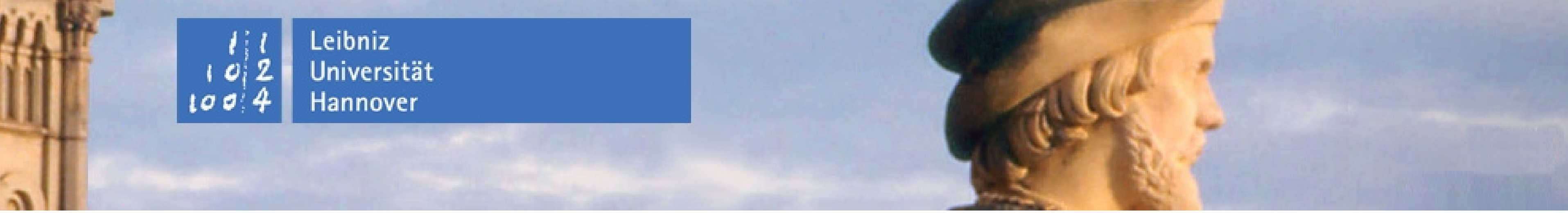

Coherence and Correlations
in
Transport through Quantum Dots

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Germany

nanostrukturen
uni hannover

Leibniz
Universität
Hannover

Leibniz
Universität
Hannover

Gottfried Wilhelm Leibniz
(1676 – 1716 in Hannover)

binary numbers as mentioned in a letter to Rudolf August von Wolfenbüttel in January 1697 (new-year letter)

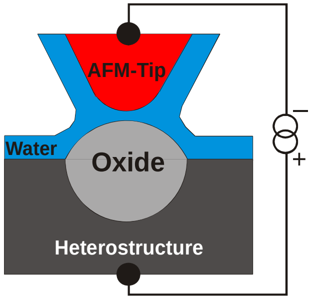
Overview

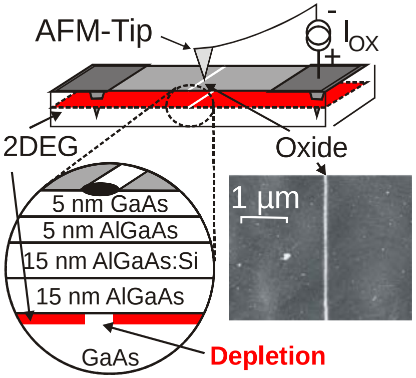
- spin effects in quantum dots
- shot noise measurements

Technology

- **lithography (GaAs/AlGaAs heterostructures)**

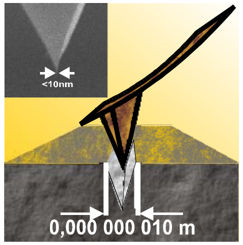
1. optical lithography
2. electron beam lithography
3. direct writing with AFM

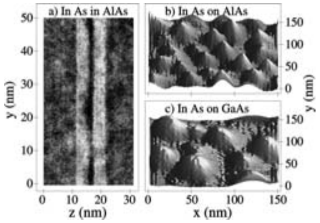




- **self-organized growth**

  quantum dots (InAs, InP, Ge)





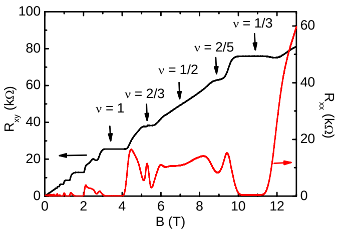
lattice mismatch between InAs

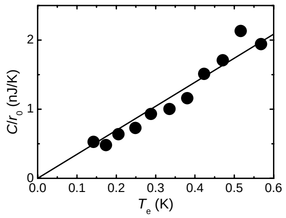
and AlAs (GaAs): 7%

Stranski-Krastanov growth

Other Fields of Research

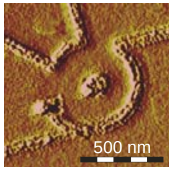
- quantum Hall effect and fractional quantum Hall effect

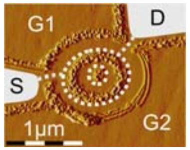


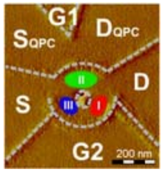


Phys. Rev. Lett. 93, 196801 (2004)
Phys. Rev. Lett. 92, 156401 (2004)
Phys. Rev. Lett. 93, 026801 (2004)
Phys. Rev. B 74, 165325 (2006)
Phys. Rev. B 74, 195324 (2006)
Phys. Rev. B 76, 153311 (2007)

- transport in quantum rings

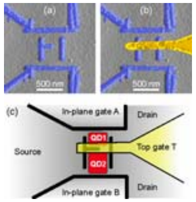


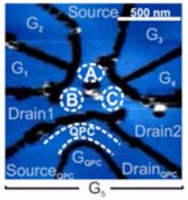


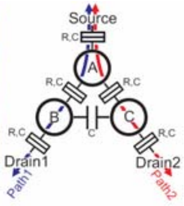


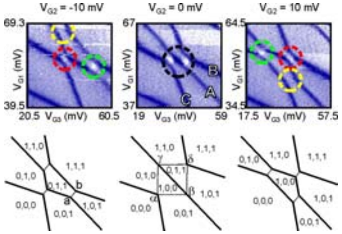
Phys. Rev. Lett. 90, 196601 (2003)
Appl. Phys. Lett. 91, 133116 (2007)
Appl. Phys. Lett. 92, 013126 (2008)

- transport through double and triple dots

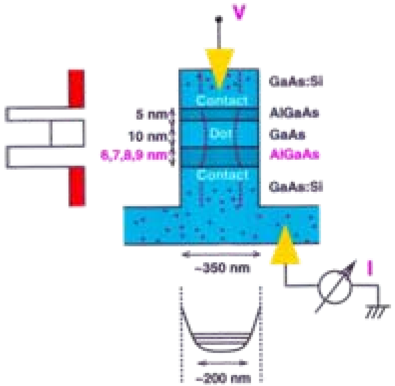




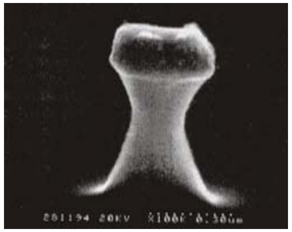




Appl. Phys. Lett. 83, 1163 (2003)
Appl. Phys. Lett. 85, 806 (2004)
Phys. Rev. B (2008)

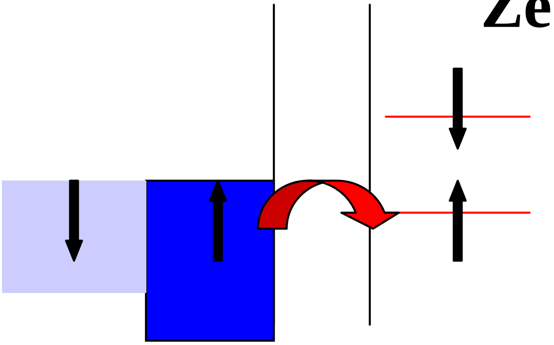


Spin-Resolved Tunneling through Quantum Dots

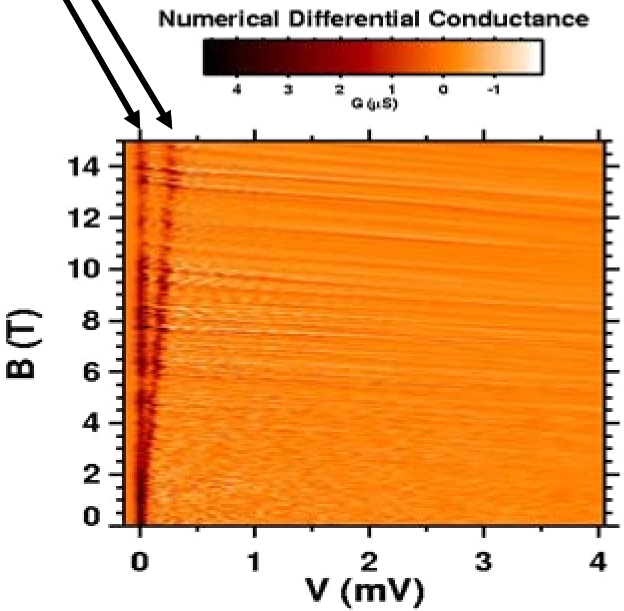


$$\Delta = g\mu_B B$$

g = - 0.12



Zeeman energy

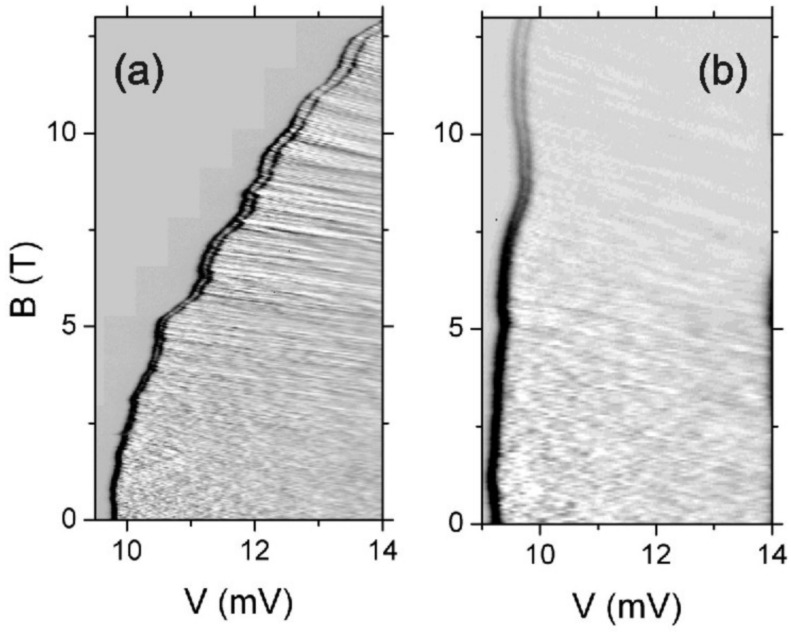


Europhys. Lett. 54, 495 (2001)

- **spin-polarized current in a magnetic field**
- **spin-resolved spectroscopy of the local density of states**

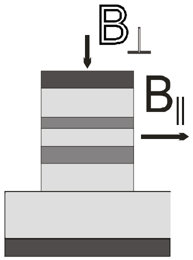
Anisotropy of Spin Splitting: Spin-Orbit Interaction

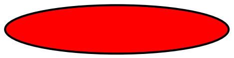
GaAs quantum dots



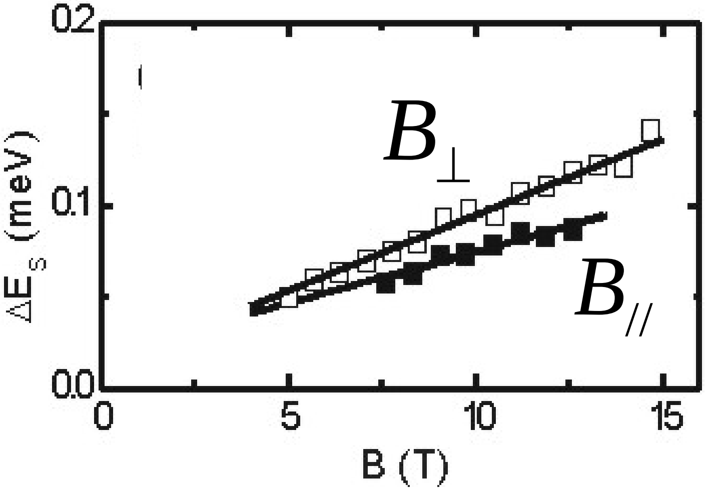
$B_\perp$ $B_{//}$

disc-like quantum dot





spin splitting



Bychkov-Rashba (structure, 0,054meV) dominates over Dresselhaus (bulk, 0.012meV) for dots in 10nm quantum well

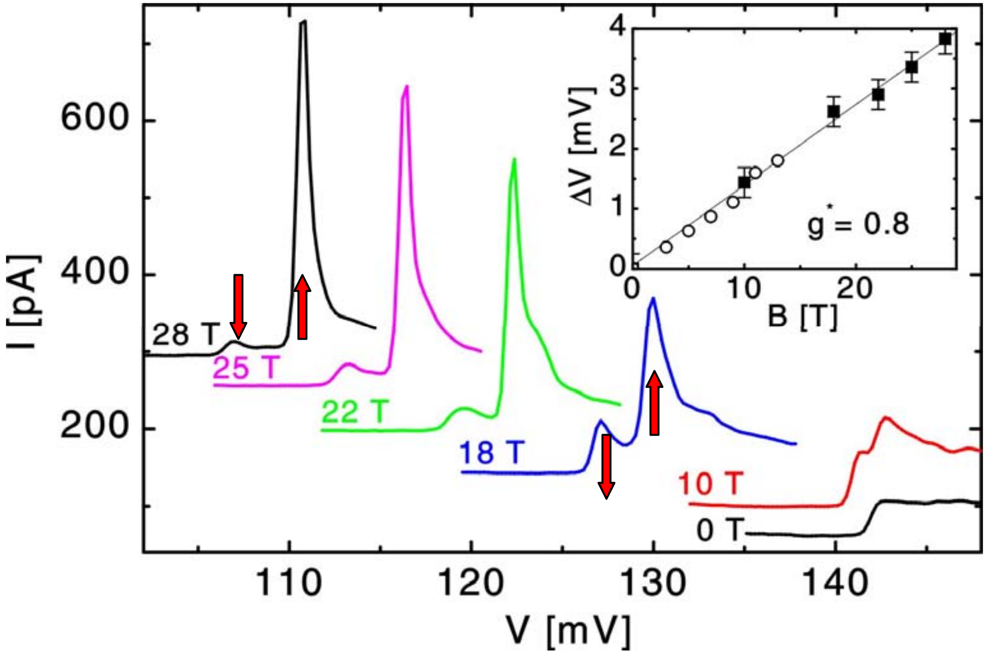
Phys. Rev. Lett. 94, 226404 (2005)

extreme anisotropy: holes in SiGe/Ge structure **Phys. Rev. Lett. 96, 086403 (2006)**

g=6.2 ⟶ 0

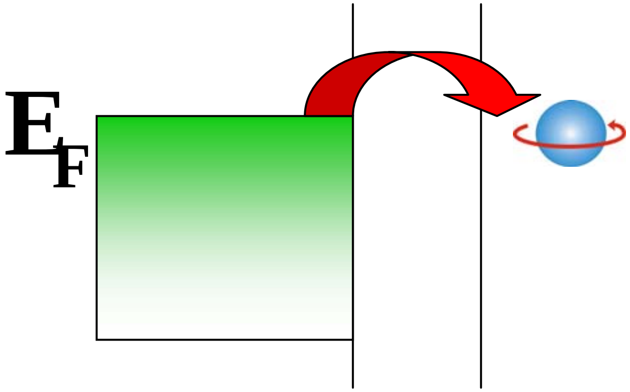
Interaction Effect in High Magnetic Fields

strong coupling in InAs quantum dots



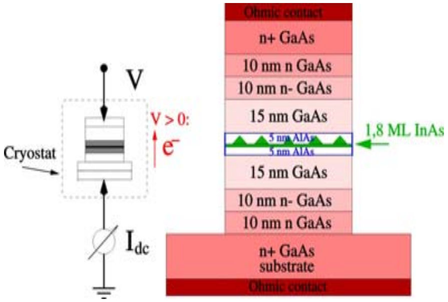
Fermi edge singularity
(Mahan 1967)

interaction of charge on dot with states in the emitter



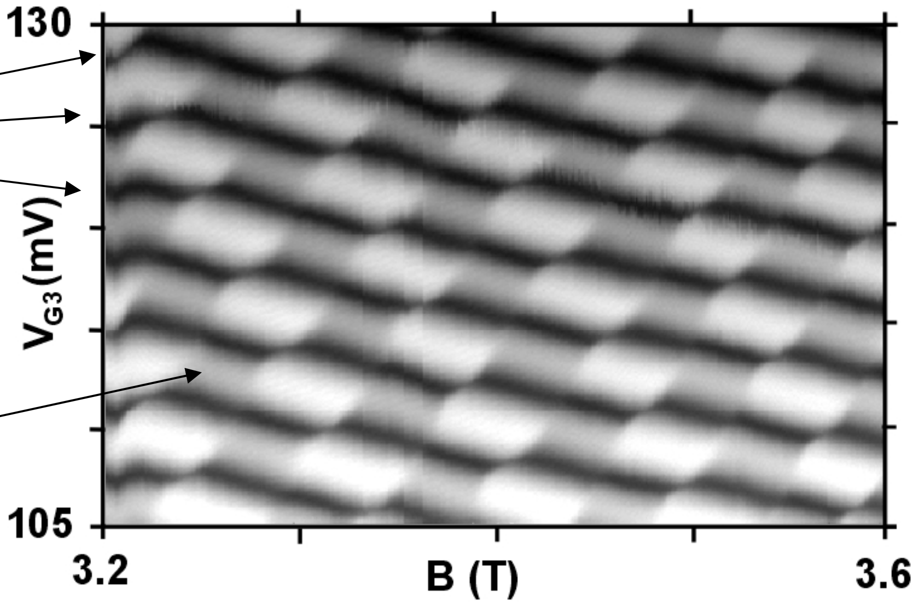
Phys. Rev. B 62, 12621 (2000)
Phys. Rev. B 74, 035329 (2006)

InAs dots between AlAs barriers



Many Electrons in Magnetic Field

single-electron
tunneling



conductance
within
Coulomb blockade
vanishes for large T

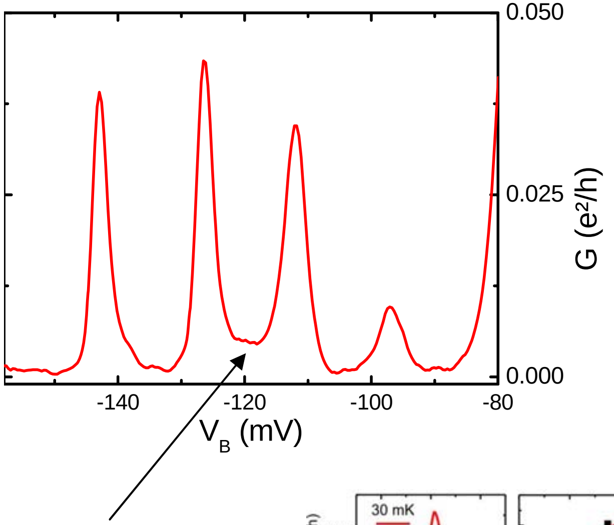
Phys. Rev. B 66, 161305(R) (2002)

Keller, PRB **64** (2001)
Stopa PRL **88**. 256804 (2003)

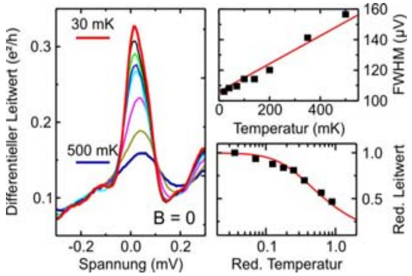
regular tiles – chequer board
periodicity of one flux quantum

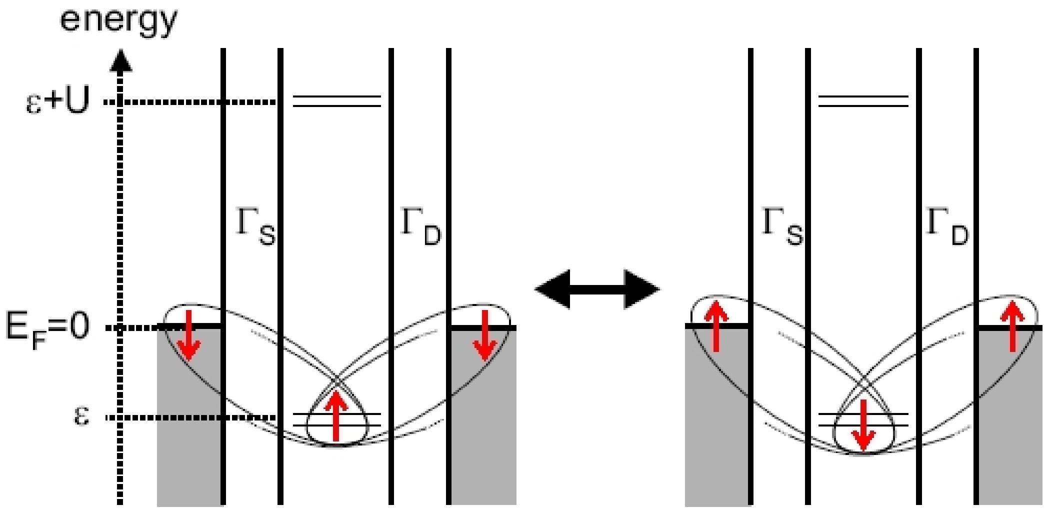
Spin-Spin Interaction: Kondo Effect

Phys. Rev. Lett. 90, 196601 (2003)



Kondo



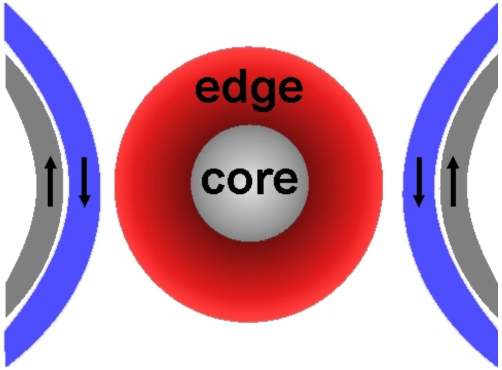


- **spin ½ on dot forms singlet with spins in leads**
- **transport via virtual state at Fermi energy involving spin flips**
- **finite conductance in Coulomb valley**

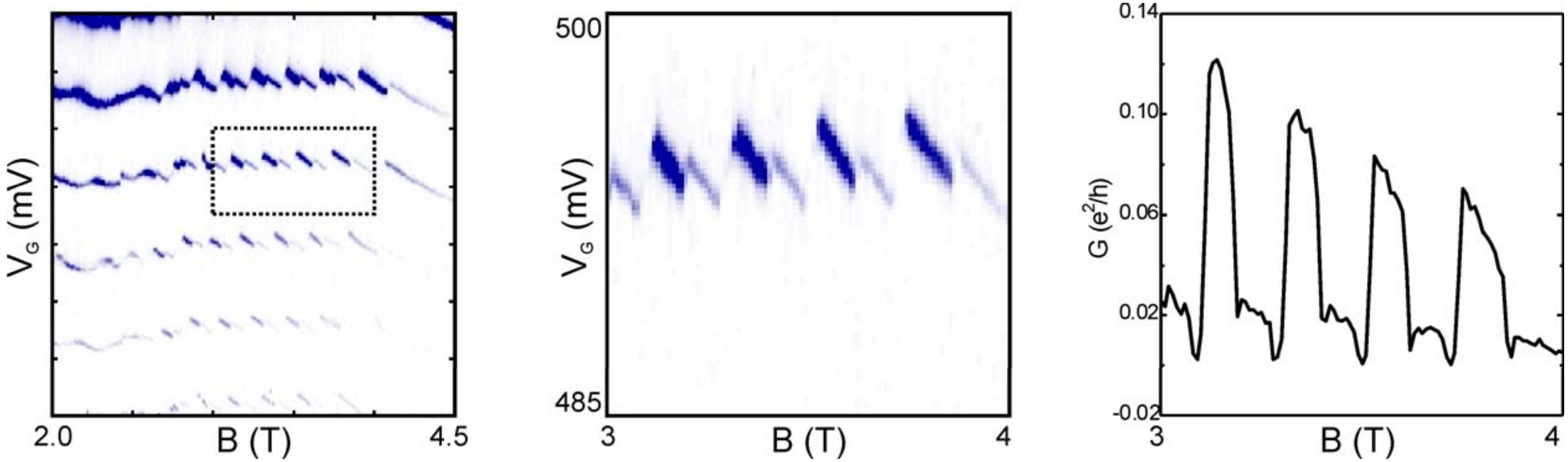
Kondo, Prog. Theor. Phys. 32, 37 (1964)
Glazman and Raikh, JETP Lett. 47, 452 (1988)
Ng and Lee, Phys. Rev. Lett. 61, 1768 (1988)
Goldhaber-Gordon et al., Nature 391, 156 (1998)
Cronenwett et al., Science 281, 540 (1998)
Schmid et al., Physica B 256, 182 (1998)

Spin Polarization in High Magnetic Fields

dot: 2 Landau levels edge/core
leads: spin polarized edge channels



spin down: strong amplitude
spin up: weak amplitude

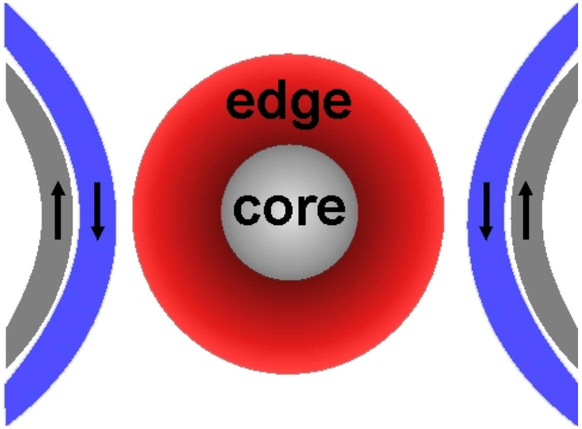


New J. Phys. 8, 298 (2006)

Ciorga et al. Phys. Rev. B **61**, R16315 (2000)

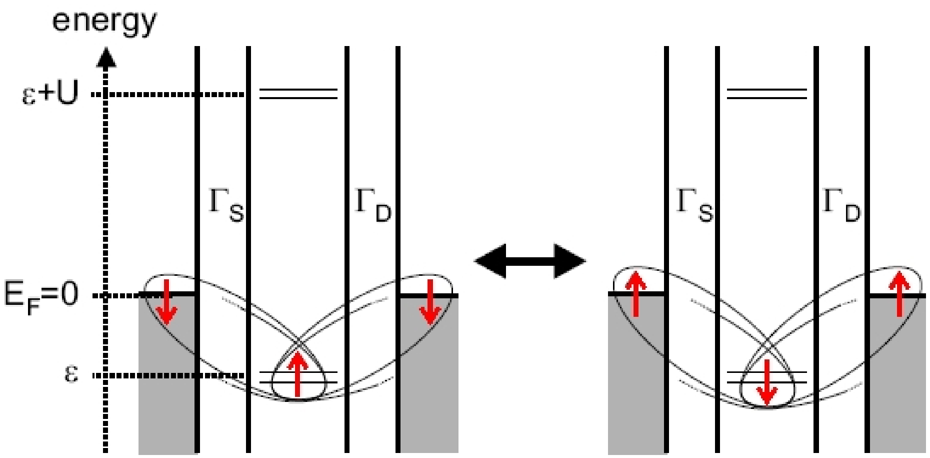
Spin Blockade versus Kondo Effect

spin blockade



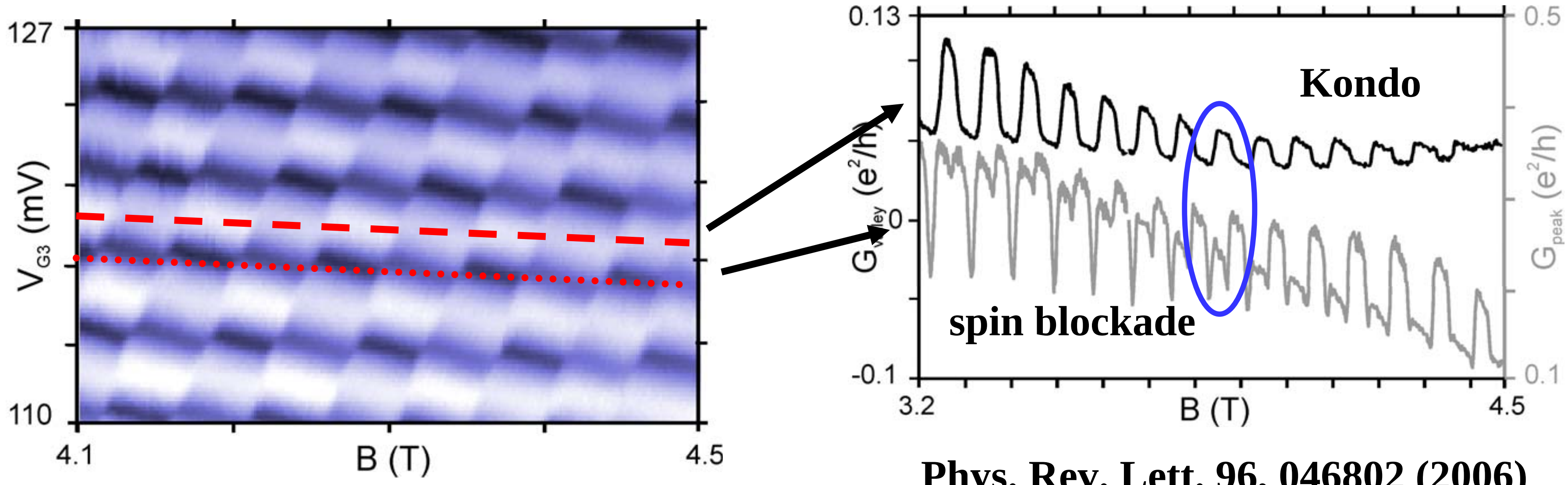
spin polarized leads necessary

Kondo effect



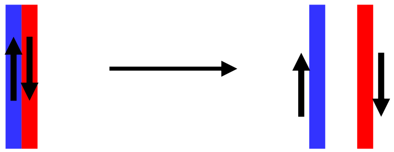
both spins in the leads necessary

Transition between Spin Blockade and Kondo Effect in Dots with Many Electrons



Phys. Rev. Lett. 96, 046802 (2006)
Phys. Rev. Lett. 96, 176801 (2006)

- with increasing B:
  spin blockade increases,
  Kondo effect decreases

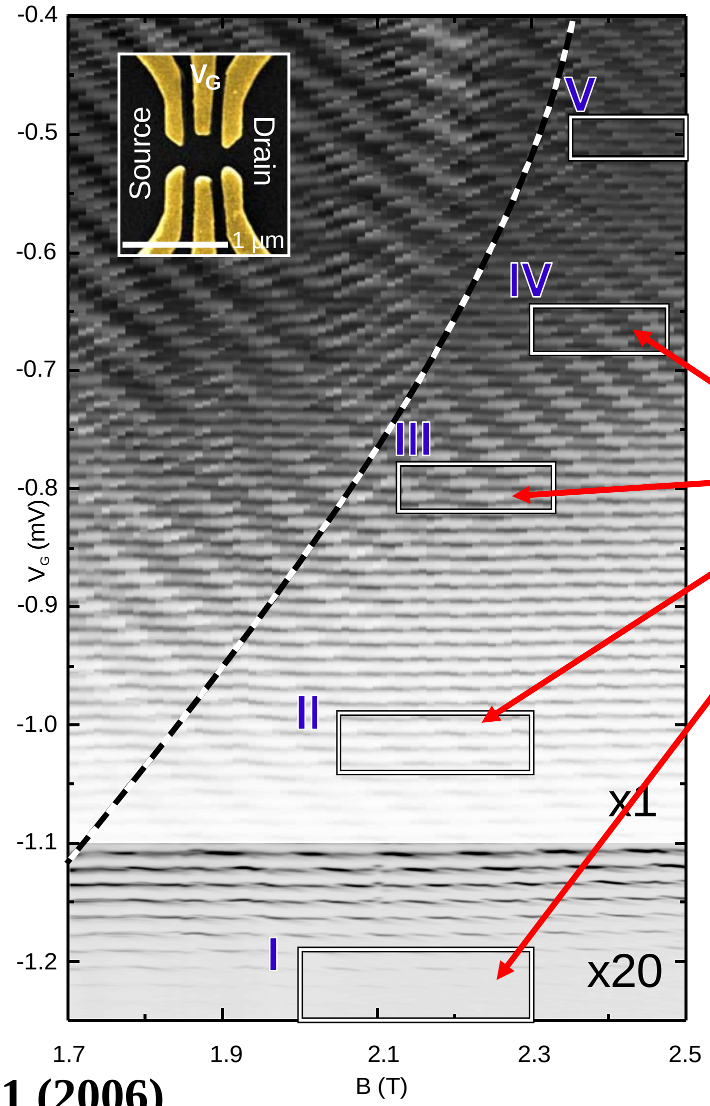


- origin: spin polarization of edge
- intermediate regime: both effects visible → spin structure

→ shell structure

Spin Structures

100 electrons



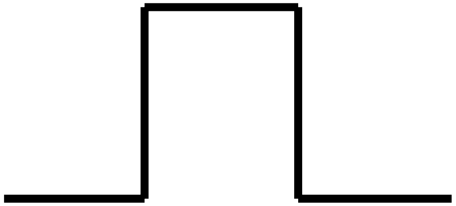
different spin configurations

Phys. Rev. Lett. 96, 176801 (2006)

Shot Noise

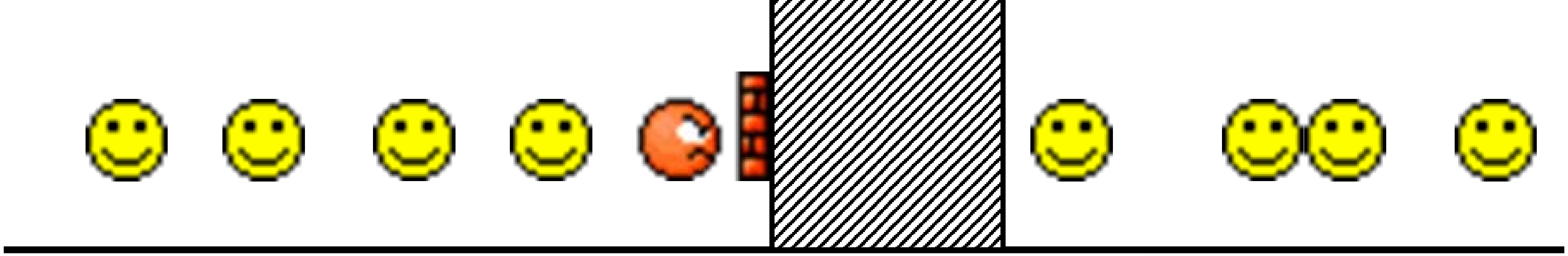
- electrical current

barrier

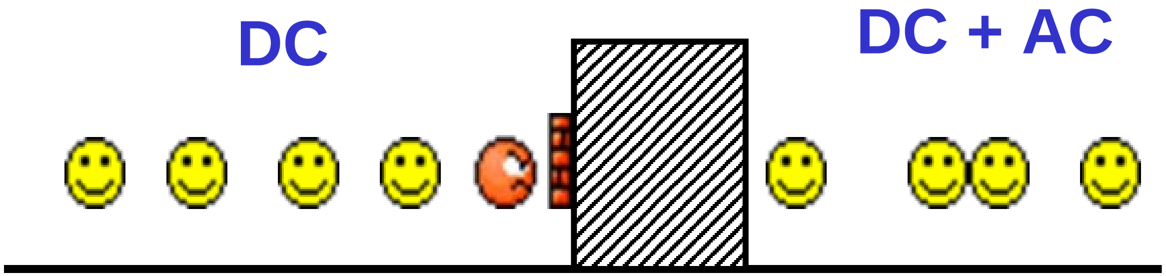


DC

DC + AC



Shot Noise



DC

DC + AC

W. Schottky,
Annalen der Physik,
57, 541 (1918)

$S_{\text{Poisson}} = 2eI$ (single barrier)

correlations can suppress noise

$$S = \alpha 2eI$$

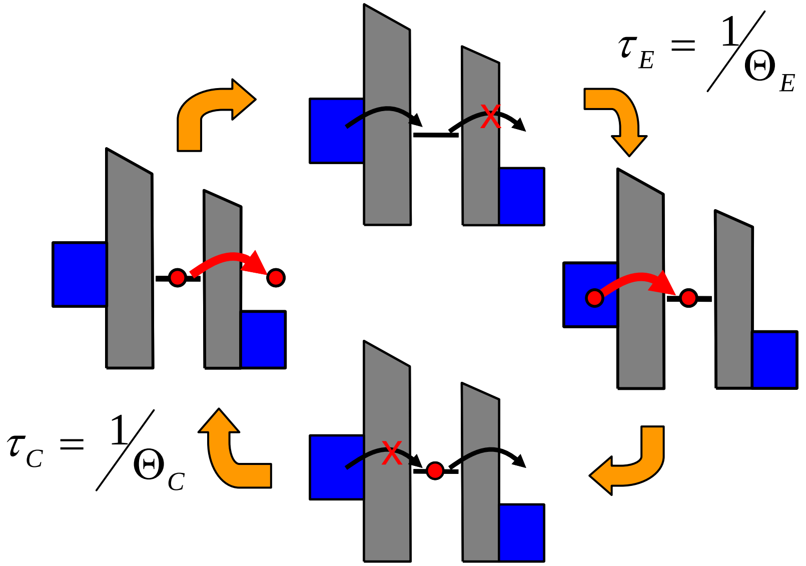
Fano factor

Ugo Fano

U. Fano, Phys. Rev. 72, 26 (1947)

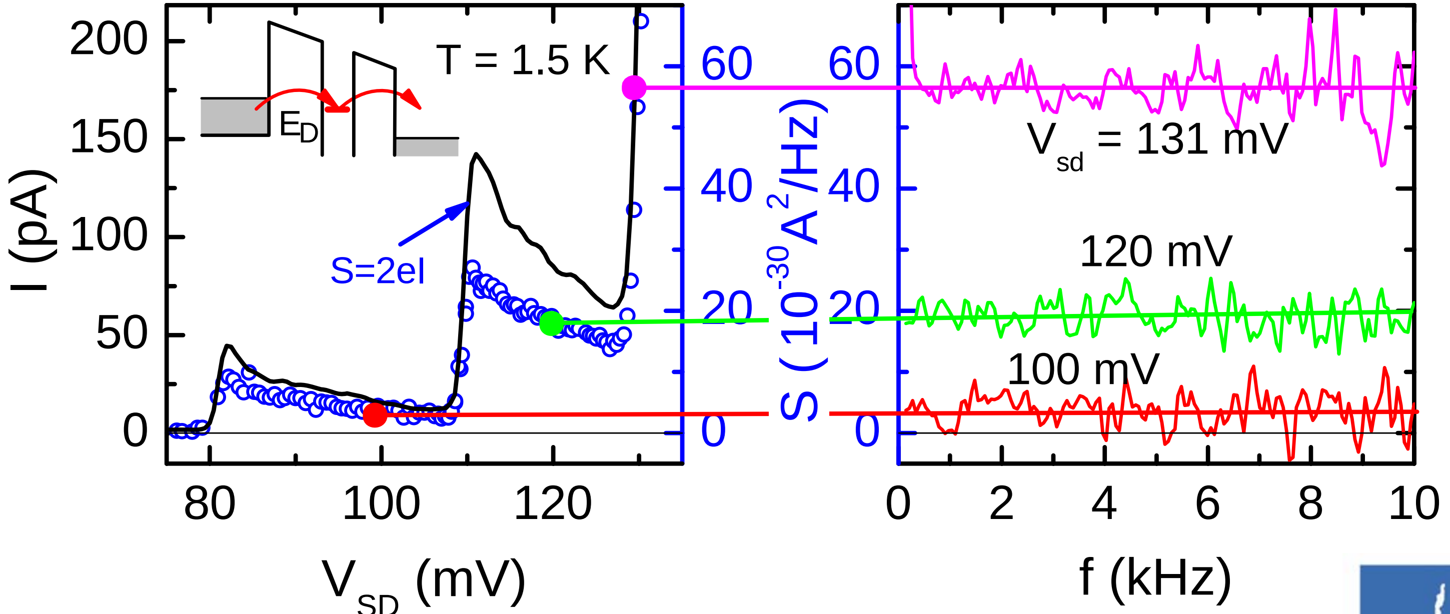
Shot Noise Measurement

- **direct measurement of current noise spectrum (PRB 66, 161303R (2002))**
- **reduction of shot noise due to Coulomb blockade**
- S = α·2eI with $\alpha = 1 - \frac{2\Theta_E\Theta_C}{(\Theta_E+\Theta_C)^2}$



$\tau_E = 1/\Theta_E$

$\tau_C = 1/\Theta_C$

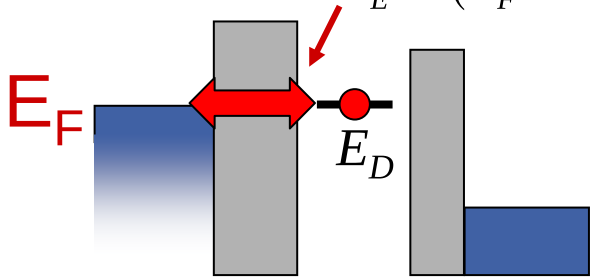


measurement resolution:
$\Delta S \sim 10^{-30}$ A²/Hz

1 kΩ resistor @ 300 K:
$S = 1.6 \cdot 10^{-23}$ A²/Hz

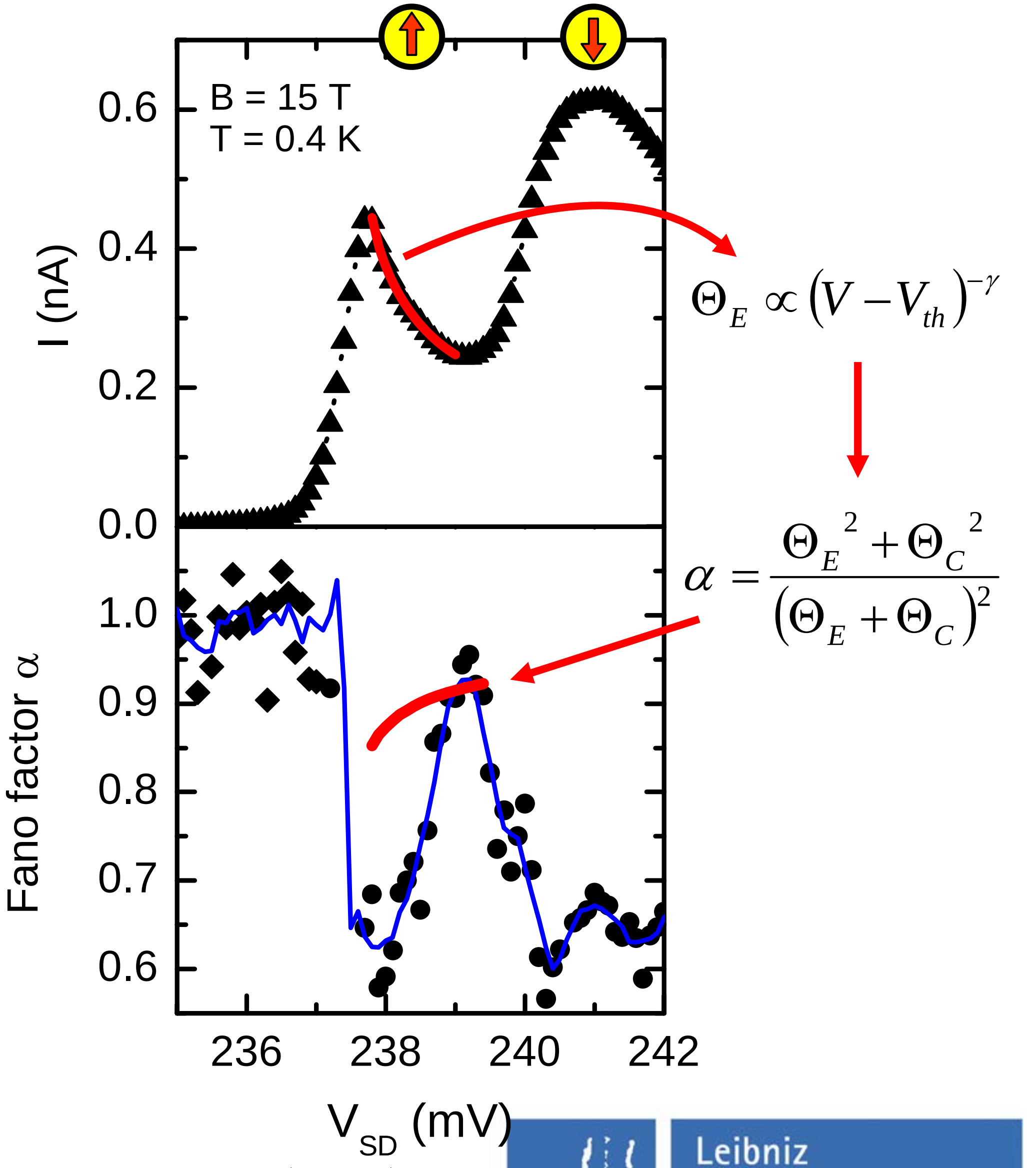
Noise at Fermi Edge Singularity

$$\Theta_E \propto \left(E_F - E_D\right)^{-\gamma}$$



PRB 62, 12621 (2000);
PRB, 74, 035329 (2006)

strong
additional noise suppression
due to Fermi edge singularity



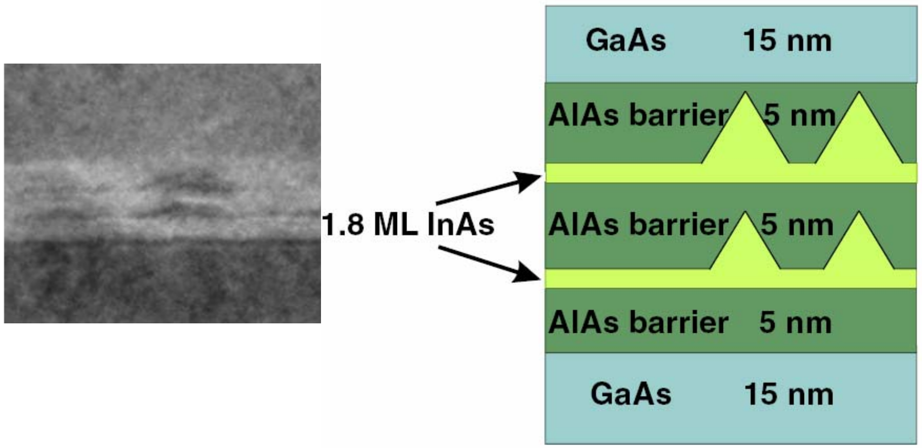
$$\Theta_E \propto \left(V - V_{th}\right)^{-\gamma}$$

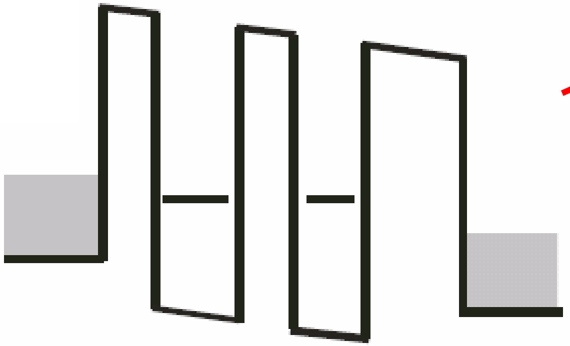
$$\alpha = \frac{\Theta_E{}^2 + \Theta_C{}^2}{\left(\Theta_E + \Theta_C\right)^2}$$

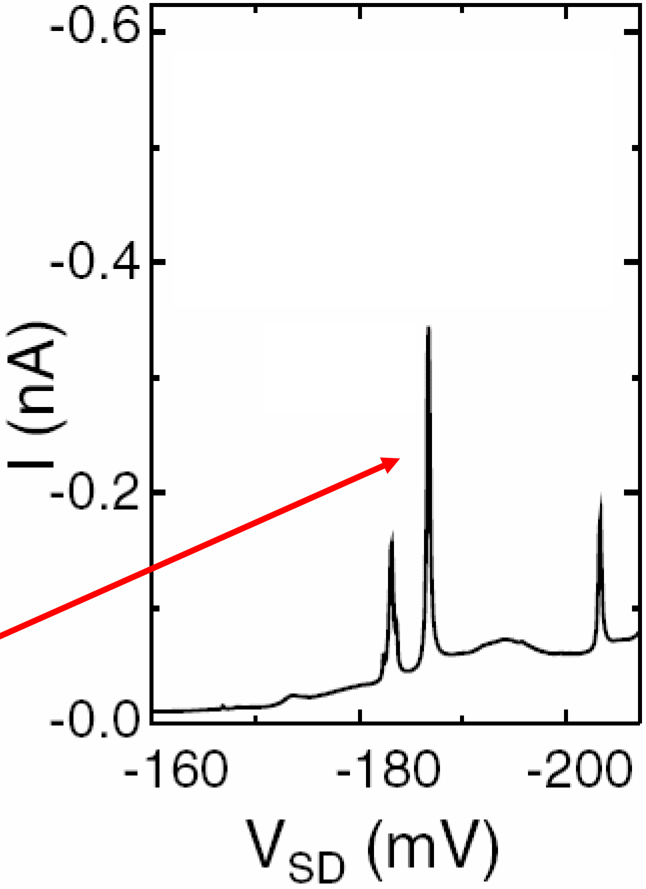
Phys. Rev. B 75, 233304 (2007)

Transport through Coupled Quantum Dots

stacks of InAs dots



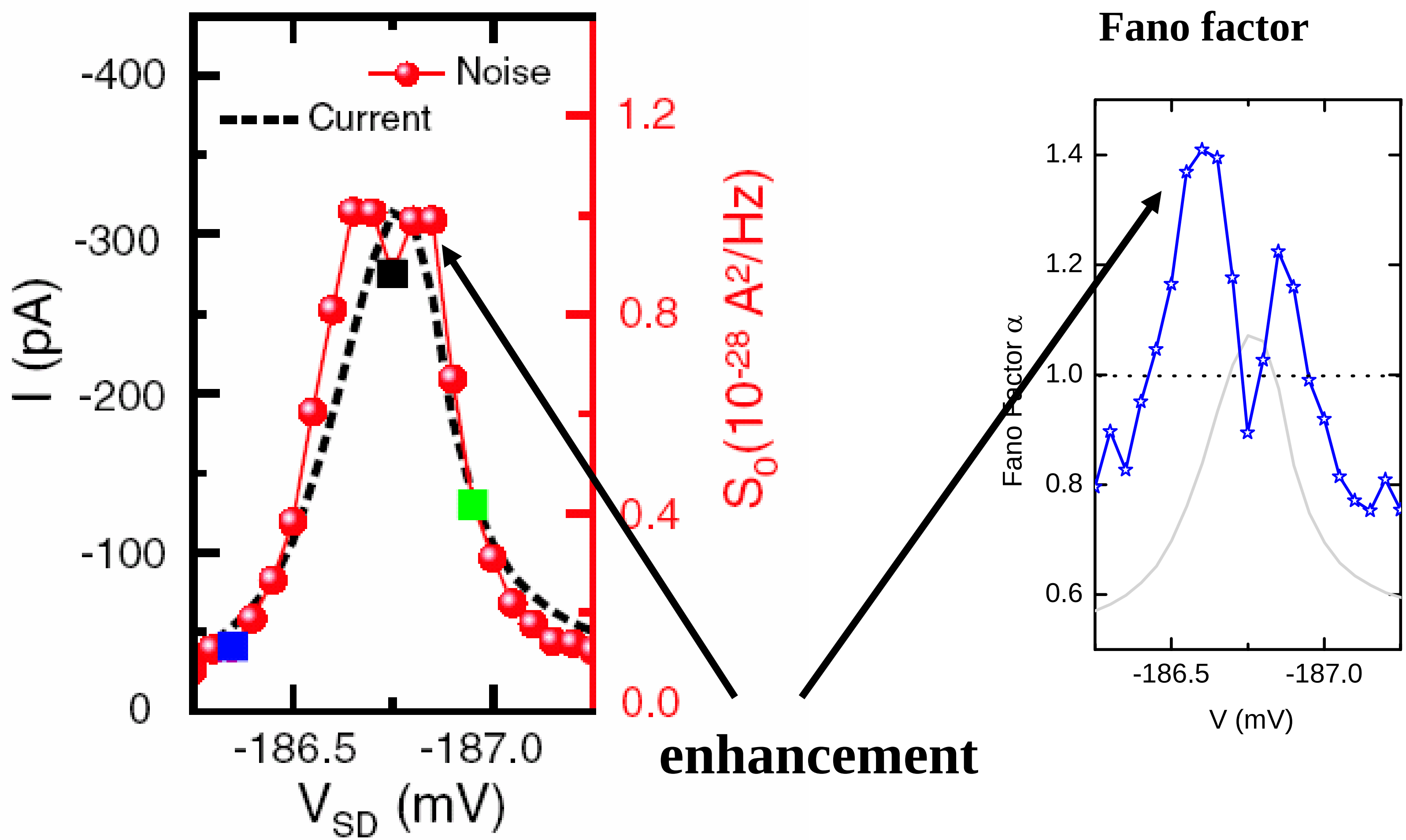




26. ICPS, IOP 171, 233 (2002)

Phys. Rev. Lett. 96, 246803 (2006)

Shot Noise in Transport through Coupled Quantum Dots



enhancement

Phys. Rev. Lett. 96, 246803 (2006)

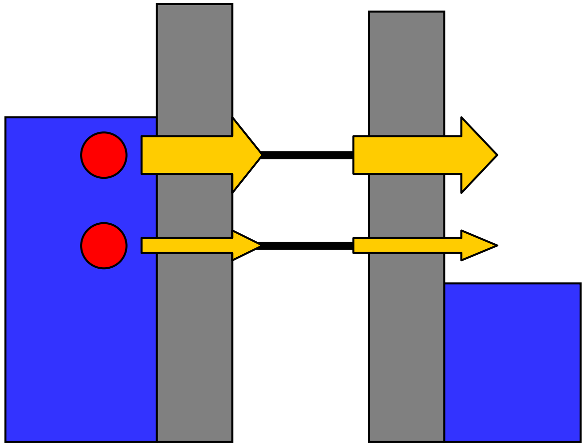
Electron Bunching

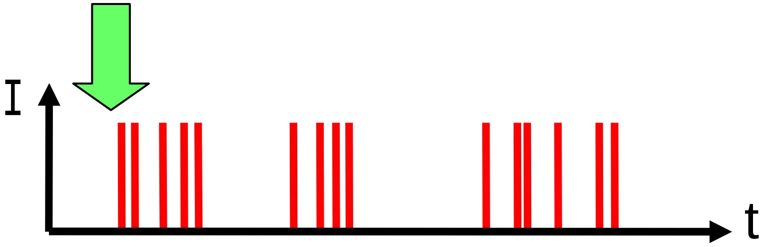
- compare: electron bunching for single quantum dots
  - observed for 2 accessible states with different tunnelling rates

e.g. Phys. Rev. B 69, 113316 (2004);

Gustavsson et al, Phys. Rev. B 74, 195305 (2006);

Zachrin et al, Phys. Rev. Lett. 98, 066801 (2007)



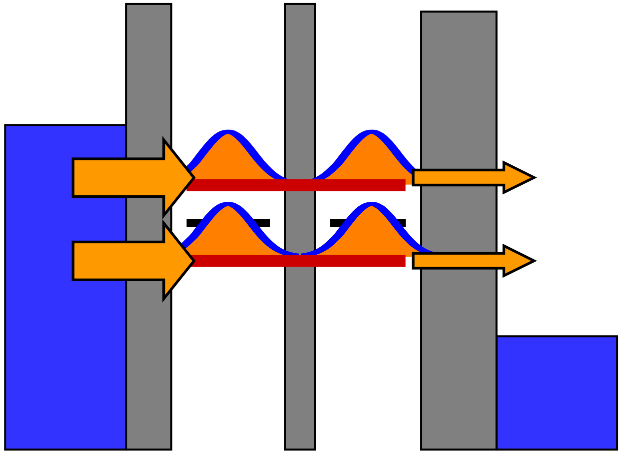


Electron Bunching

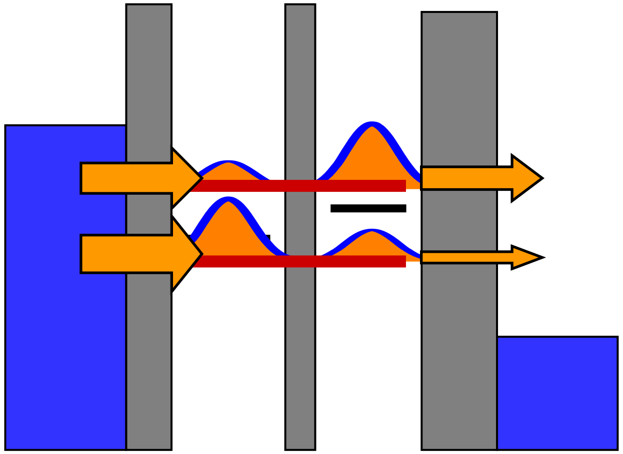
here: two molecular states for coherently coupled dots

- **energies aligned: symmetric system and equal rates ⇒ $\alpha < 1$**
- **energies detuned: asymmetric distribution and tunnelling rates**

⇒ bunching



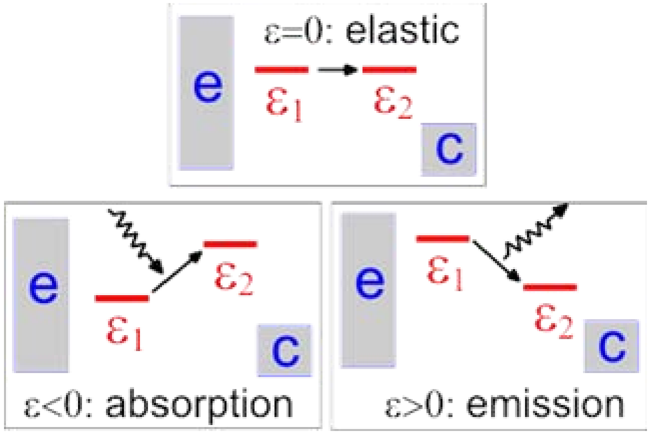
$E_L = E_R$

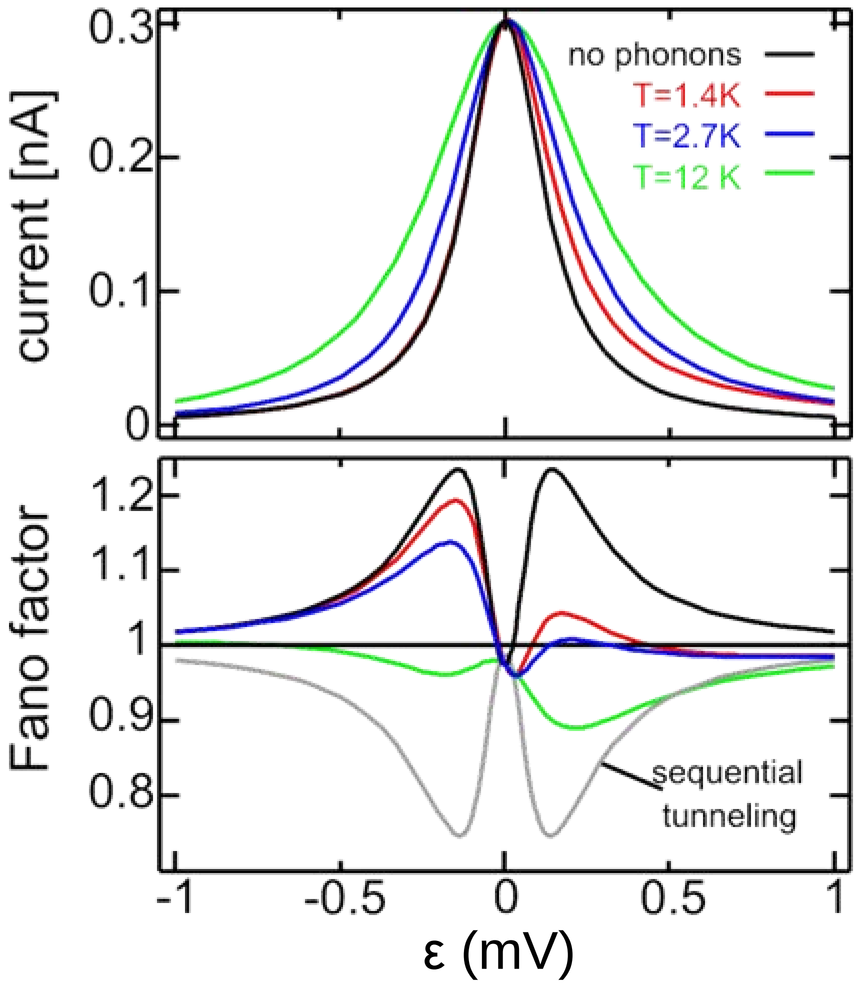


$E_L < E_R$

Quantum Coherence

- **theory (Kiesslich, Berlin)**
- **coherent coupling of QDs**
- **dephasing due to phonon absorption and emission**
- **reproduces super-Poissonian noise and temperature dependence**

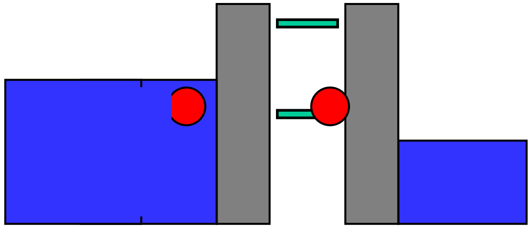


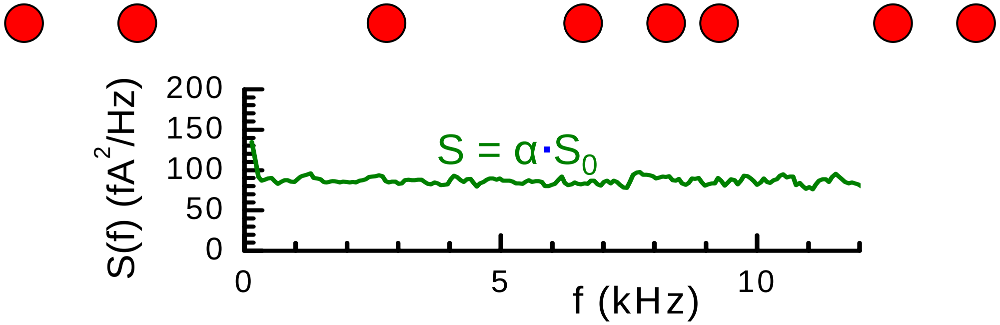


Phys. Rev. Lett. 99, 206602 (2007)

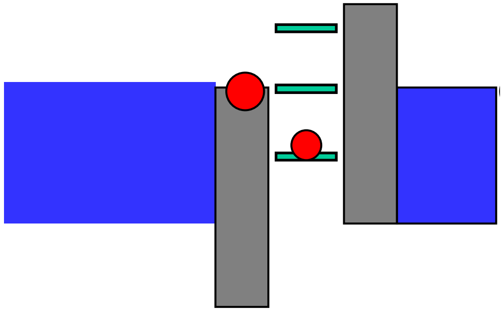
Putting Electrons on a String

- shot noise caused by randomness of tunneling events



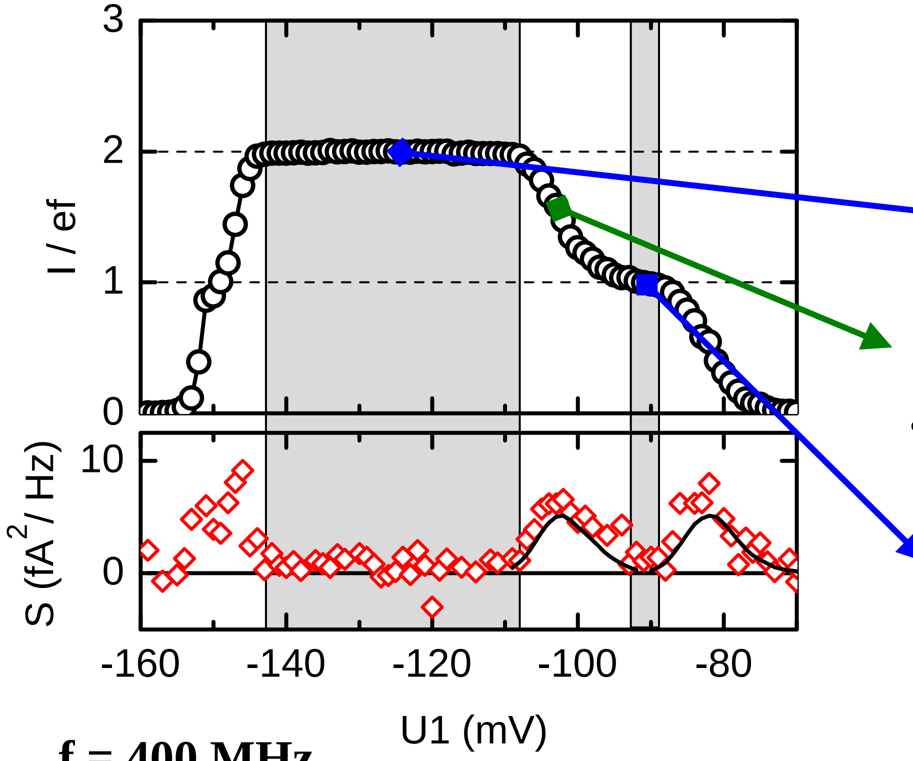


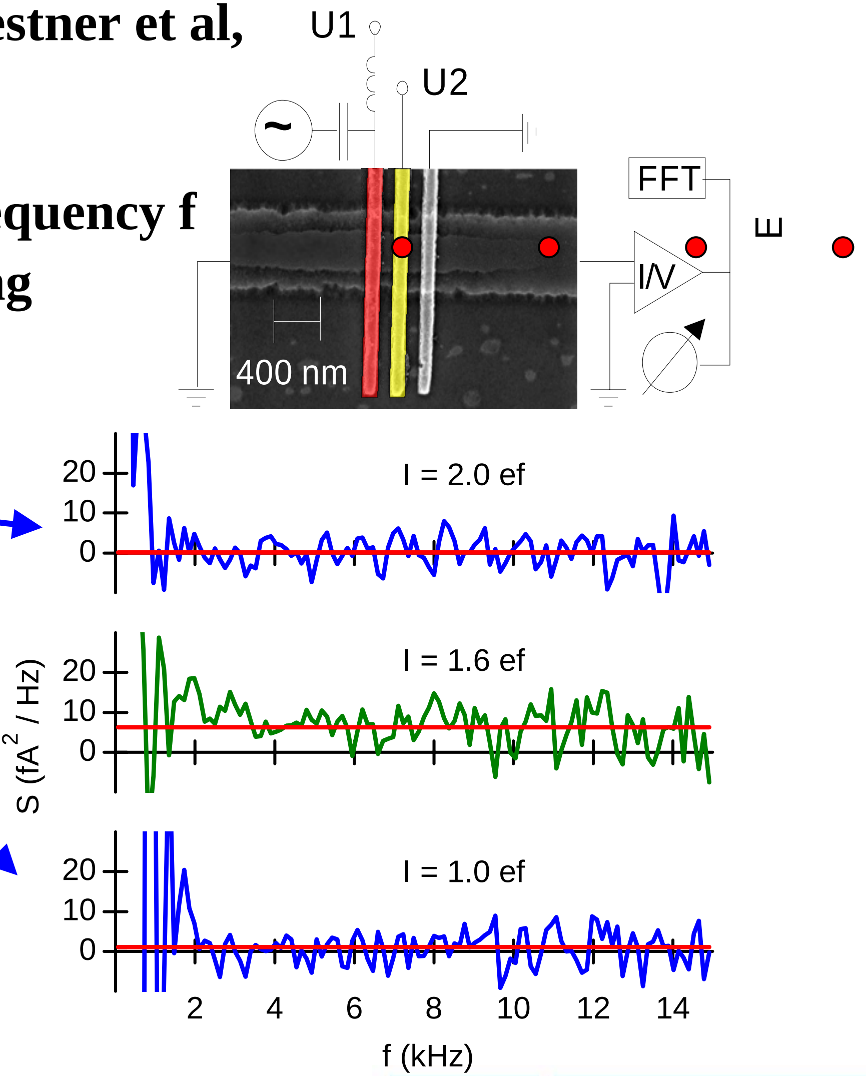
- suppression of randomness
  - by driven electron pump
  - electrons at well defined times → no noise expected



Noise Suppression in an Electron Pump

- **electrons pumped by actively driven barriers (Blumenthal et al, Nat. Phys. 2007, Kaestner et al, arXiv:0707.0993)**
- **quantized current plateaus I = nef**
  - **n electrons per cycle; repetition frequency f**
- **noise suppressed for quantized pumping**



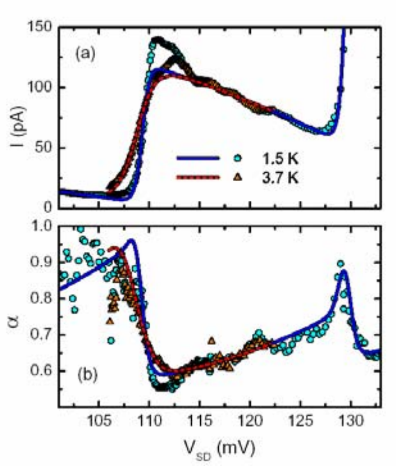


f = 400 MHz

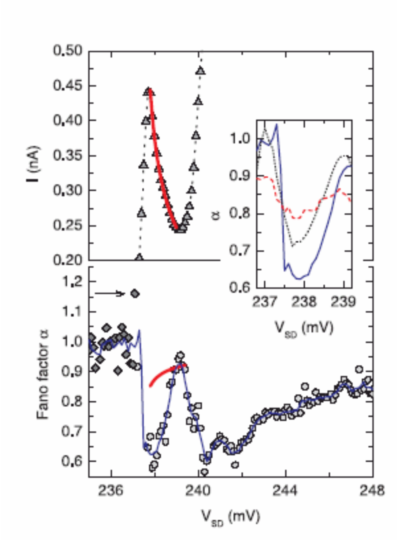
Appl. Phys. Lett. 92, 082112 (2008)

Shot Noise and Electron Counting in Quantum Dots

single dots

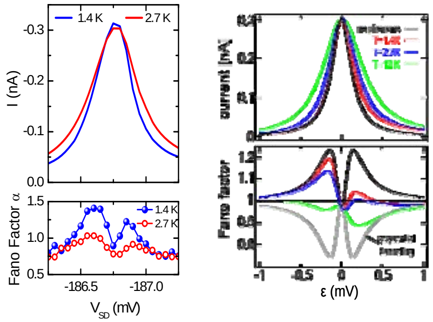


Phys. Rev. B 66,161303 (2002)
Phys. Rev. B 69, 113316 (2004)
Phys. Rev. B 70, 033305 (2004)

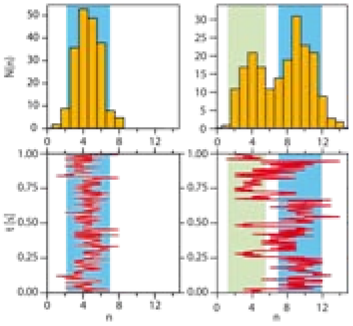


Phys. Rev. B 75, 233304 (2007)

coupled dots



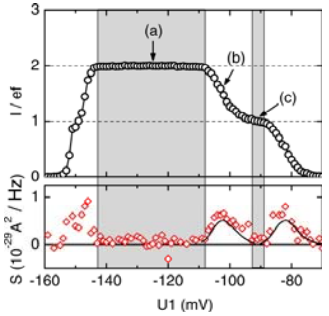
Phys. Rev. Lett. 96, 246803 (2006)
Phys. Rev. Lett. 99, 206602 (2007)



bimodal counting statistics

Phys. Rev. B 76, 155307 (2007)

noise in electron pump



Appl. Phys. Lett. 92, 082112 (2008)

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