Spin effects in a quantum dot

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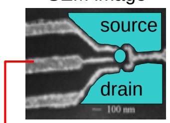
Abstract

We study the line shape of the zero-bias Kondo anomaly in the differential conductance of a small (~100 nm in diameter) semiconductor quantum dot. When the coupling of the dot to the leads is weak, Kondo peaks with full width at half maximum (FWHM) less than 20 μV can be observed. The FWHM decreases as V_G is tuned away from the location of the Coulomb blockade peak in the linear conductance, and it is a sensitive function of temperature T for T<100 mK. A value for the intra-dot exchange coupling J was also extracted from a singlet-triplet transition. Finally, the dependence of the line shape on the external magnetic field is discussed.

Experimental details

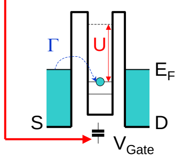
- Dot patterned in a 2DEG via depleting voltages applied to gate electrodes

SEM image



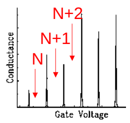
Heterostructure properties:

- GaAs / AlAs
- Shallow 2DEG (16 nm below surface)
- Carrier density: 7.3×10^{11} cm^{-2}
- Mobility 9.1×10^{4} cm^2/(V•s)



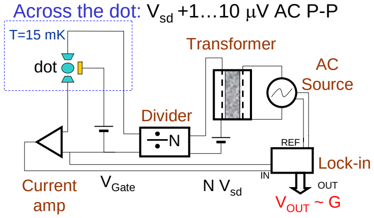
Coulomb Blockade:

- U: Charging energy
- Γ: Tunneling rate
- V_{Gate} controls:
  - ➢Dot potential
  - ➢Occupancy N



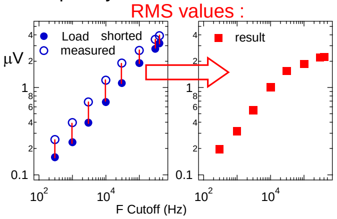
- Measuring the differential conductance G of the dot via a lock-in technique

Across the dot: V_{sd} +1…10 μV AC P-P



- 2DEG plane can be rotated relative to the direction of the external magnetic field B
- measurement circuit designed to minimize voltage noise to prevent
  - » smearing of the nonlinear features in the conductance
  - » excessive Joule heating of the 2DEG
- V_{Noise} measured with Ithaco 1201 amplifier across a 100 kΩ test load (circuit connected and equipment running)
- Frequency band tested : 3 Hz – 400 kHz

RMS values :



2.5 μV rms noise voltage: generated by the current amplifier (Ithaco 1211)

Kondo Effect

- Quantum dot with spin ⇔ artificial magnetic impurity

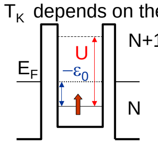
At low T:

- "hybridization" of electron states in the leads with the localized state due to tunneling
- electrons in the leads screen the dot spin to form an S=0 many-body state (singlet), producing a sharp resonance in the local density of states at E_F
  - ➢ current flows via the singlet, while the single-particle level transport is Coulomb-blockaded
- Kondo temperature T_K : new scale describing the singlet binding energy

$$T_K^{Theory} = \frac{\sqrt{\Gamma U}}{2} \mathrm{Exp}\left(\frac{\pi\varepsilon_0(\varepsilon_0+U)}{\Gamma U}\right)$$

Simplest case: dot spin s=1/2 (odd N), s=0 (even N)

- Kondo expected in valleys with odd N only
- T_K depends on the dot parameters:

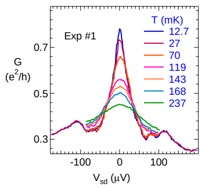


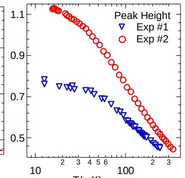
Two different regimes at odd N:

- "Kondo": ε_0>0.5 Γ (Impurity state far below E_F, , N is a good quantum number)
- "mixed-valence": ε_0<0.5 Γ

- Temperature Dependence measured at two V_{Gate} values

peak shape *peak height*

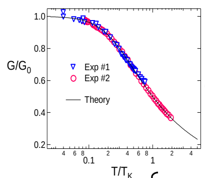




- Shape is complex: satellite features at ±100 μV
- Peak shape sensitive to T below 20 mK

⇒ ***Electrons are cold***

Quantitative analysis



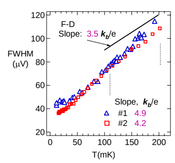
- G_0, T_K determined from fit to the empirical form

$$G = G_0\left(\frac{T_K'^2}{T^2 + T_K'^2}\right)^s, \quad T_K'^2 = \frac{T_K^2}{2^{1/s} - 1},$$

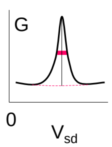
representing a NRG calculation.

Fits give: $T_K = \begin{cases} 317 \text{ mK}, \#1 \\ 190 \text{ mK}, \#2 \end{cases}$

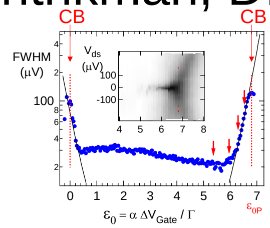
Note: $G(T_K)=G_0/2$



FWHM definition:



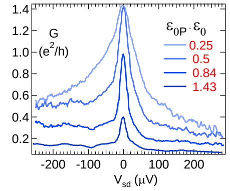
- $T/T_K \to 0$: FWHM= (2±0.3) T_K
- FWHM linear in T above ~ 0.15 T_K
- Slope close to the width of Fermi-Dirac function $f(\varepsilon, T)$



Γ= 290 μeV
U/Γ= 6.8
Solid line: $0.2T_K^{Theory}$
Inset: right-hand Coulomb Blockade (CB) peak region

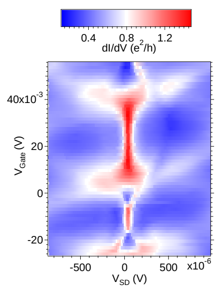
$|\varepsilon_0$-$\varepsilon_{0P}|$ > 0.3:

FWHM is well-defined



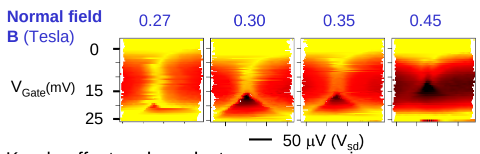
- Near the CB peaks (ε_0-ε_{0P} <1, mixed-valence)
  - » FWHM follows $T_K(\varepsilon_0)$ dependence predicted for the Kondo regime
  - » exponent agrees with Γ, U determined independently
  - » prefactor 5 times less than theoretical
- Away from the CB peaks (ε_0-ε_{0P} >>1, Kondo), where we expect T>>T_K
  - » broadening larger than expected: FWHM ~10 k_B/e T
    - ⇒ *noise still limiting?*
  - » FWHM varies with ε_0

Triplet Kondo effect

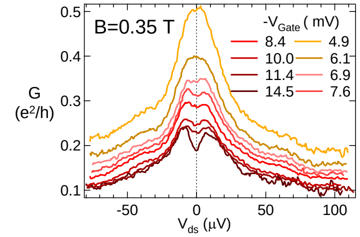


- Kondo observed both at even and odd N (earlier reported by Schmid *et al*., 2000)
- Singlet-triplet transition is seen: |J|~200 μeV
- Sharp edges near zero bias: excitation at fixed N between closely spaced levels for which the energy has a different gate voltage dependence

Kondo Peak splitting

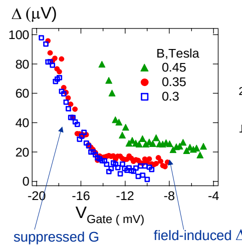


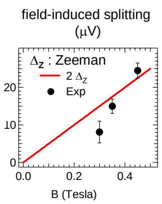
- Kondo effect and conductance suppression can appear in the same valley (same N)
- The Kondo feature is "split" by the region of suppressed G even at B=0 (singlet-triplet transition)
- Increasing B:
  - » shifts the point where the suppressed G region begins across the valley
  - » decreases G globally
  - » splits the Kondo peak outside the suppressed region



- As V_{Gate} is lowered, the conductance at zero bias drops, revealing the peak splitting Δ
- Δ appears constant with V_{Gate} until the depressed region is reached

⇒ ***behavior expected for Zeeman effect***





- from the region of the suppressed conductance (Δ>0, B→0) to the field-induced peak splitting:
  - *- continuous transition*
- Δ approaches 2 Δ_Z with B increasing (similar to Kouwenhoven *et al*., 1999)
- smaller values (~1.3 Δ_Z) found previously at large fields (~7 T) (Goldhaber-Gordon *et al*., 1999)

Conclusion

- Improved circuit makes 20<T<100 mK accessible
- In the Kondo regime, the conductance G(T) agrees well with theory for spin ½ dot
- The Kondo resonance width FWHM was studied as a function of position ε_0 in the Kondo valley:
  - ➢mixed-valence regime: FWHM(ε_0) dependence matches $T_K(\varepsilon_0)$ predicted for Kondo regime (prefactor 5 times smaller)
  - ➢Kondo regime : (T_K << T) : unexpected variations of FWHM with ε_0 by as much as 50%, FWHM too large to be explained by thermal broadening alone
- Kondo feature often observed at even occupancy number N, which can be understood as a spin 1 Kondo effect
- Sharp edges near V_{sd} =0 with nontrivial dependence on V_{Gate}, V_{sd}, B
  - ➢understood in terms of singlet-triplet excitations
  - ➢coupling arising from Hund's rules can be estimated for the quantum dot (|J|~200 μeV was found)

Acknowledgments

This work was supported by NSF Division of Materials Research, NSF NSEC, and US Army Research Office. One of us (G.G.) is grateful to NSERC for partial financial support.