

Quantum Dots III

1. Open Dot Experiments

2. Kondo effect

3. Few Electron Dots

4. Double Quantum Dots

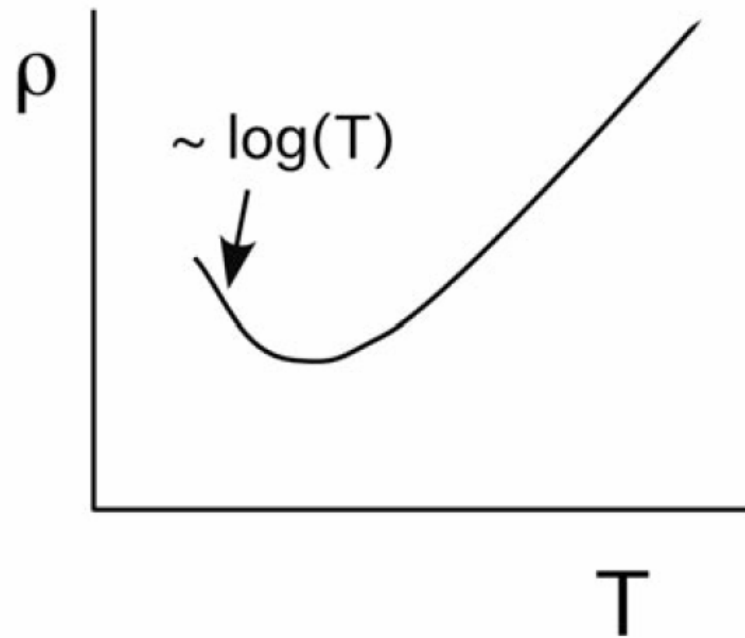
Goldhaber-Gordon et al., Nature **391**, 156 (1998)

Cronenwett et al., Science **281**, 540 (1998)

S. Cronenwett, Ph. D. Thesis (2001)

Kondo Effect in Metals

1930s experiments:

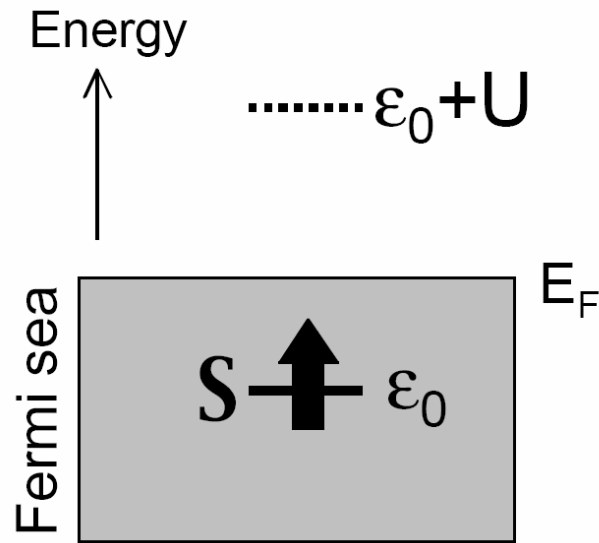


1960s: (exp) related to magnetic impurities

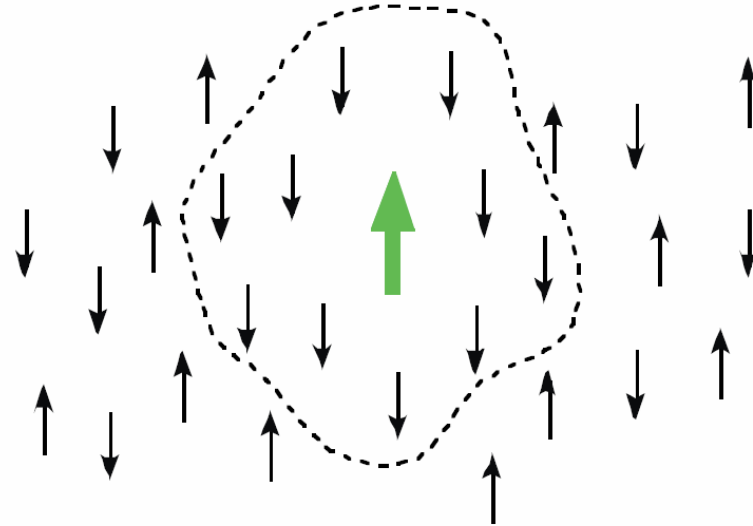
theoretical explanation by Jun Kondo
spin-flip scattering on mag. impurities

$$\rho \sim \underbrace{\rho_0}_{\text{lattice}} + \underbrace{aT^5}_{\text{phonons}} - b \log(T)$$

Kondo Effect in Metals: Model



new energy scale: Kondo temperature T_K
 formation of spin-singlet screening cloud



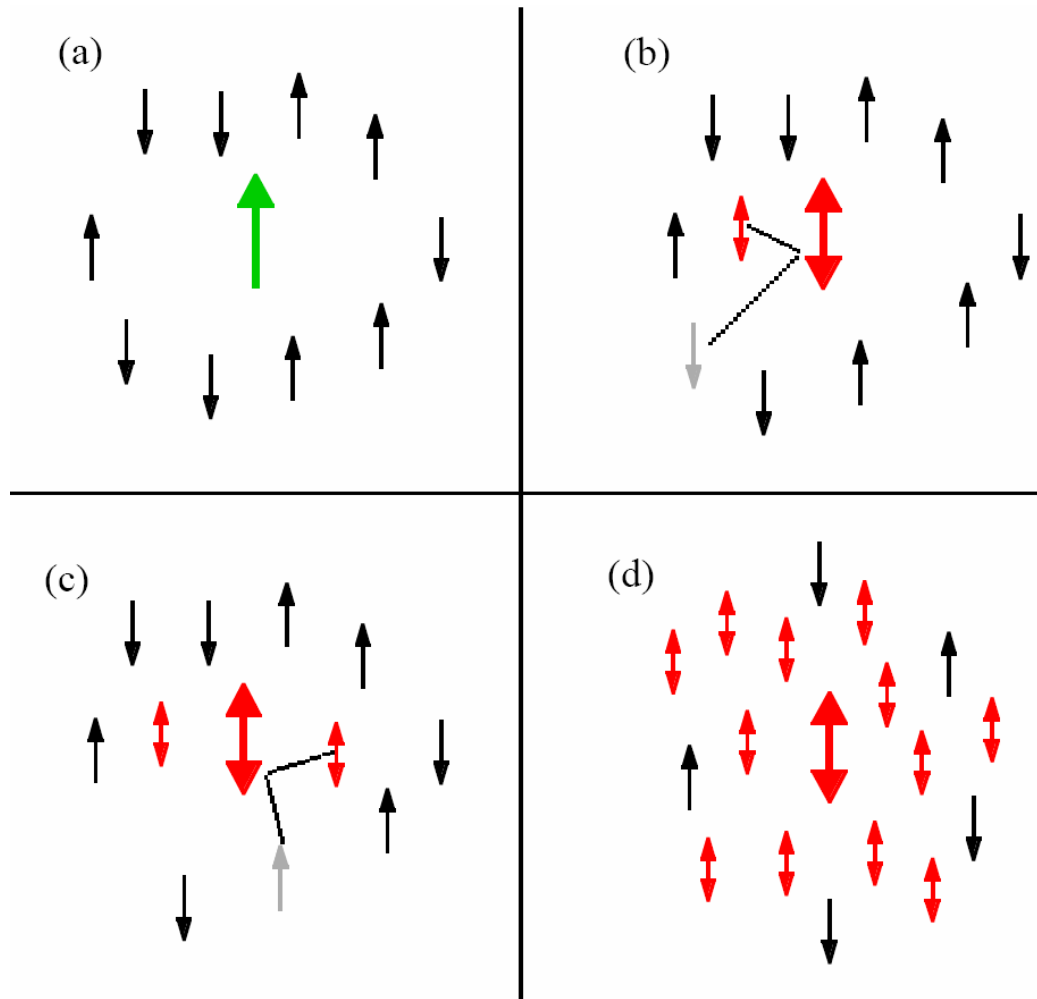
cloud: more effective scatterer
 increase in resistance

Anderson Hamiltonian

$$H_A = \sum_{\sigma; k < k_f} \epsilon_{k\sigma} c_{k\sigma}^\dagger c_{k\sigma} + \sum_{\sigma} \epsilon_{\sigma} d_{\sigma}^\dagger d_{\sigma} + \frac{1}{2} U n_{\sigma} n_{\sigma'} + \sum_{\sigma; k < k_f} t_{k\sigma} c_{k\sigma}^\dagger d_{\sigma} + H.c..$$

free electrons	localized electrons	on site charging	coupling between localized and free ele.
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Kondo Effect in Metals: spin flip scattering

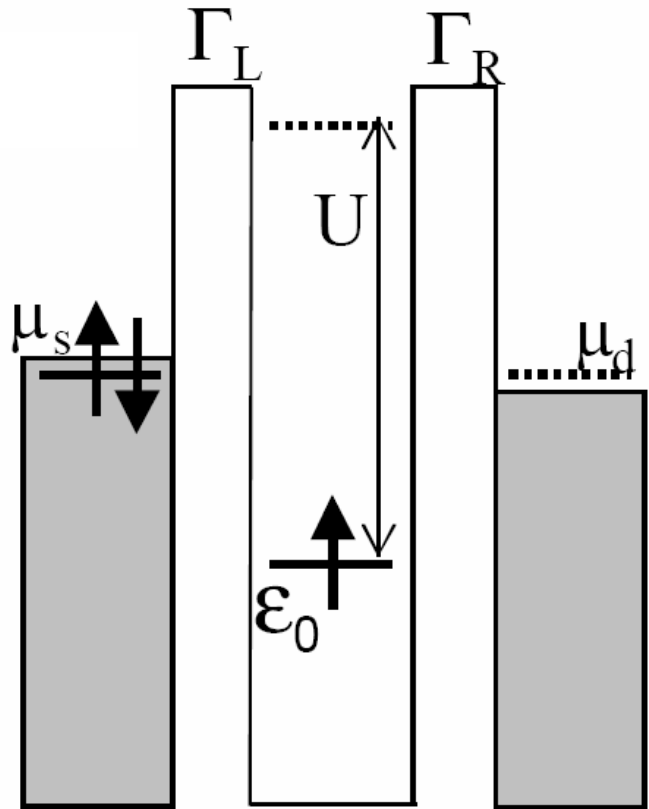


each scattering event
engangles impurity with
conduction electron

singlet cloud formation

temperature scale T_K

Kondo Effect in Quantum Dots

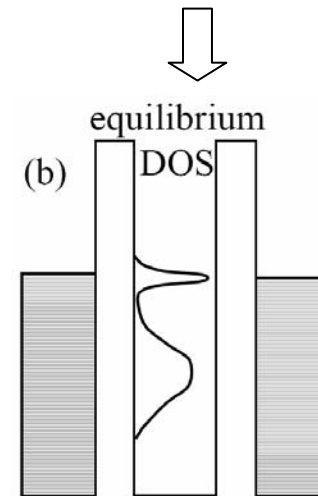
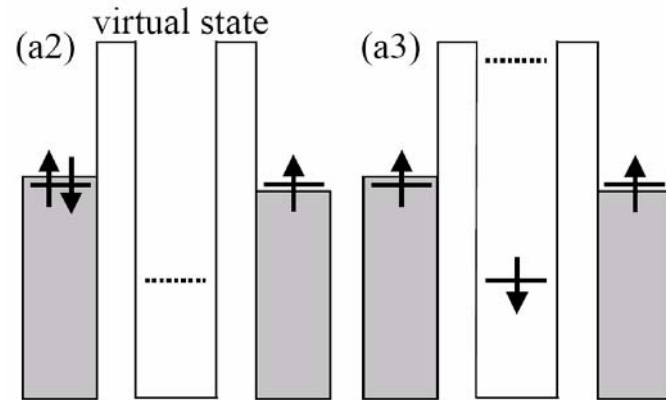


unpaired spin

$$T_K \propto \sqrt{U\Gamma} \exp(\pi\epsilon_0/2\Gamma)$$

$$\Gamma = \Gamma_L + \Gamma_R$$

spin-flip cotunneling (elastic)

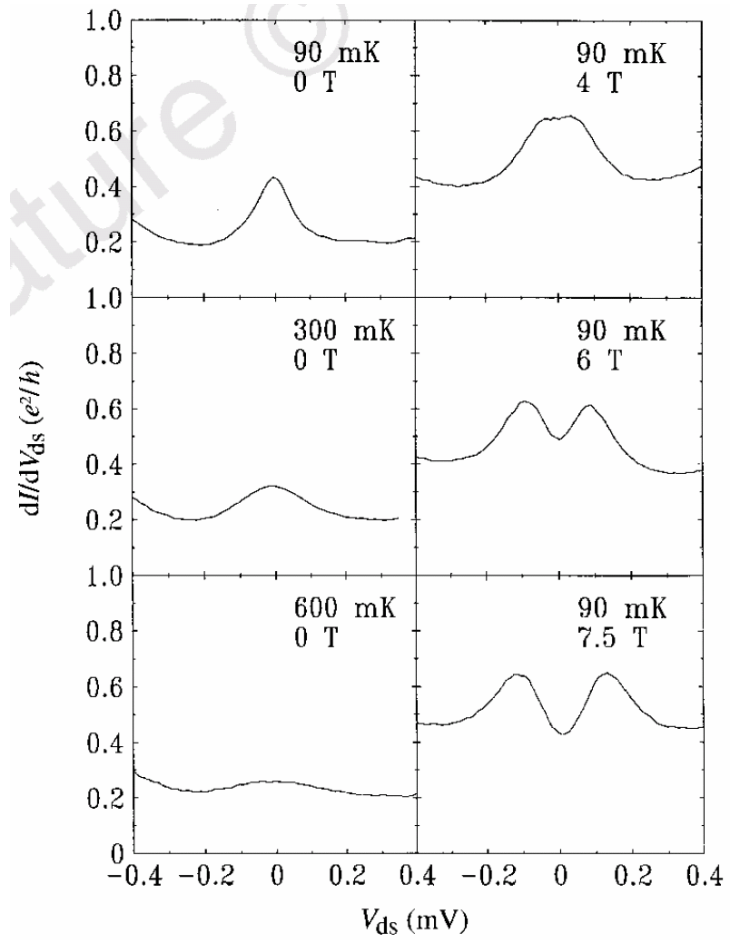
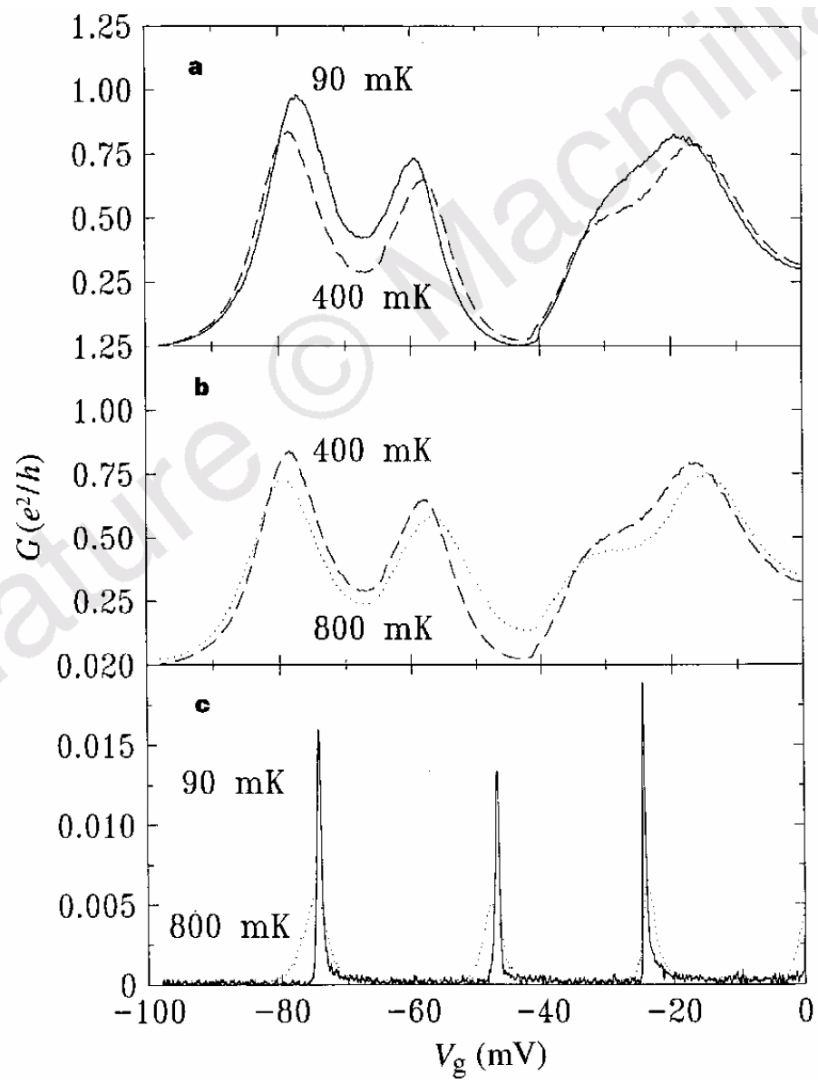


for $T < T_K$: DOS at $\mu_{S,D}$ enhanced zero bias conductance!!

for $T \gg T_K$ DOS peak suppressed

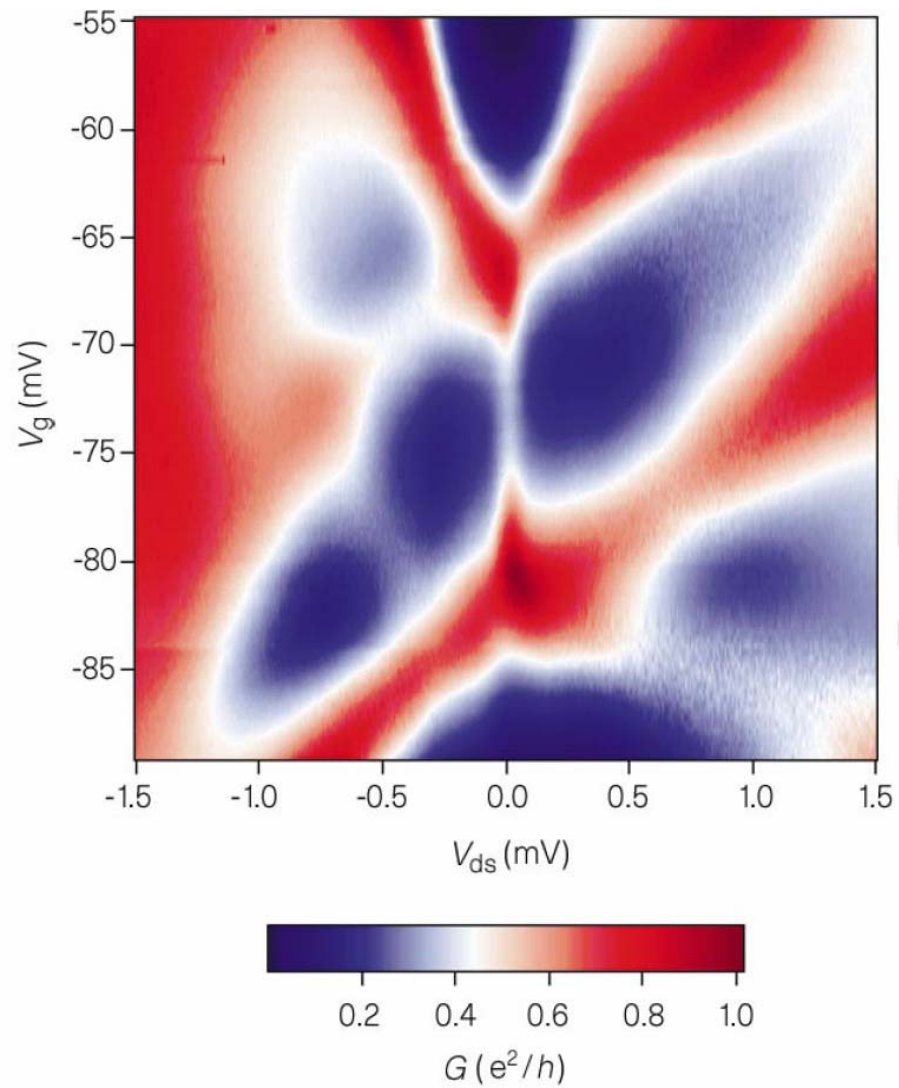
dots: parameters tunable
SINGLE impurity

Kondo Effect in Quantum Dots: Experiment



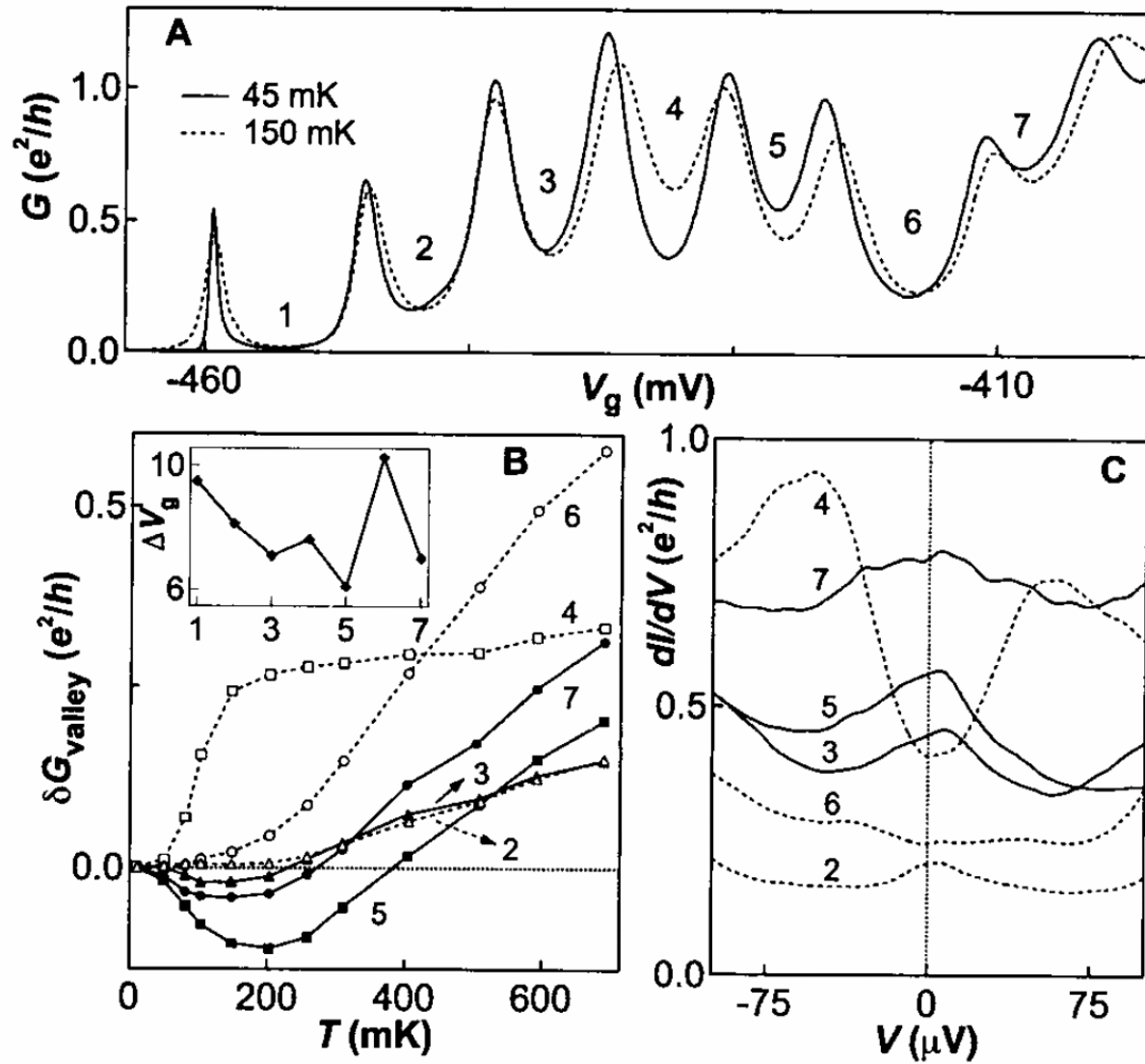
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Kondo Effect in Quantum Dots: Experiments

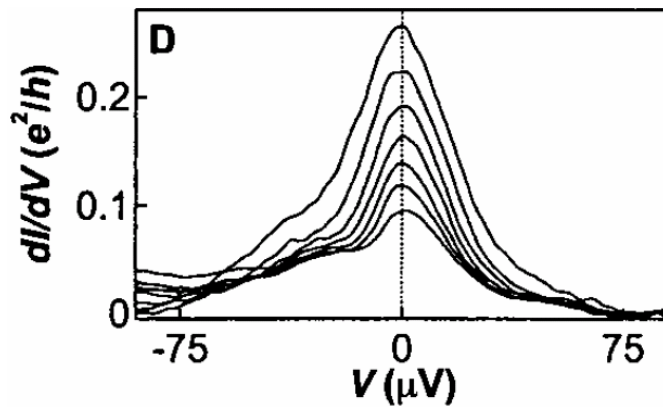
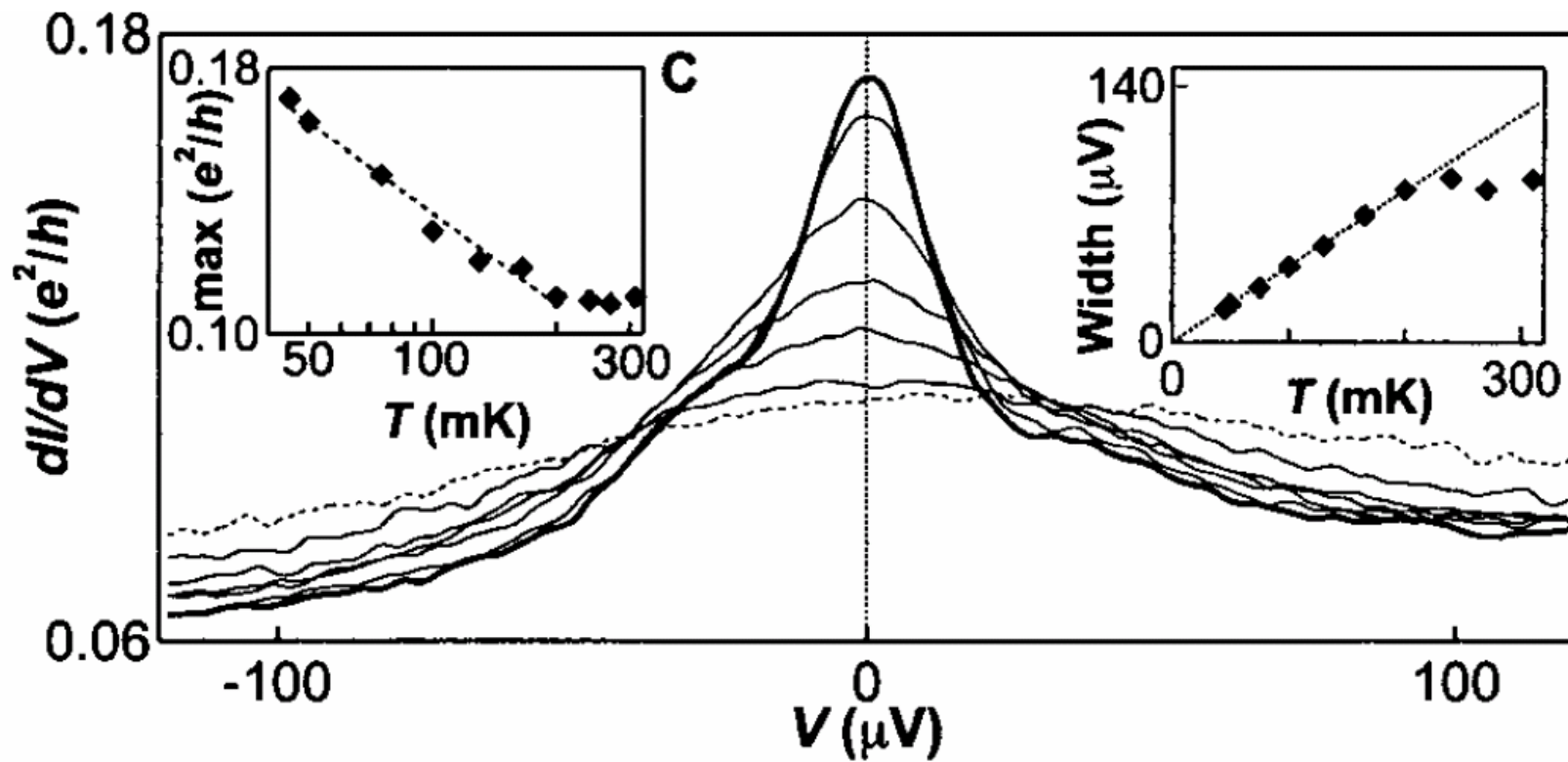


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Kondo Effect in Quantum Dots: Experiments

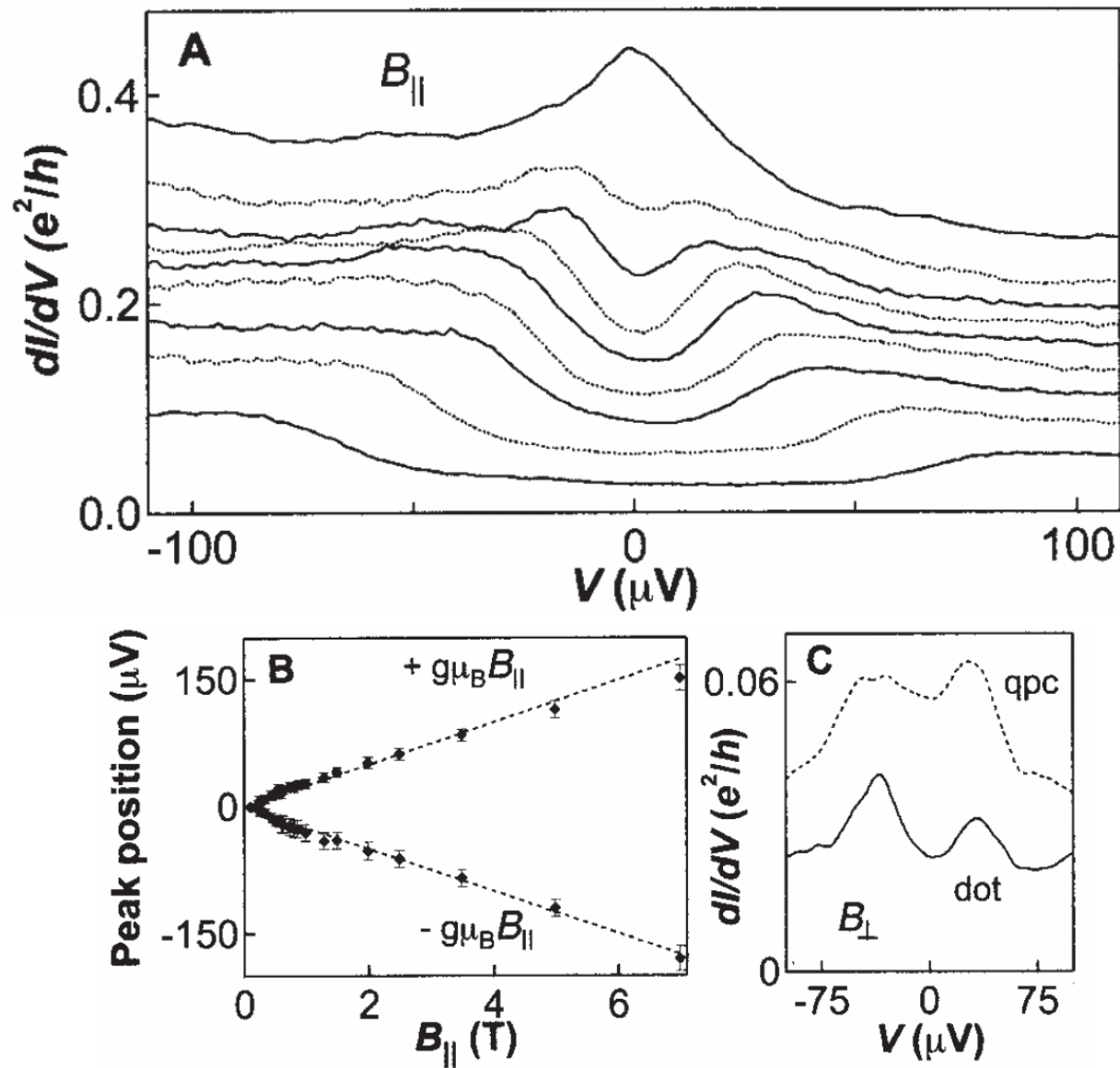


Kondo Effect in Quantum Dots: Experiments



gate voltages
into odd valley

Kondo Effect in Quantum Dots: Experiments



Cronenwett et al., Science **281**, 540 (1998)

Kondo Effect in Quantum Dots: Experiments

