Nonequilibrium Kondo phenomena in single-electron transistors

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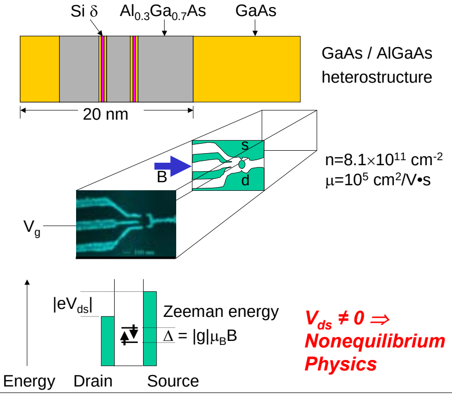
Abstract

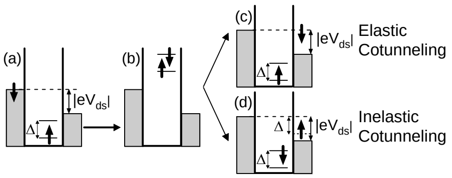
We have measured the spin splitting in a parallel magnetic field B of localized states in single-electron transistors (SETs) using a new method, inelastic spin-flip cotunneling. In the same devices we have also measured the splitting with B of a Kondo peak. We have found that the Kondo peak splitting appears only above a threshold field as predicted by theory, but that the magnitude of the splitting is larger than predicted.

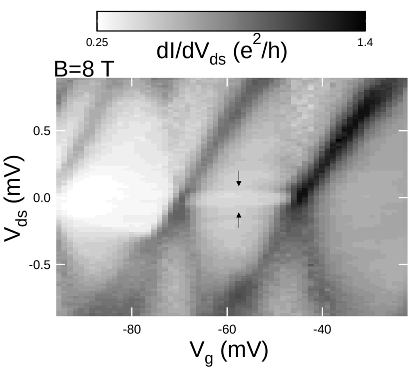
Single-electron transistors



$V_{ds} \neq 0 \Rightarrow$ Nonequilibrium Physics

Inelastic spin-flip cotunneling

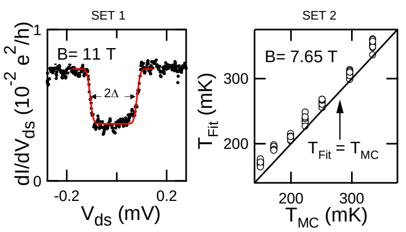




First Observation in SETs !

From Lambe and Jaklevic (PR **165**, 821 (1968)):

$$dI/dV_{ds} = a + b\left[F\left(\frac{eV_{ds}+\Delta}{k_BT}\right) + F\left(\frac{-eV_{ds}+\Delta}{k_BT}\right)\right]$$



Lowest T_{FIT} of 46 mK

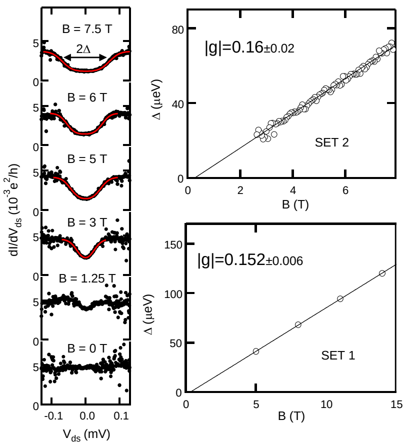
⇓

22 μeV upper bound for intrinsic line width

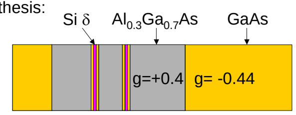
⇓

0.2 ns lower bound for excited spin state decoherence time

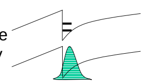
Zeeman splitting from spin-flip cotunneling



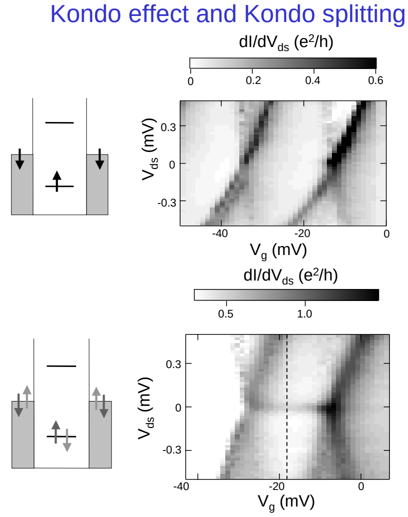
- Same small g-factor at different occupancies and in two samples in different dilution refrigerators
- Result confirmed by electron addition spectroscopy
- Hypothesis:



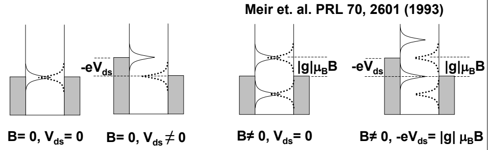
Penetration of the wavefunction in the AlGaAs caused by the strong electric field

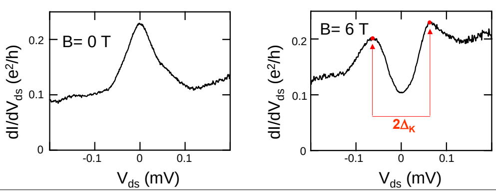


Kondo effect and Kondo splitting



Meir et. al. PRL 70, 2601 (1993)

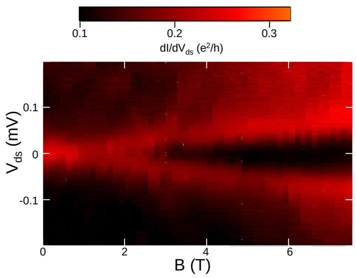


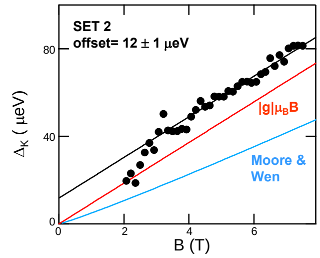


Theoretical predictions

- Kondo splitting appears only above a threshold magnetic field. (**T. A. Costi, PRL 85, 1504 (2000)**)
- The splitting between the Kondo peaks 2 Δ_K is always less than twice the Zeeman energy: 2 Δ_K < 2 $|g|\mu_B B$ at all fields. (**Moore & Wen, PRL 85, 1722 (2000)**)

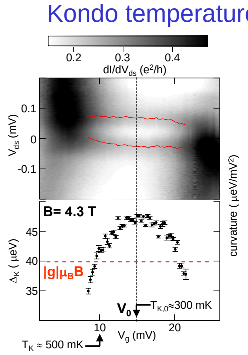
Magnetic field dependence of Δ_K



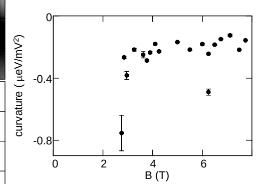


Different sample, colder fridge: offset= 10 ± 2 μeV

Kondo temperature dependence of Δ_K



- **SETs allow us to control Kondo Temperature!**
- **Haldane Formula:** $T_K = T_{K,0}\exp(\pi\alpha_g{}^2e^2(V_g-V_0)^2/\Gamma U)$



Consistent with $\delta\Delta_K \propto \log(1/T_K)$, Not $\delta\Delta_K / B \propto \log(1/T_K)$

Conclusion

- We have made the first observation of the inelastic spin-flip cotunneling threshold in SETs.
- We have used inelastic spin-flip cotunneling to precisely measure the Zeeman splitting in an SET.
- We have measured the splitting of a Kondo peak in a magnetic field and found that the splitting appears only above a threshold field as predicted by theory. However, $\Delta_K > |g|\mu_B B$ in contradiction to theory.
- Future Plans: Further measurements to explore the dependence of Δ_K on T_K and B.

Acknowledgments

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