $w_{kk'}$ 

*tdk*

 $V_{dk}$ 

 $\Gamma_V = \pi |V|^2 \rho_{\rm sub}$ Pol.= 33% spin up  $\Gamma_V\approx .2eV$ splitting  $\tilde{\phantom{0}}$ few meV  $\Gamma^{\uparrow}_t = \pi |t|^2 \rho^{\uparrow}_{\rm tip}$  $B_{eff} = 60 - 70$  T

![](_page_27_Figure_3.jpeg)

![](_page_28_Figure_1.jpeg)

### Results:

#### Conductance

![](_page_29_Figure_2.jpeg)

# Future Experiments?

Soft magnetic material

![](_page_30_Picture_2.jpeg)

# Future Experiments?

Soft magnetic material

![](_page_31_Picture_2.jpeg)

B

#### Future Experiments?

Soft magnetic material

B

Anti-ferromagnetic Material

![](_page_32_Picture_3.jpeg)

Does the Kondo effect survive?

## Summary

SP-STM breaks the spin symmetry of a Kondo system (similar to applied magnetic field)

- Leads to splitting of Kondo peak (spin up/down)
- Which in turn splits the Fano resonance of the conductance

Reference: Phys. Rev. B 76, 100408(R) (2007)

Thank you.