Spin transport in Quantum Dots and Quantum Point Contacts

M. Ciorga

Outline

Quantum Point Contacts

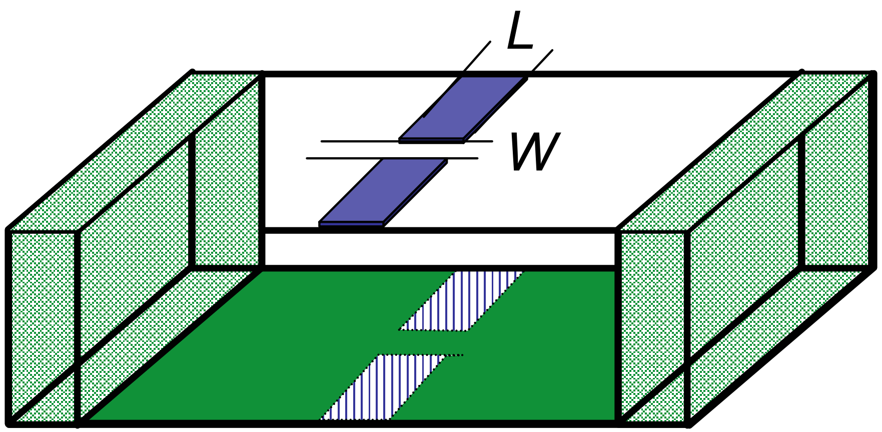
- Conductance quantization
- Ballistic transport - magnetic electron focusing
- Spin filtering

Lateral Quantum Dots

- Energy spectrum of quantum dots (Fock-Darwin)
- Coulomb blockade spectroscopy
- Few electron lateral quantum dot connected to spin polarized leads – Spin Blockade Spectroscopy
- Tuning the spin of the dot with number of electrons N, magnetic field and electric field

Quantum Point Contacts

For a review see:
H. van Houten, C. W. J. Beenakker, B. J. van Wees, Quantum point contacts, in *Nanostructured Systems,* M. A. Reed, Ed. (Academic Press, San Diego, 1992), vol. 35, pp. 9-112.



Ballistic regime
W,L<<*l*

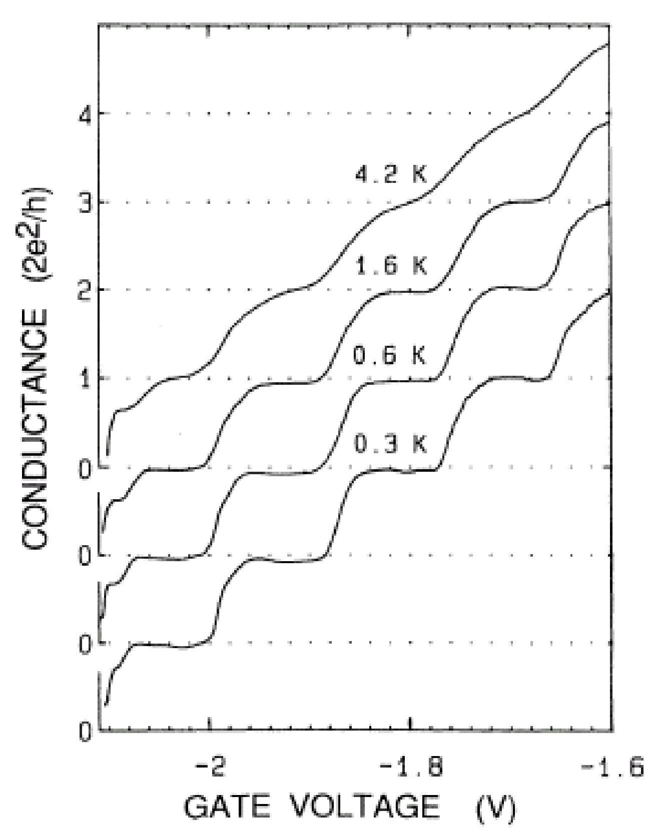
For AlGaAs/GaAs systems

$$n_s \approx 2\times 10^{11} cm^{-2},\ \mu \approx 2\times 10^{6} cm^{2}/Vs$$

$$l \approx 10\mu m,\ \ \lambda_F \approx 60nm$$

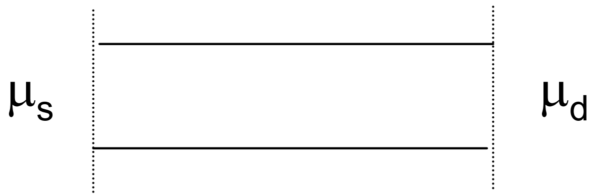
Conductance quantization

B. J. van Wees *et al*., PRL. **60**, 848 (1988)
D. A. Wharam *et al*., J. Phys. C **21**, L209 (1988)



From B. Van Wees *et al.* PRB 43, 12431 (1991)

The origin of the quantization



$$G = I/V = eI/(\mu_s - \mu_d)$$

$$I = e\sum_{n=1}^{N}\int_{\mu_s}^{\mu_d} dE\,\frac{1}{2}\rho_n(E)v_n(E)T_n(E)$$

1D DOS $\rho_n(E) = 2/\pi\,(dE_n/dk)^{-1}$

$$v_n(E) = dE_n(k)/\hbar dk$$

The energy dependence of the 1D density of states exactly cancels that of the velocity

$$G = \frac{2e^2}{h}\sum_{n=1}^{N} T_n(E_F)$$

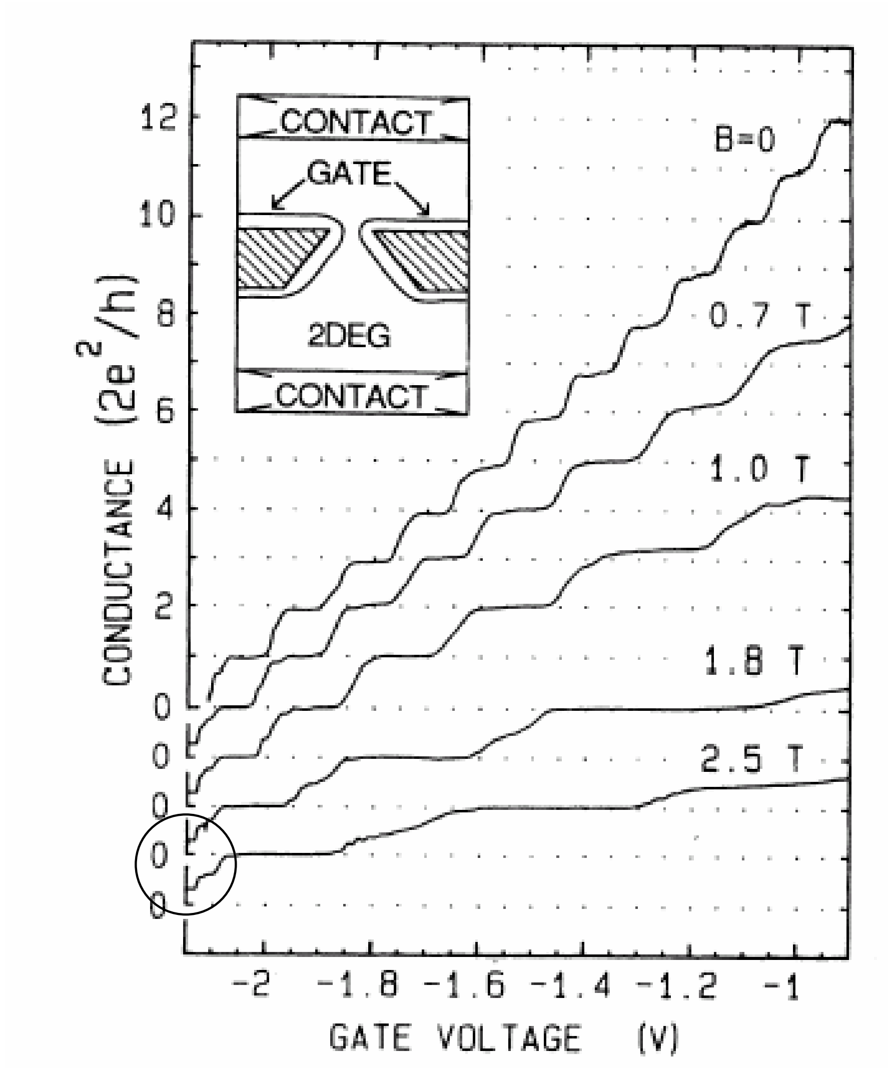
In the limit of no backscattering – fully transmitted modes

$$\sum_{n=1}^{N} T_n(E_F) = N \qquad G = \frac{2e^2}{h}N$$

In classical limit $N \approx \mathrm{Int}\left[\frac{k_F W}{\pi}\right]$

Conductance quantization in magnetic fields

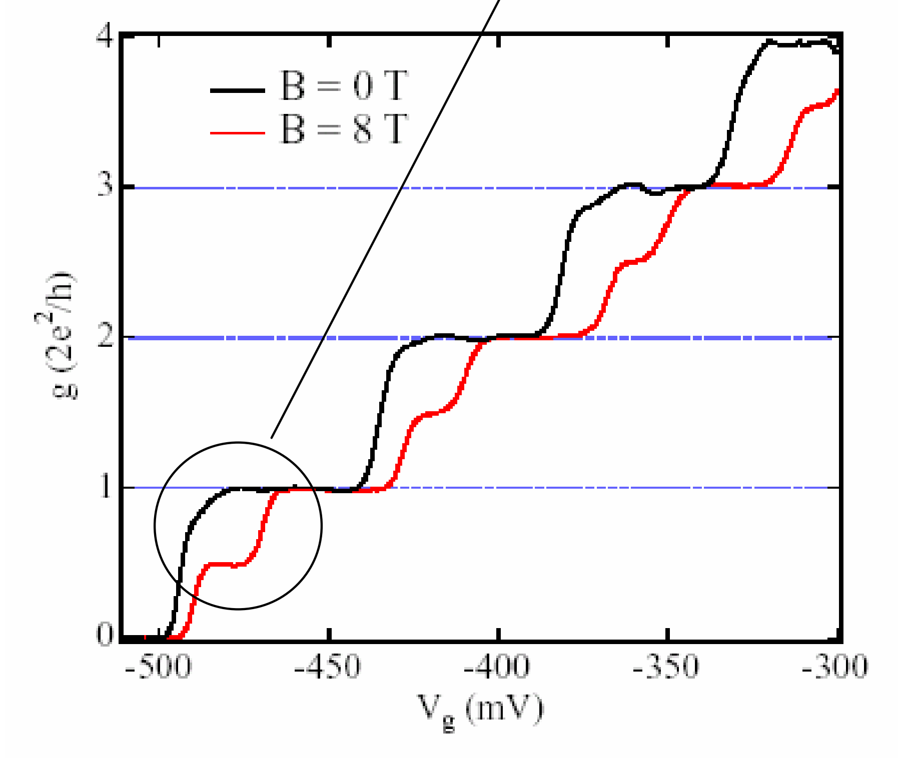
$B_\perp$



From B. Van Wees *et al.* PRB *38*, 3625 (1988)

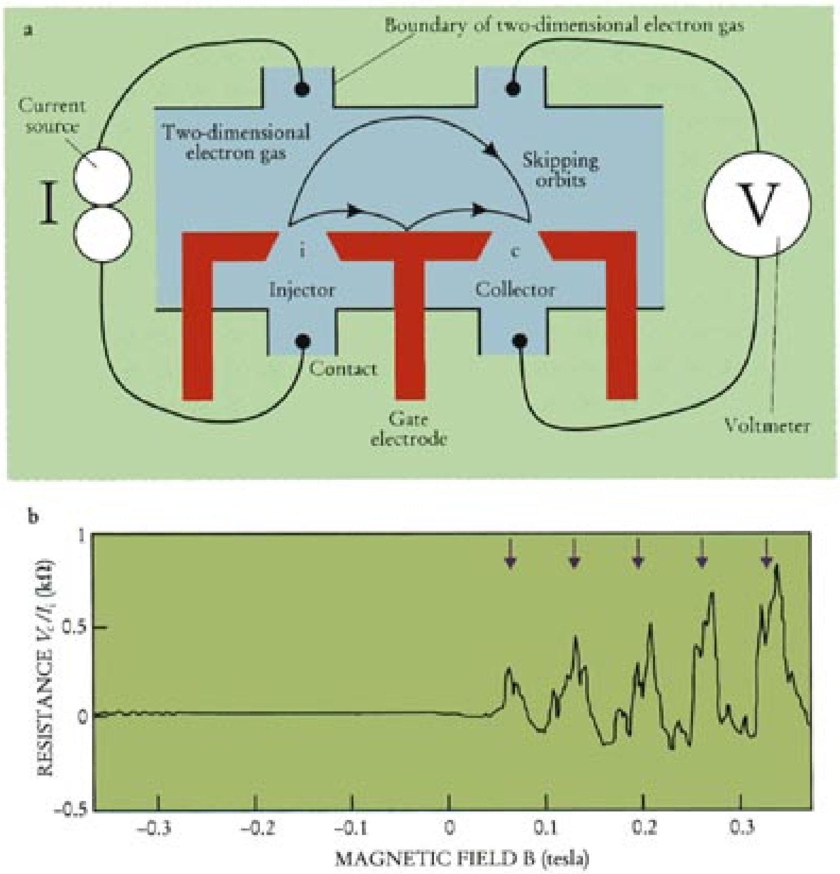
Spin resolved channels

$B_{||}$



From S. Cronenwett, PhD thesis, Stanford University, 2001

Transverse electron focusing



Electrons collected at the „collector" point contact at integer multiples of cyclotron orbit diameter

$$d_c=2p_F/eB$$

Peaks observed in voltage/resistance for

$$B=n \times 2p_F/eL$$

Adapt. from H. van Houten *et al*., Europhys. Lett. **5**, 721 (1988); Phys. Rev. B **39**, 8556 (1989).

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Detecting Spin-Polarized Currents in Ballistic Nanostructures

R. M. Potok,[1] J. A. Folk,[1,2] C. M. Marcus,[1] and V. Umansky[3]
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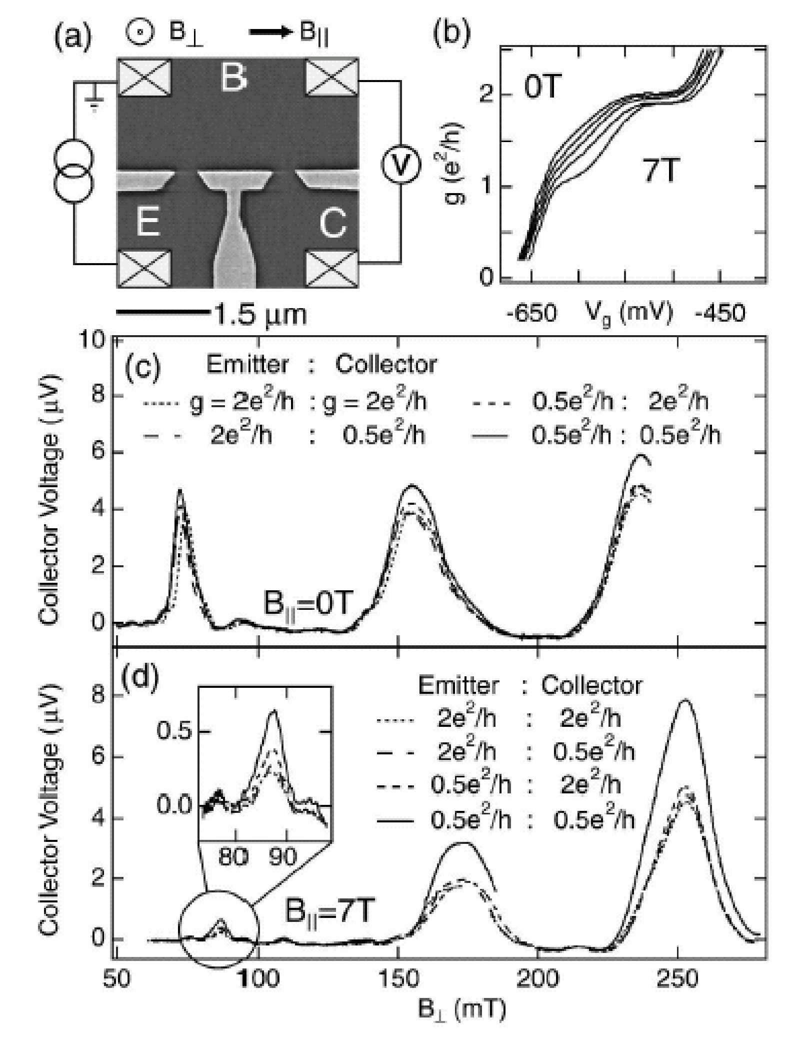
[2]Department of Physics, Stanford University, Stanford, California 94305
[3]Braun Center for Submicron Research, Weizmann Institute of Science, Rehovot 76100, Israel
(Received 19 June 2002; published 9 December 2002)



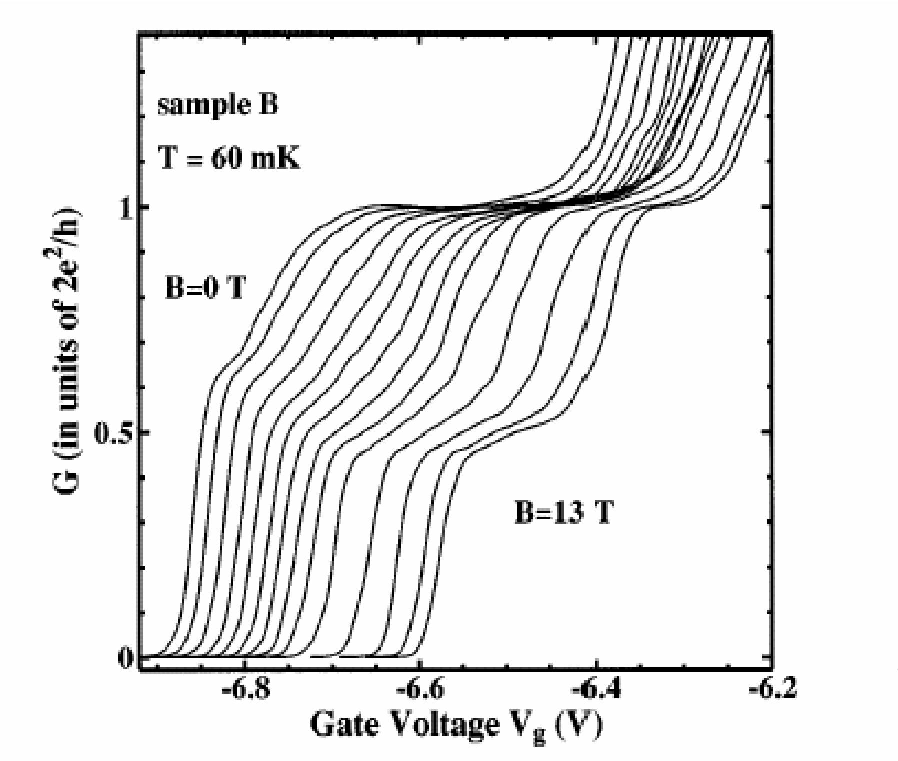
$$V_c = \alpha \frac{h}{2e^2} I_e \left(1 + P_e P_c\right)$$

Collector voltage is in case of P_e=P_c=1 two times higher then in unpolarized case!

Measured spin polarization of > 70%
$B_{||}$ =7T, T=300mK

Also: J. Folk *et al.* Science **299**, 679 (2003)

“0.7 structure” - spin polarization at zero field(?)



K.J.Thomas *et al*., PRL **77**, 135 (1996)

Other experiments

K. J. Thomas *et al.,* Phys. Rev. B **58**, 4846 (1998).

A. Kristensen *et al.,* Physica (Amsterdam) **249B–251B**, 180 (1998);

K. S. Pyshkin *et al.,* Phys. Rev. B **62**, 15 842 (2000);

S. Nuttinck *et al.,* Jpn. J. App. Phys. **39**, L655 (2000).

A. Kristensen *et al.,* Phys. Rev. B **62**, 10 950 (2000).

B. E. Kane *et al.,* App. Phys. Lett. **72**, 3506 (1998).

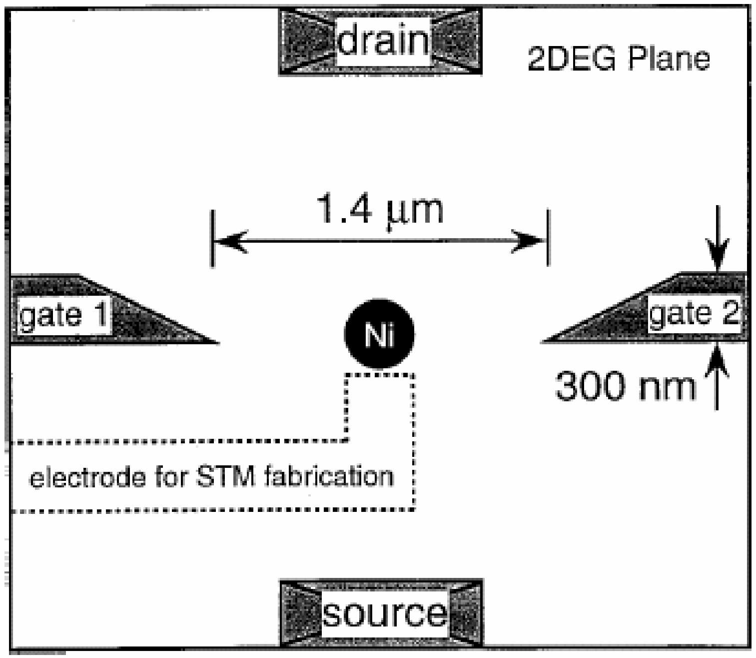
Some evidence of Kondo Physics

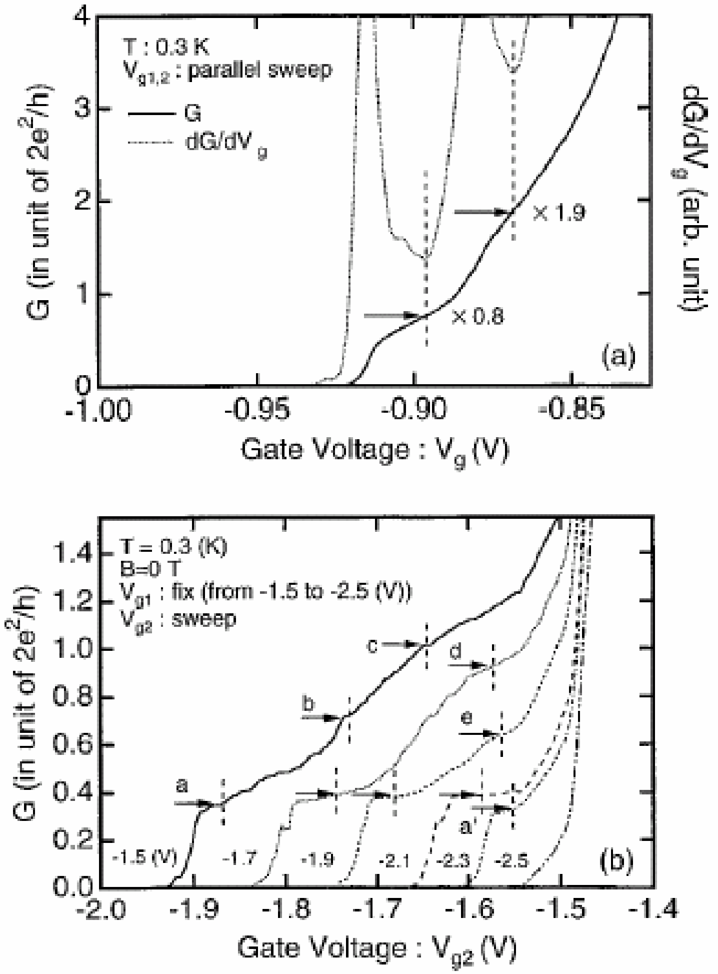
S. Cronenwett et al. PRL 88, 226805 (2002)

PHYSICAL REVIEW B VOLUME 61, NUMBER 15 15 APRIL 2000-I

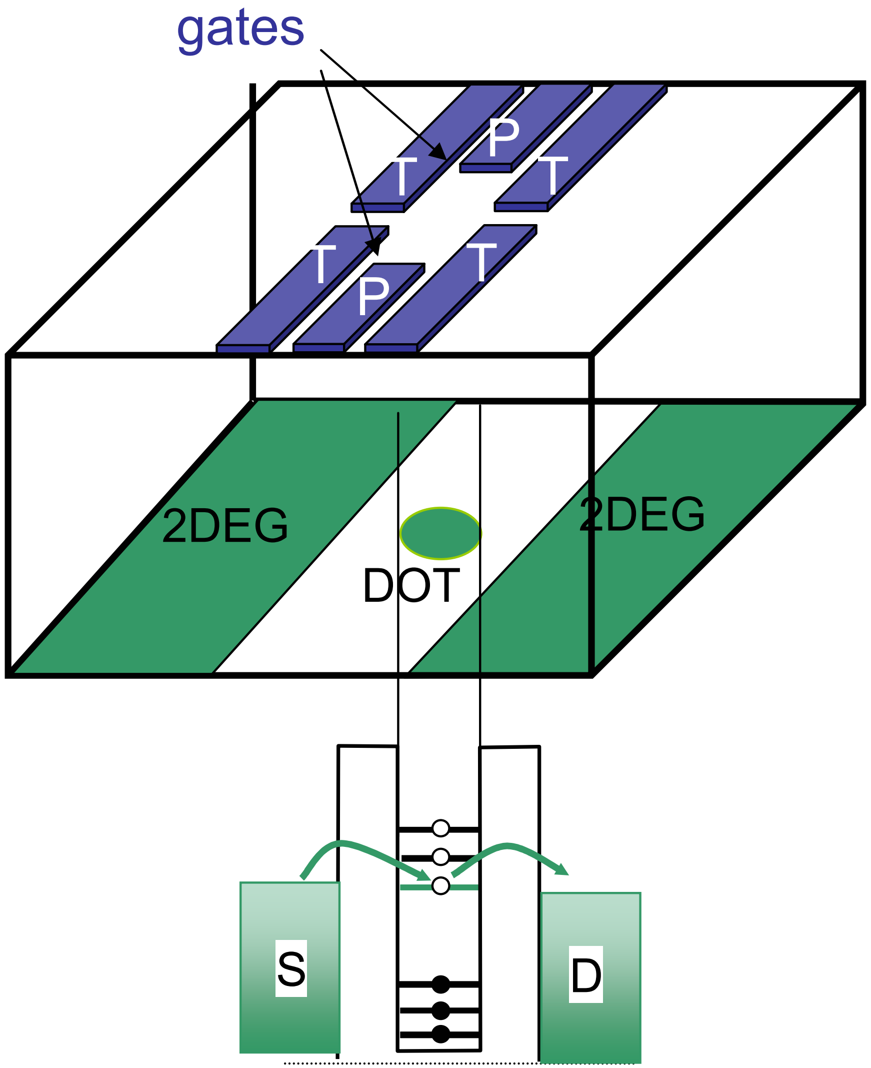
Conductance steps observed in adiabatic ferromagnetic quantum-dot point contacts made in the $In_{0.5}Ga_{0.5}As/In_{0.5}Al_{0.5}As$ heterojunction

T. Kikutani *et al.*

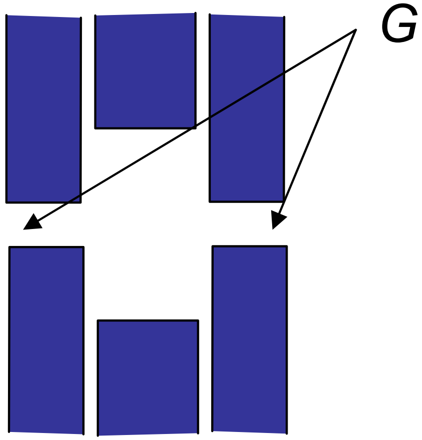




Lateral quantum dot



Two regimes of transport through the dot



Open dot

$$G > \frac{e^2}{h}$$

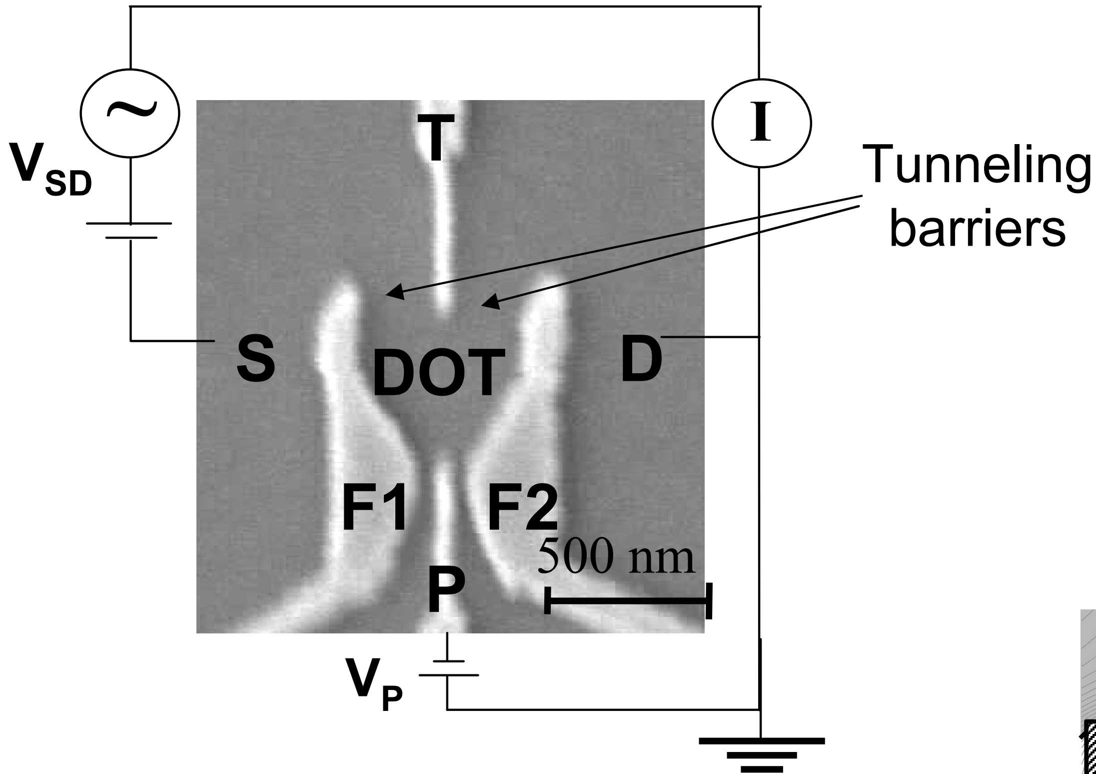
At least one mode transmitted through constrictions
Transport classically allowed

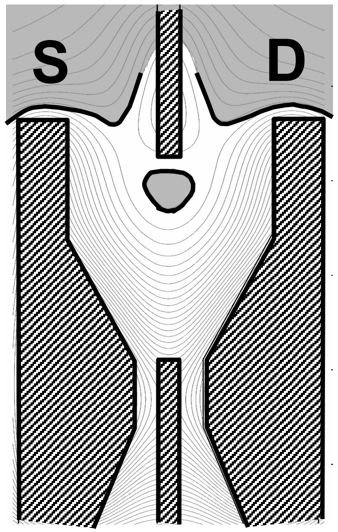
Closed dot

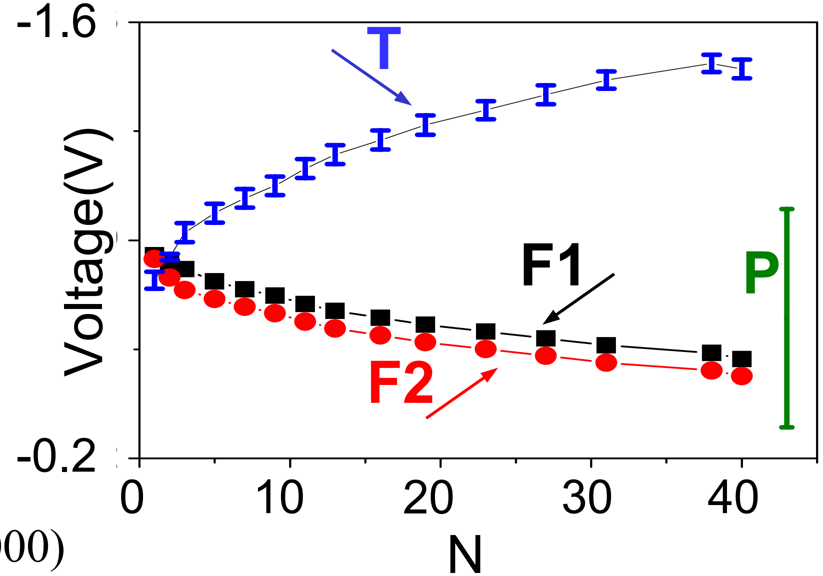
$$G < \frac{e^2}{h}$$

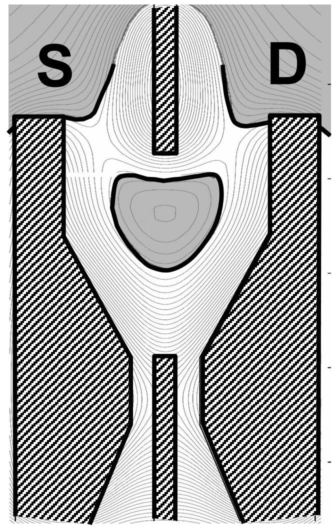
Less than one mode transmitted through constrictions
Transport classically forbidden
Tunneling through barriers at QPC’s
Coulomb blockade effects if kT<U

0, 1, 2,…N electrons Lateral Dot Device









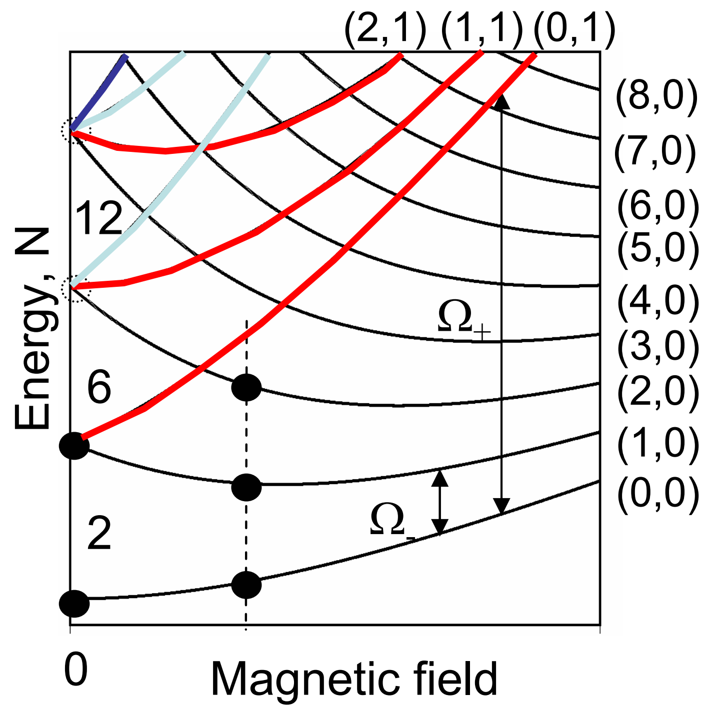
M. Ciorga *et al.*,
Phys. Rev. B **61**, R16315 (2000)

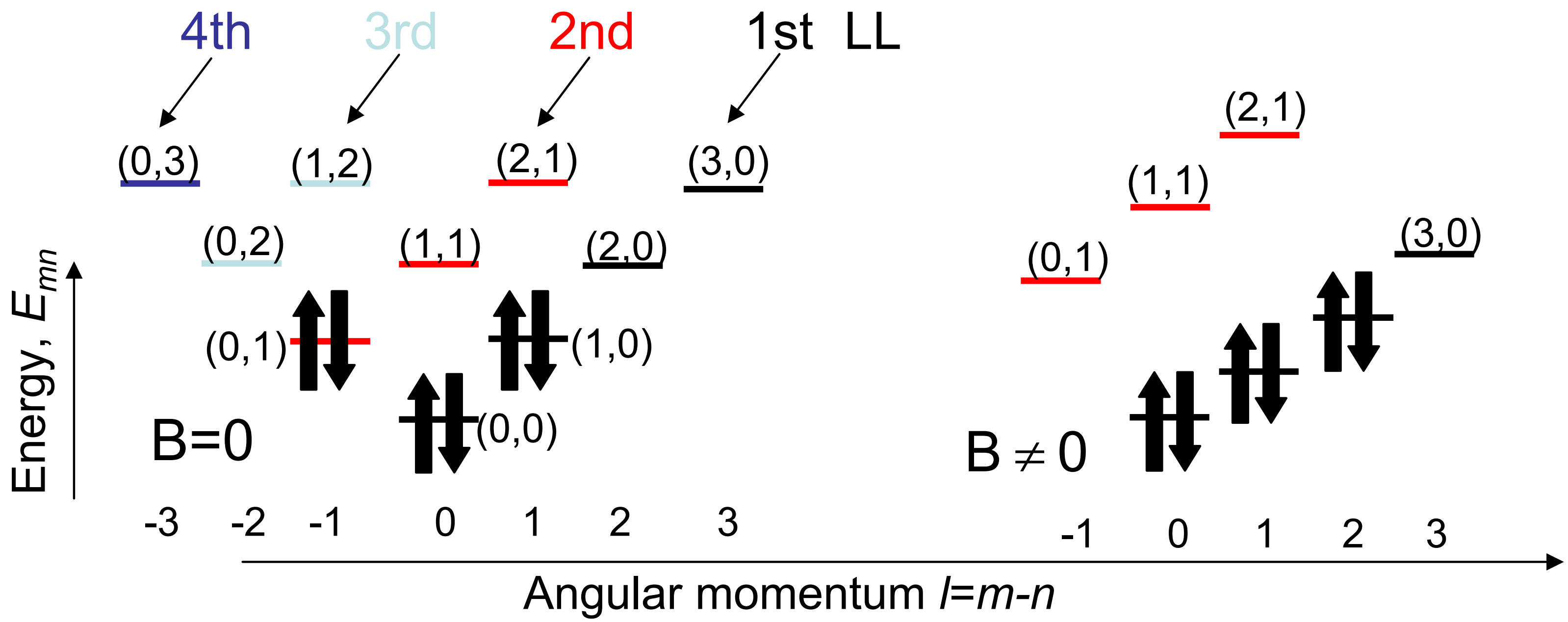
Darwin-Fock Spectrum

Parabolic confining potential with frequency ω_0, single-particle levels (spin not included)

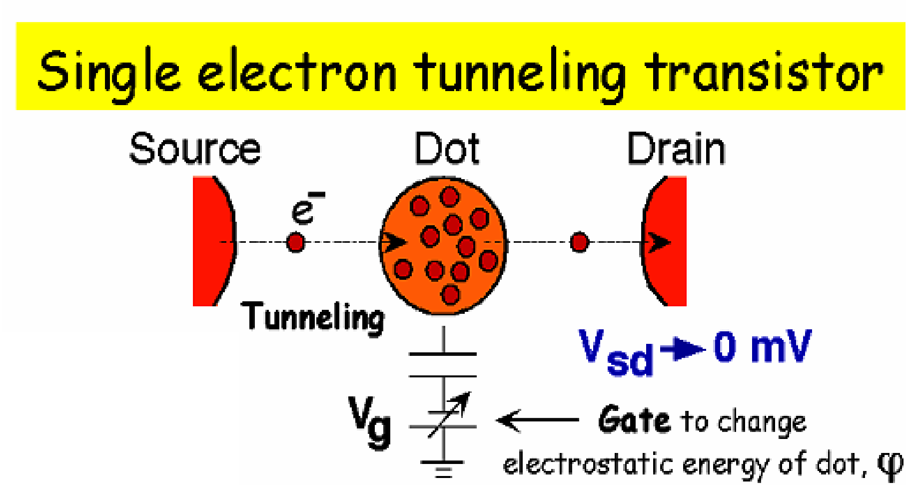
$$\varepsilon_{mn} = \hbar\Omega_+(n+1/2)+\hbar\Omega_-(m+1/2)$$

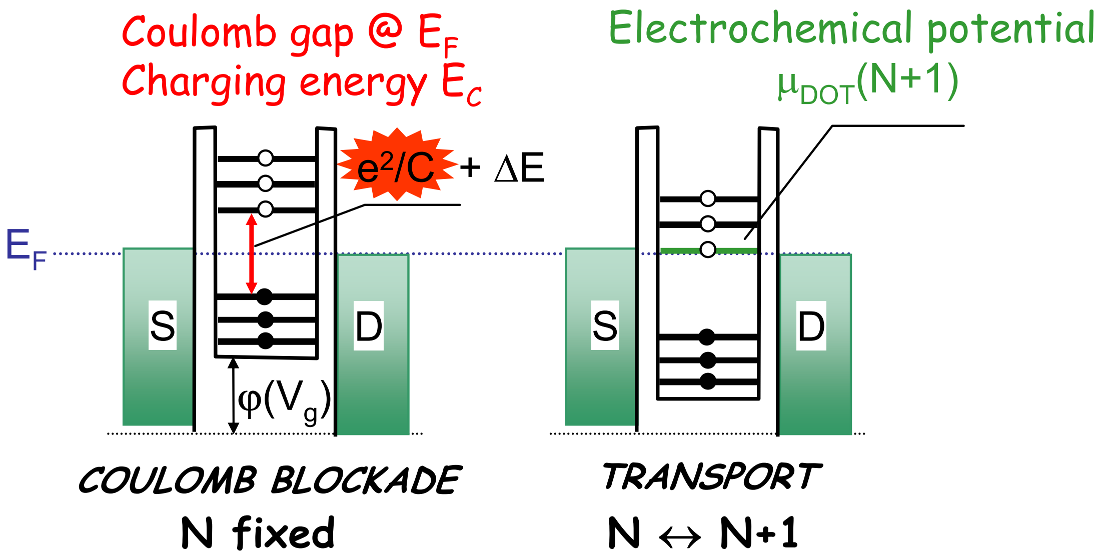
$$\Omega_\pm = \sqrt{\omega_0^2+\omega_c^2/4}\pm\omega_c/2$$





Coulomb Blockade Spectroscopy



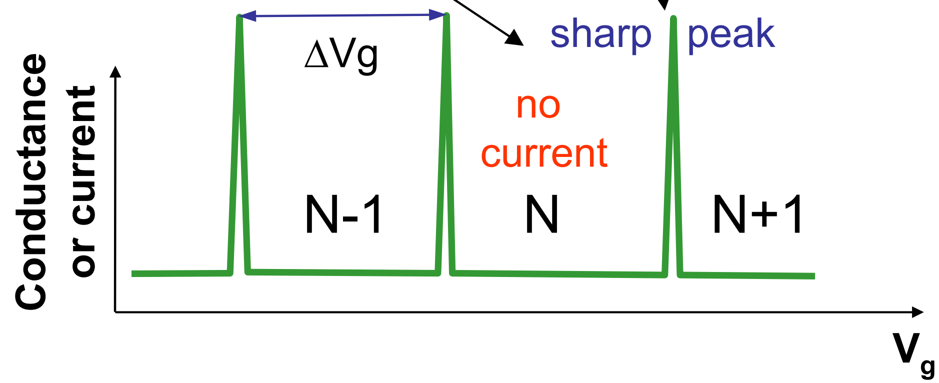


$$E(N)= (e(N-N_0)-C_gV_g)^2/2C + \sum E_N$$

$$\mu_{DOT}(N)=E(N)-E(N-1)$$

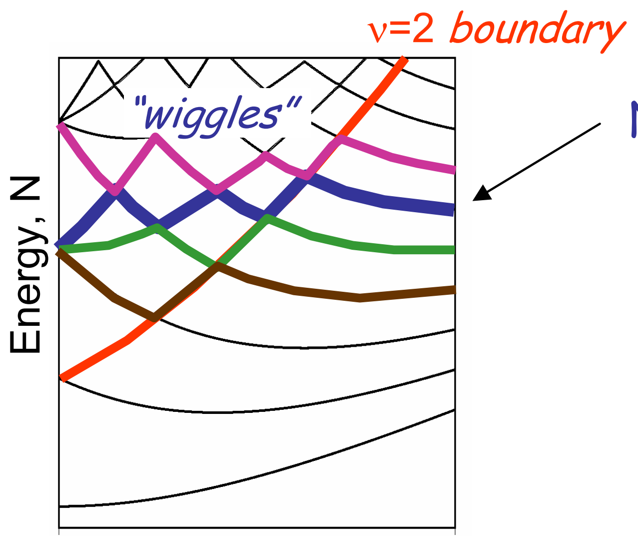
$$\alpha\Delta Vg = E_c + \Delta E(B)$$

SPECTROSCOPY

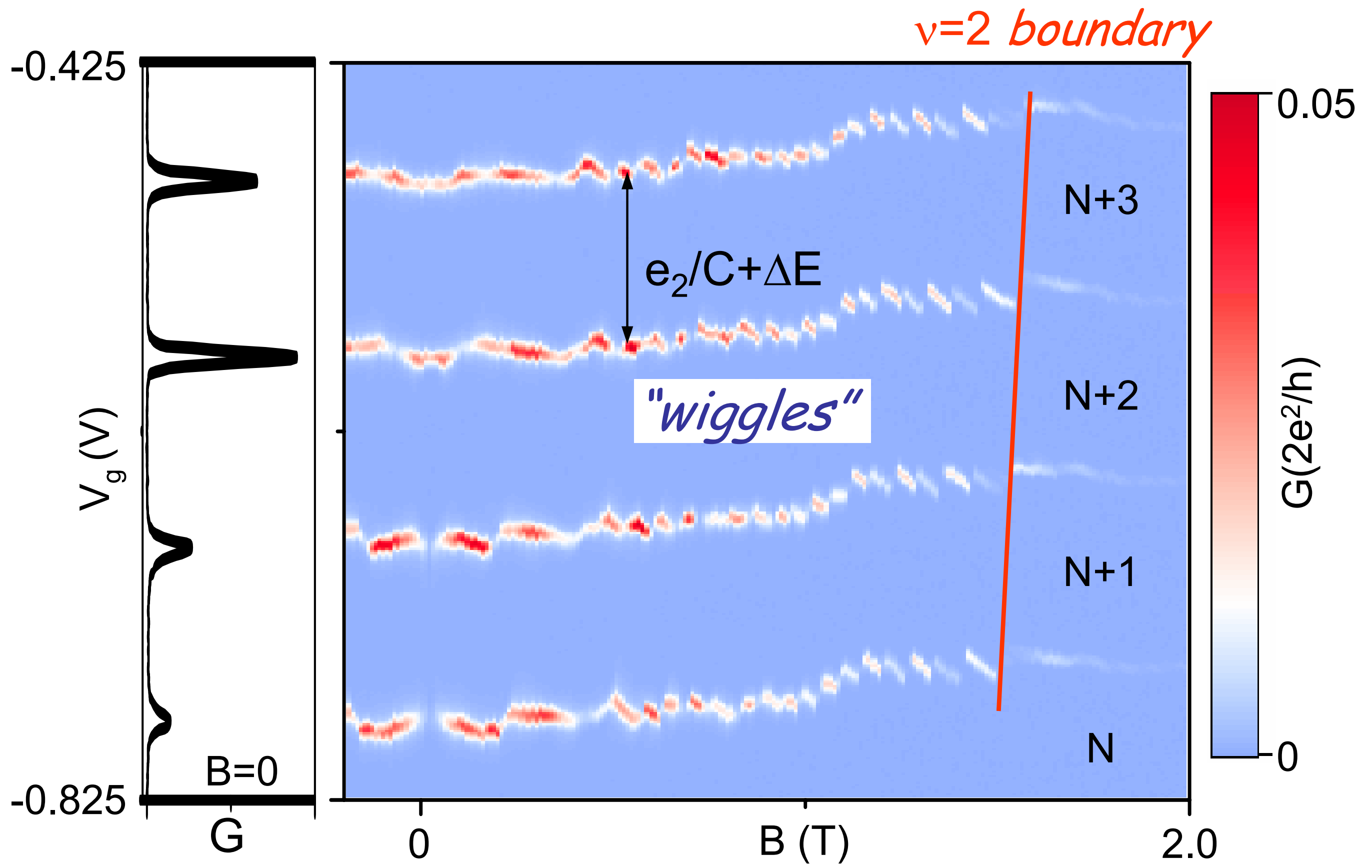


Peak spacing ➡ "addition spectrum"

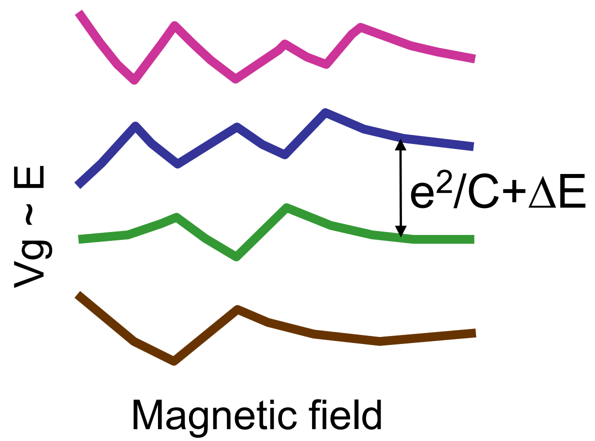
Coulomb Blockade Spectroscopy



Nth CB peak follows $\mu(N)$ not E_N

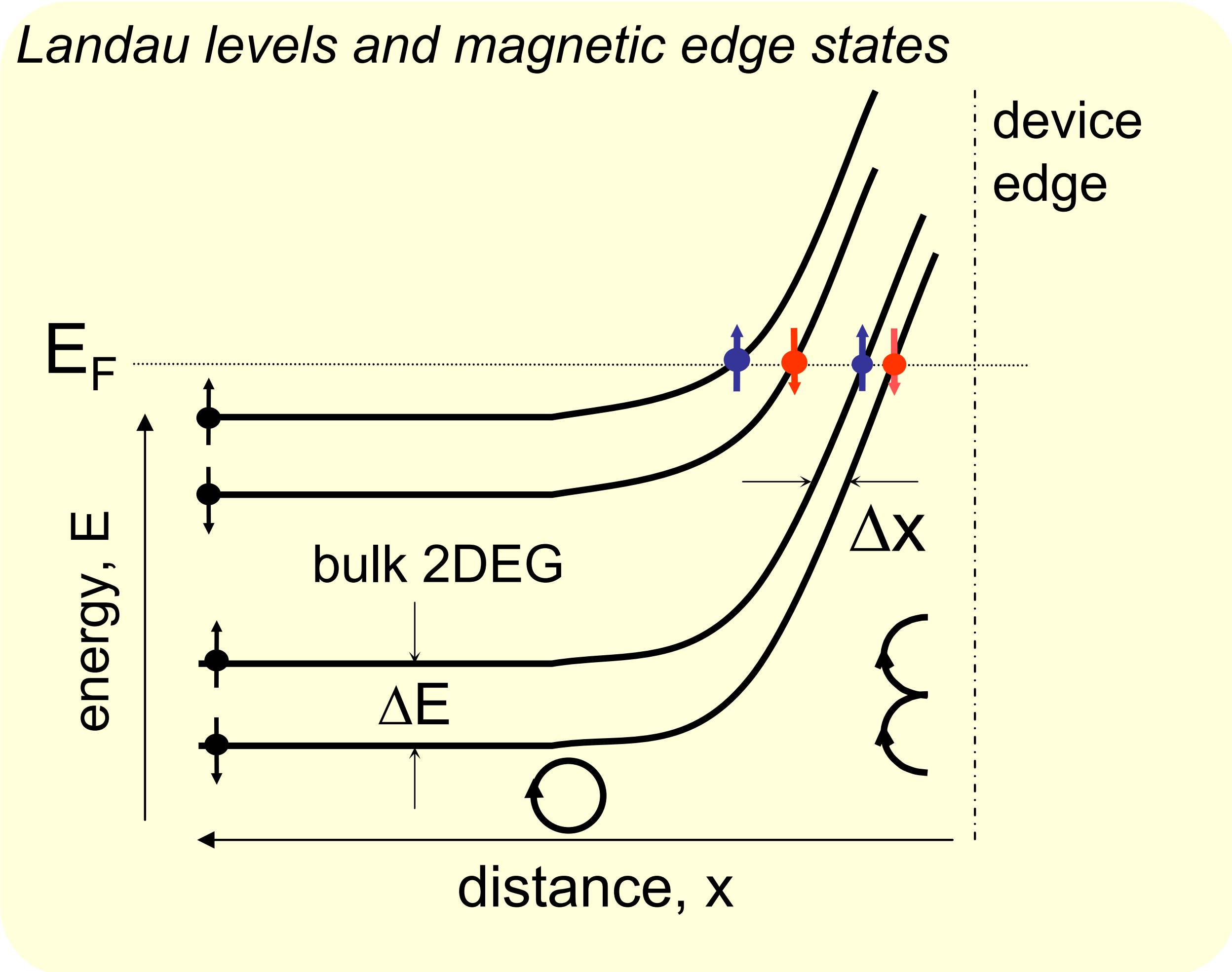


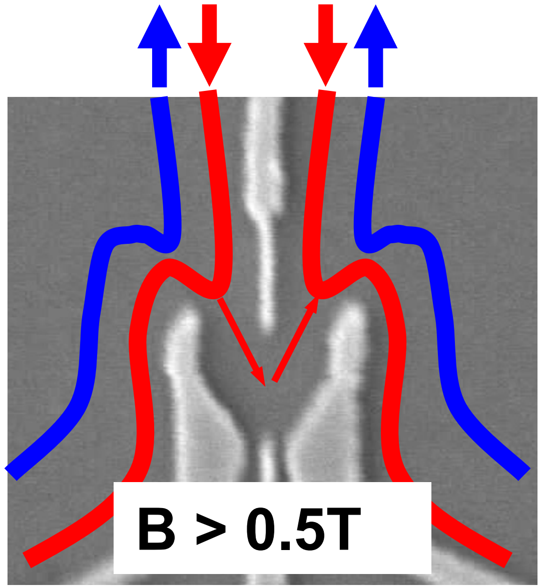
+ charging energy
$E_C=e^2/C$

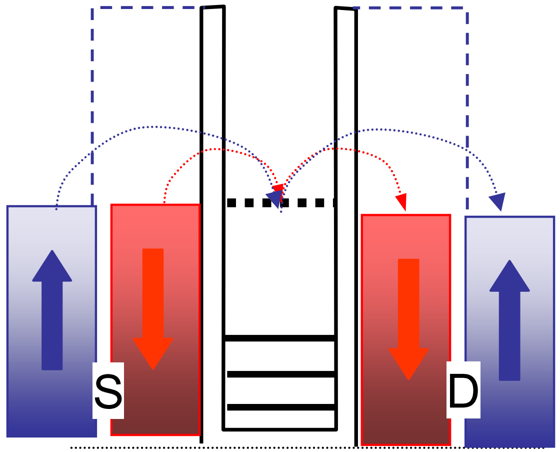


Spin polarized injection/detection

Magnetic edge states ➡ Spin polarized leads





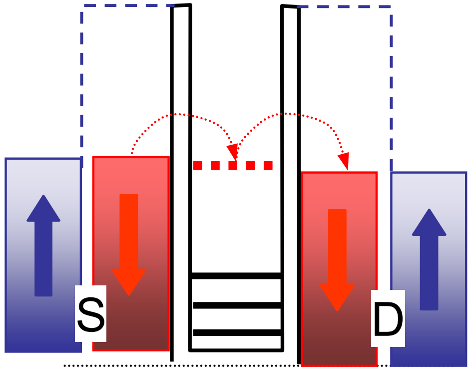


A. S. Sachrajda *et al.*, Physica E **10**, 493 (2001)

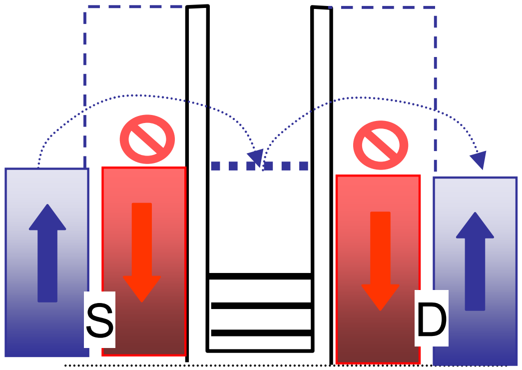
Spin blockade spectroscopy

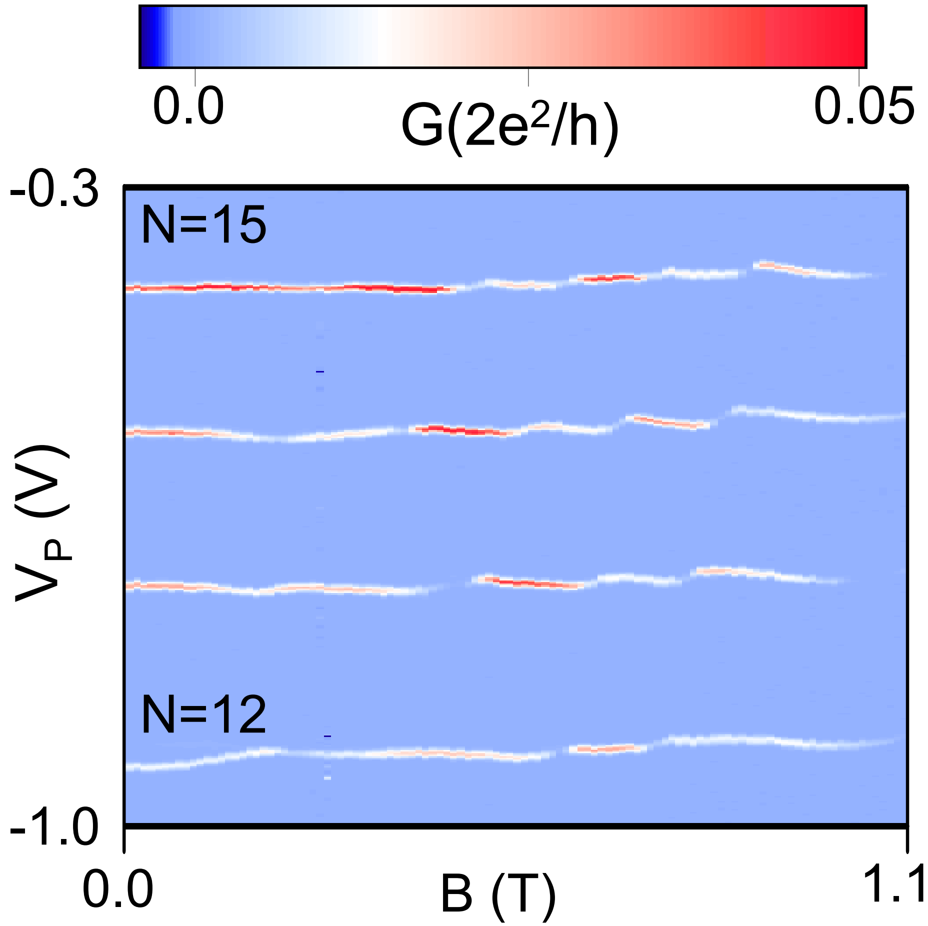
$\mu(N)=E(N)-E(N-1)$

$\mu(N)\downarrow$
no spin blockade
HIGH
current amplitude



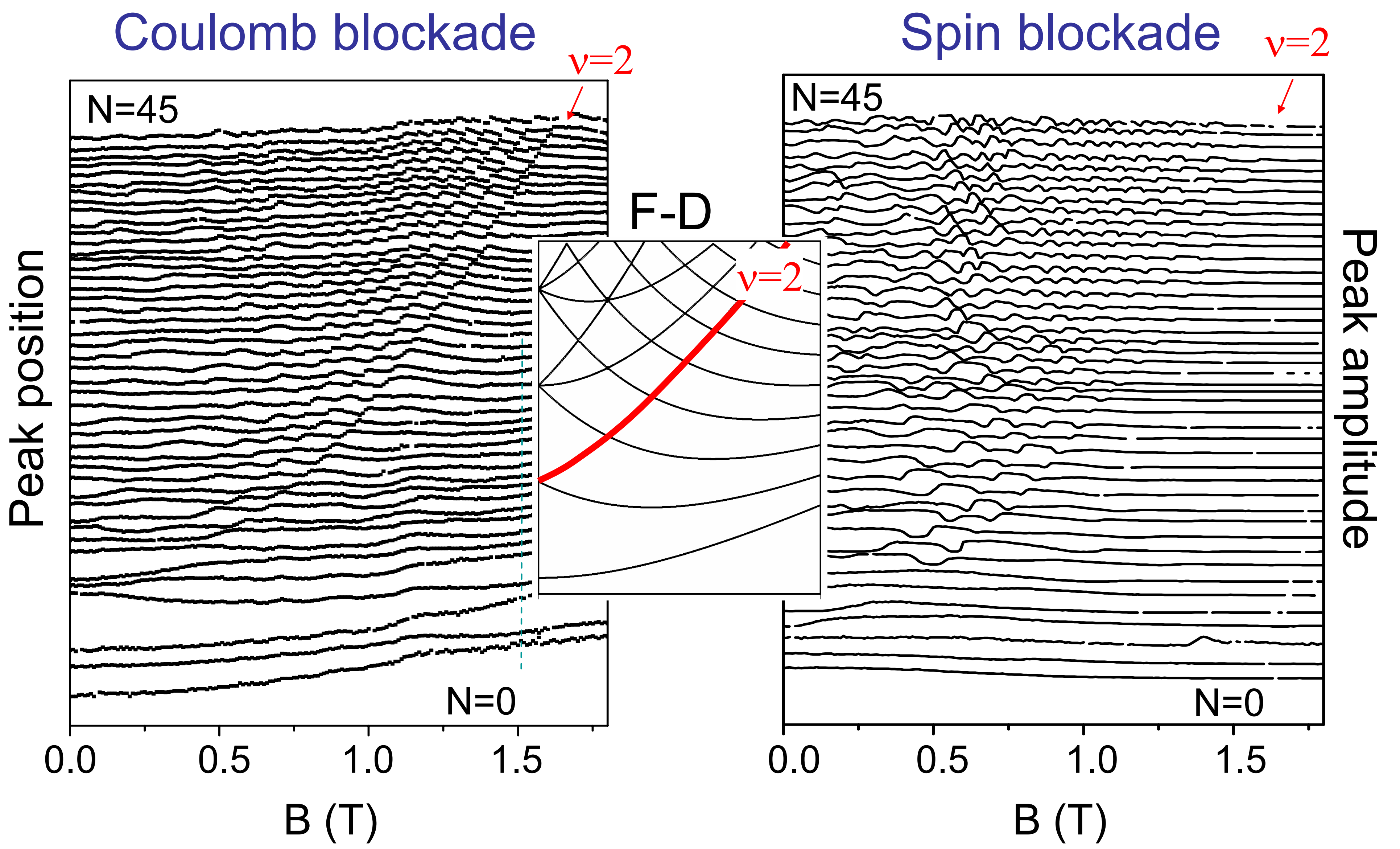
$\mu(N)\uparrow$
spin blockade
LOW
current amplitude





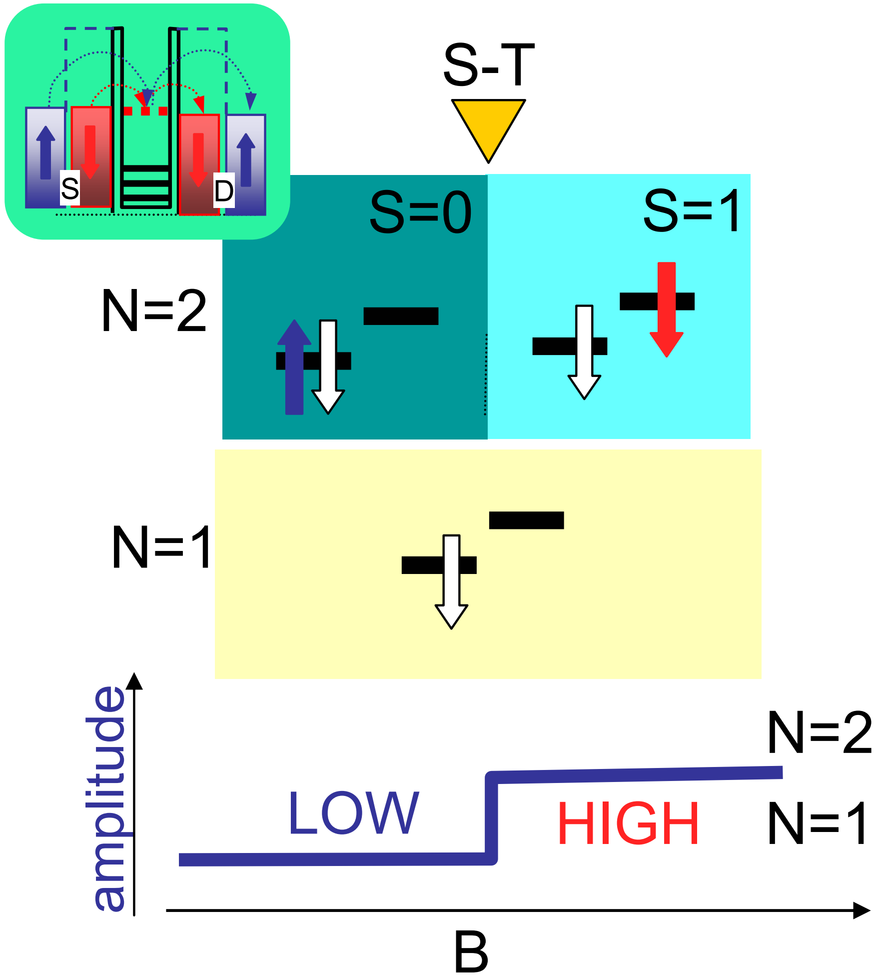
P. Hawrylak *et al.*, Phys. Rev. B **59**, 2801 (1999)
M. Ciorga *et al.*, Physica E **11**, 35 (2001)
A. S. Sachrajda *et al.*, Physica E **10**, 493 (2001)

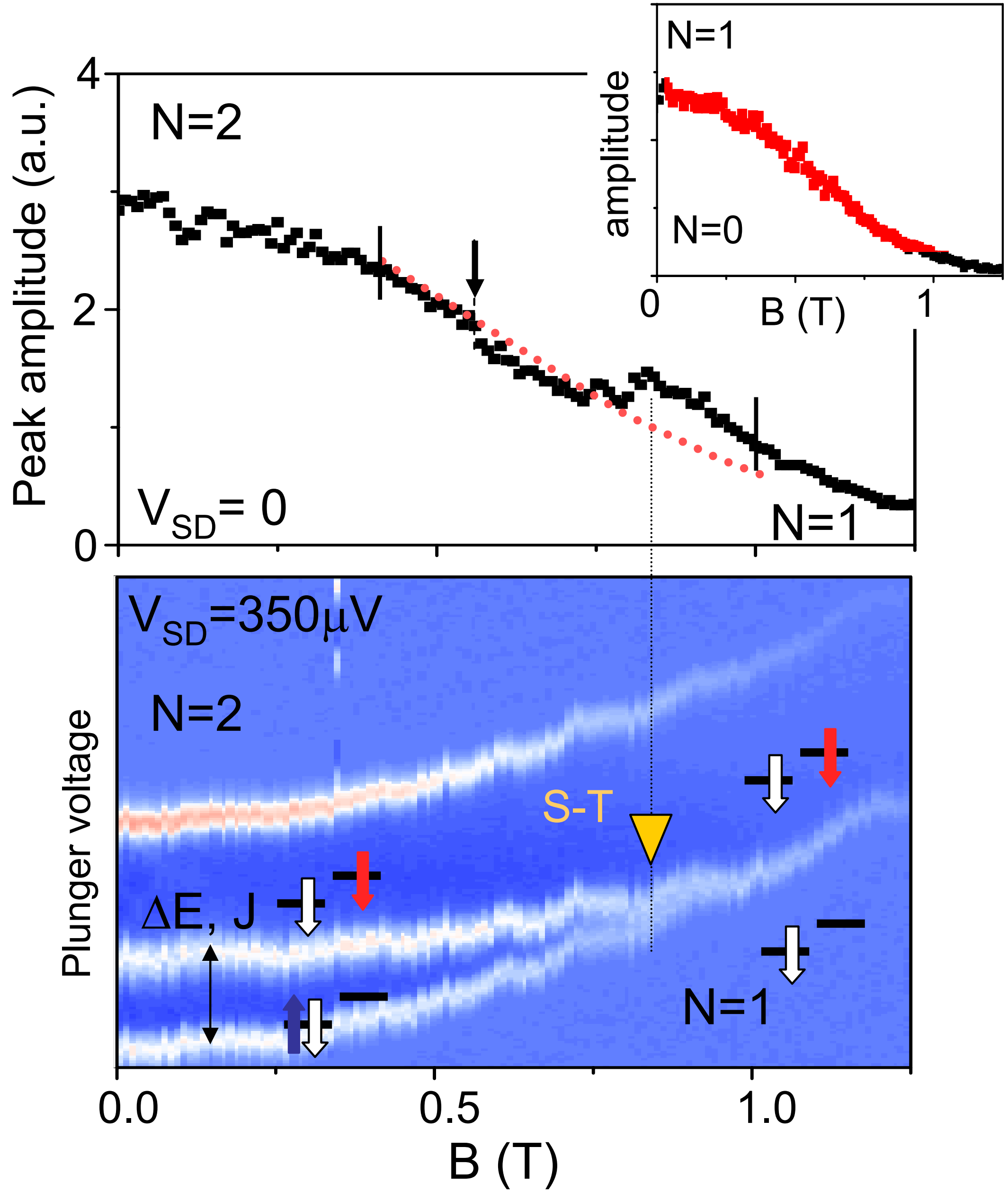
Coulomb and spin blockade spectroscopy spectra



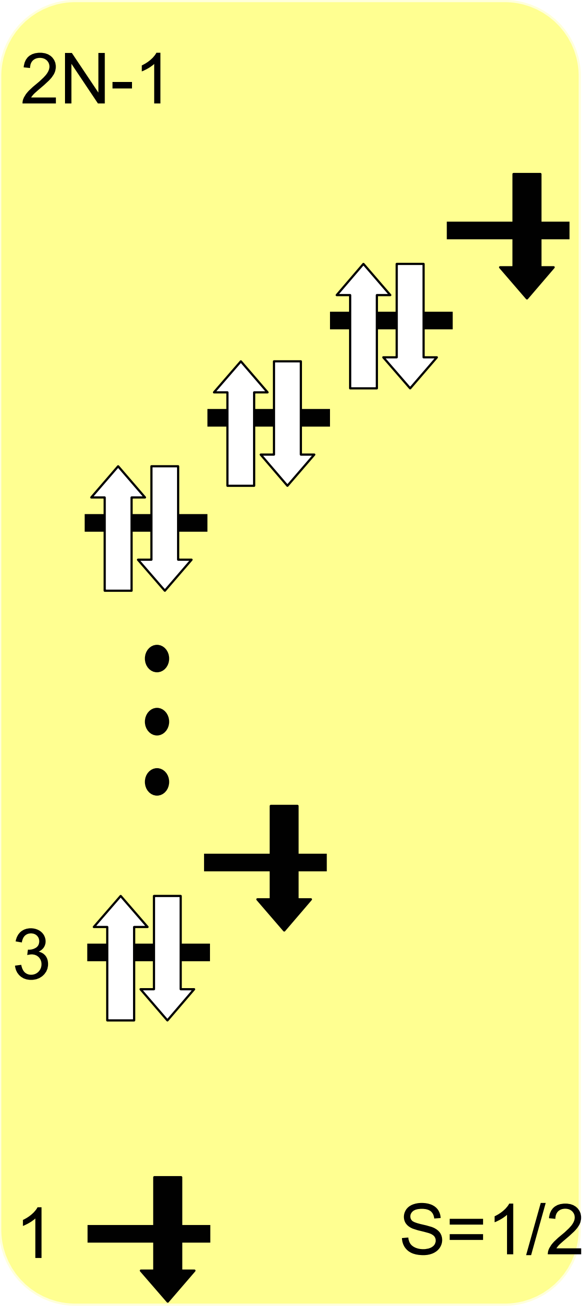
Magnetic field induced singlet-triplet transition for N=2

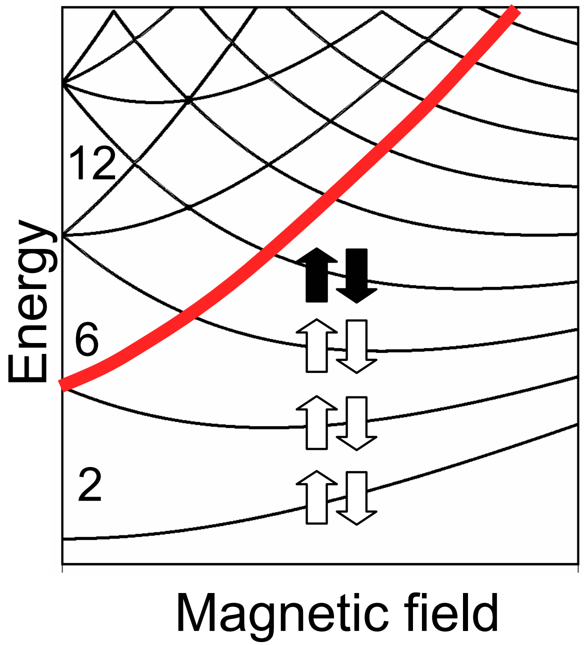
Current readout

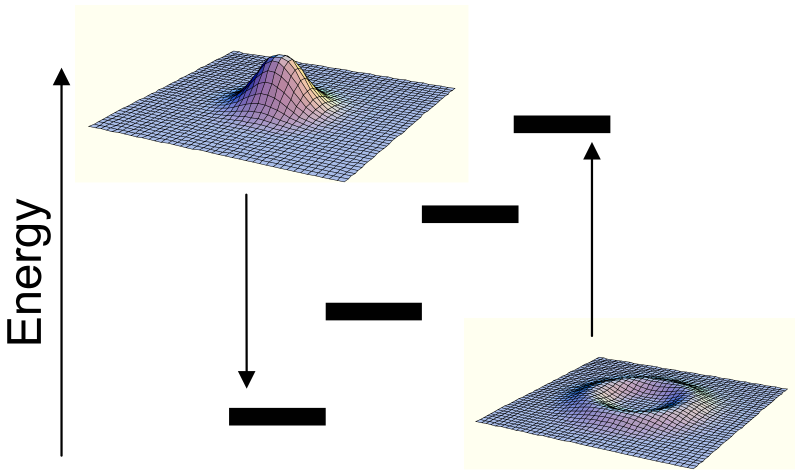


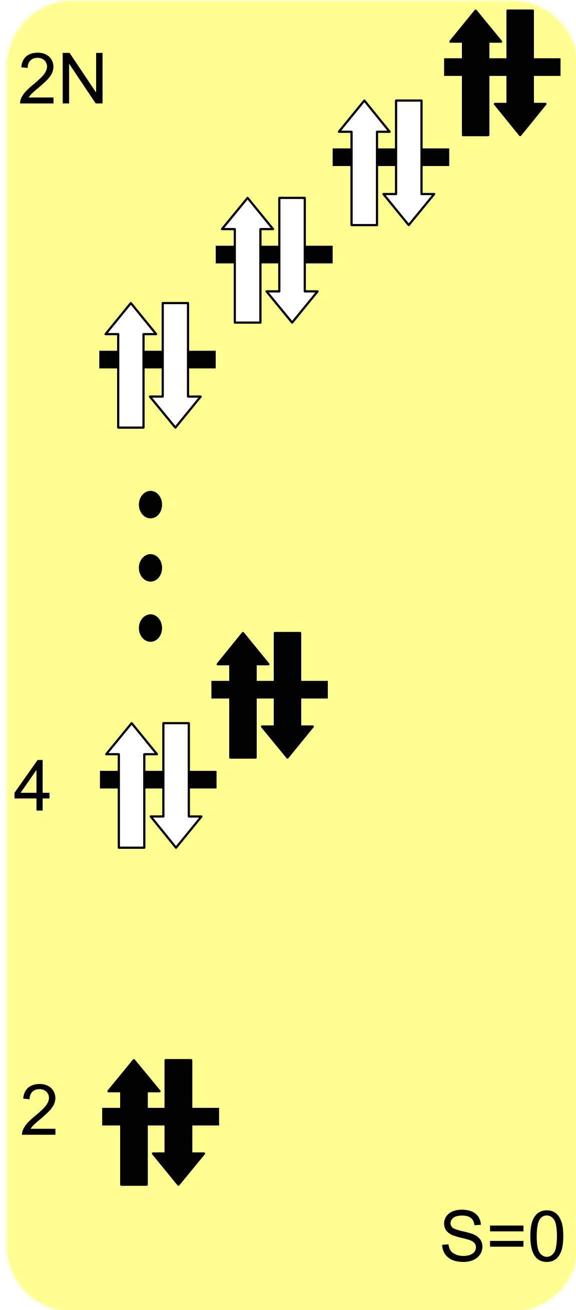


Building N-electron dot at ν=2

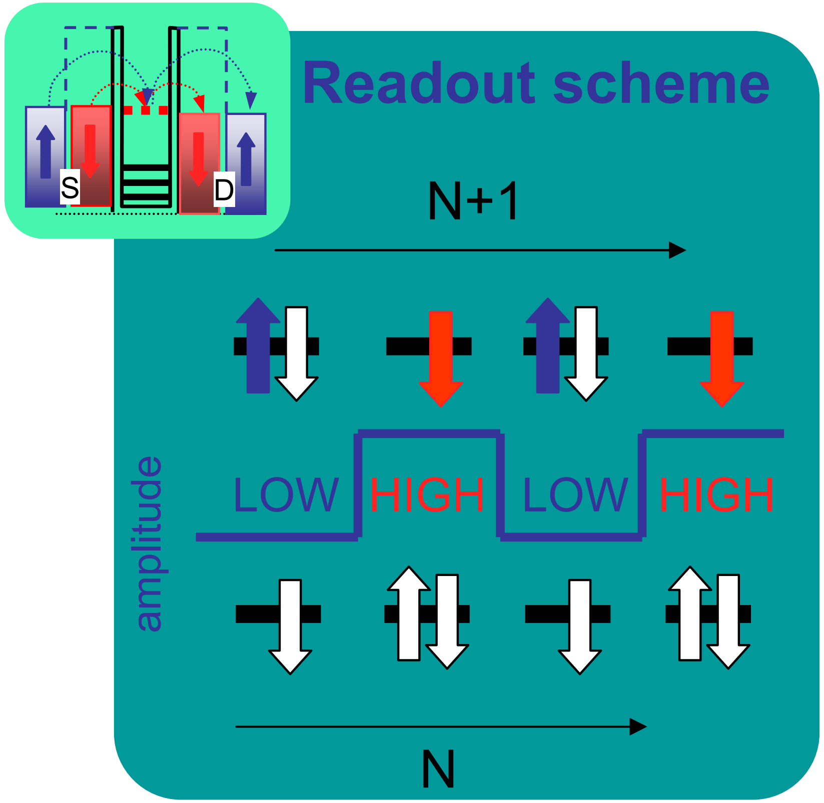


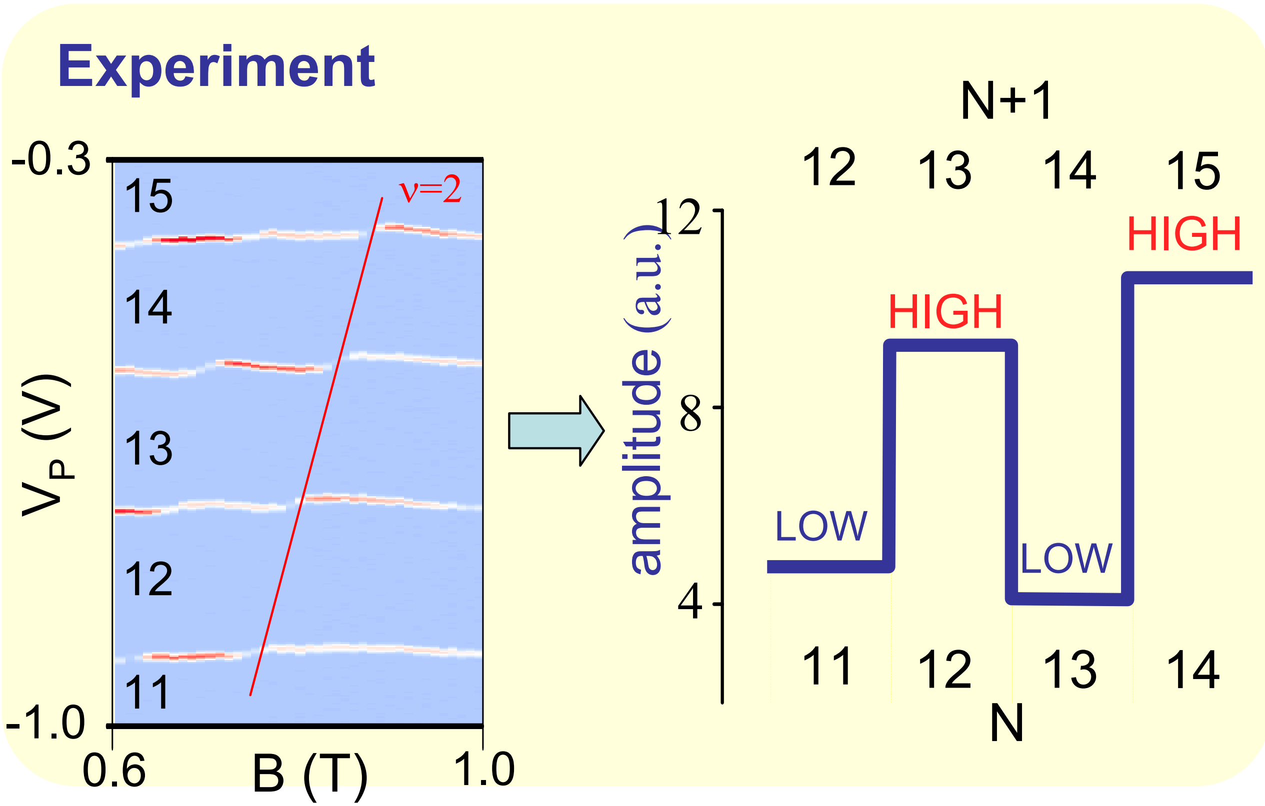




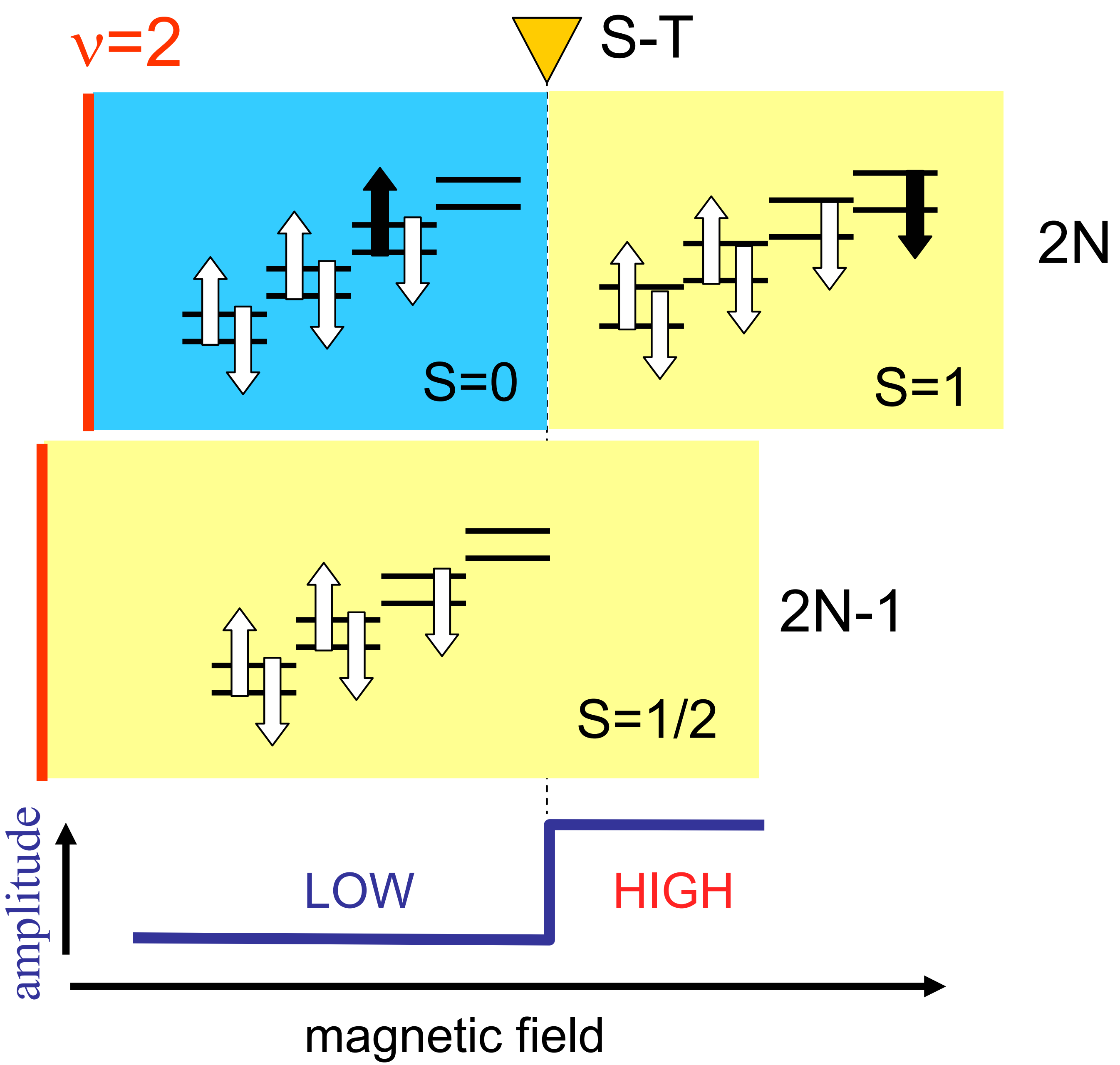


Tuning the spin of ν=2 phase by changing N

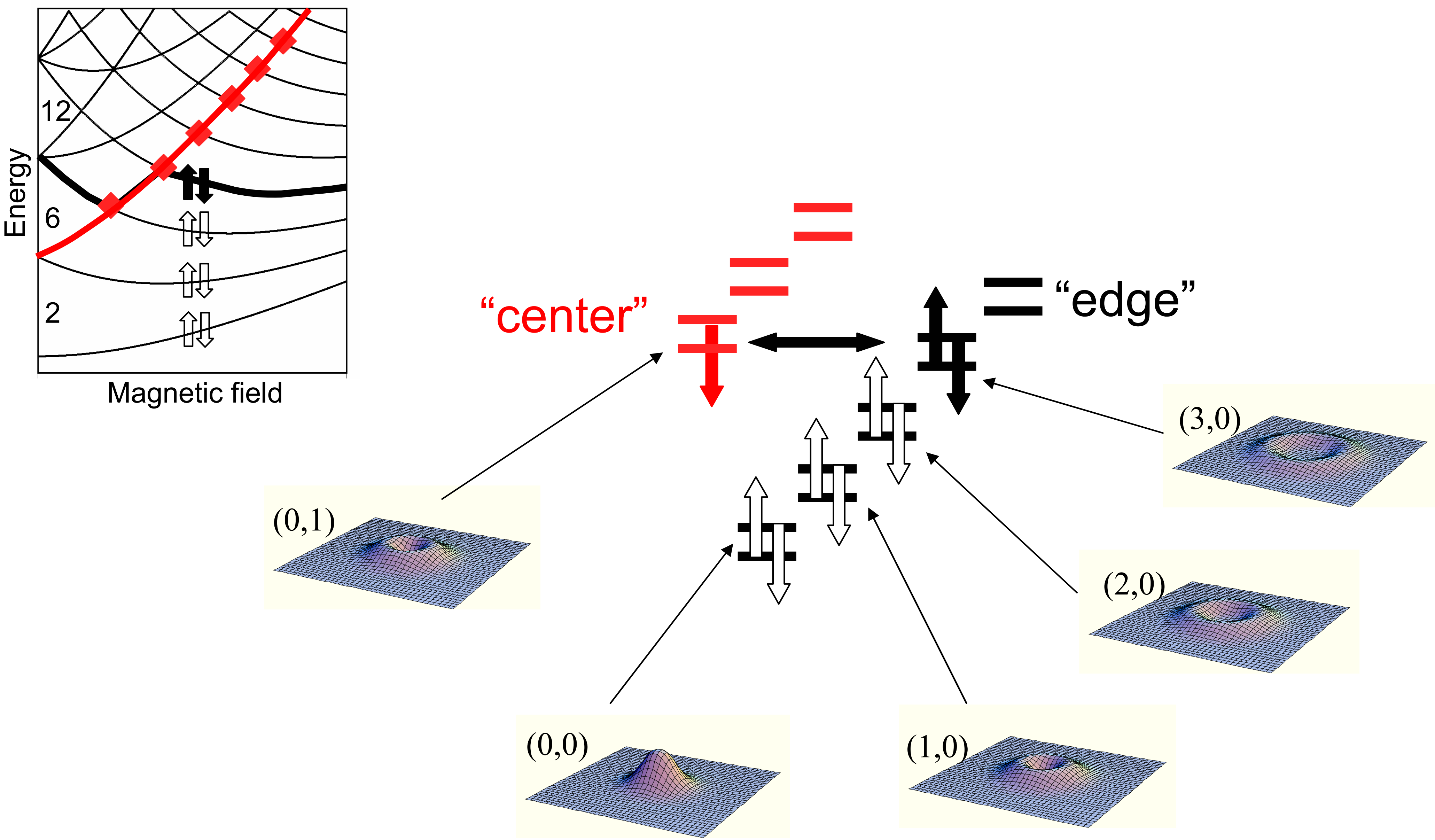




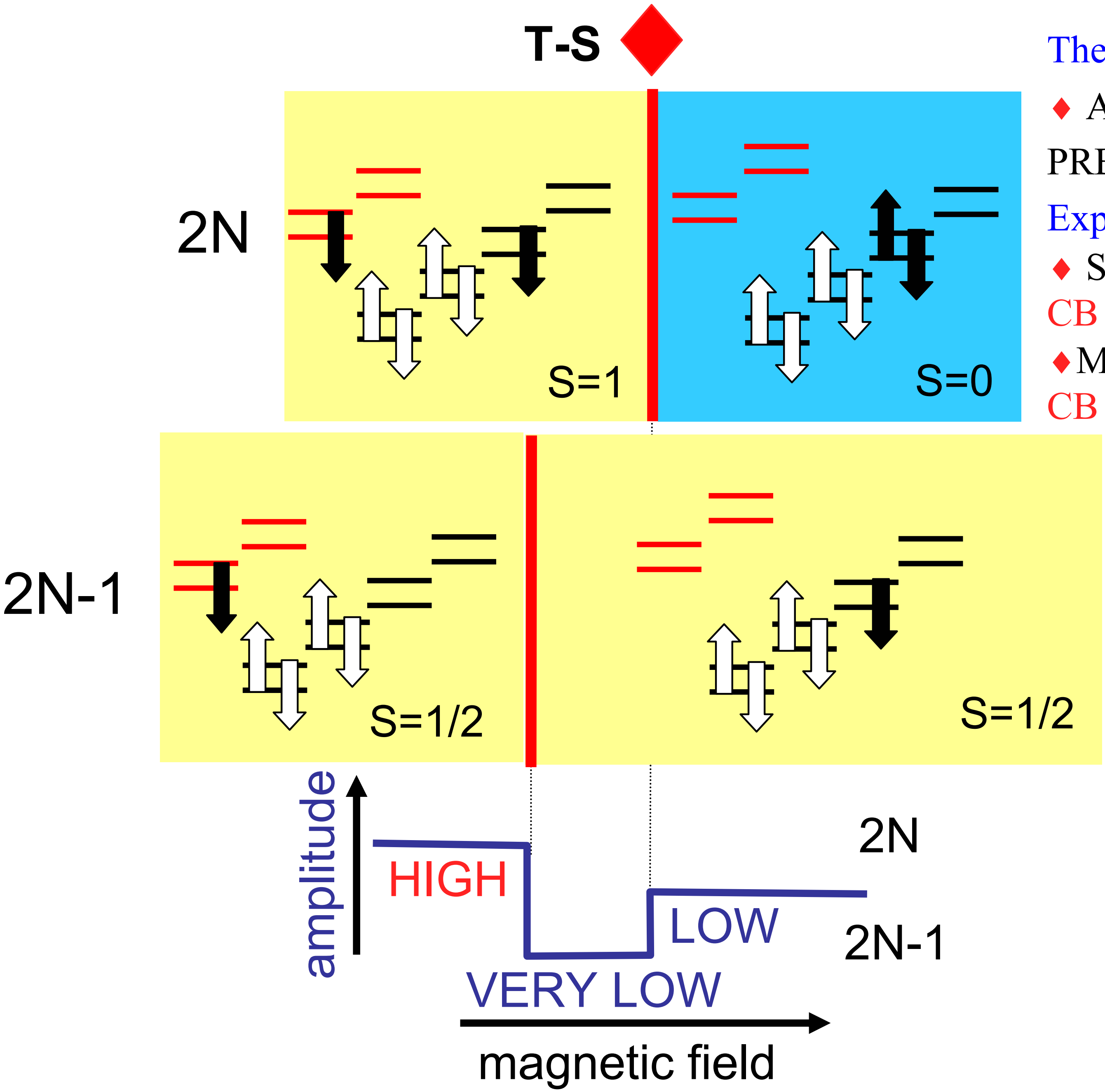
Singlet-triplet transition - first spin flip



Transferring electrons to the center of the dot



Singlet-triplet transition to the center



Theoretical investigation:

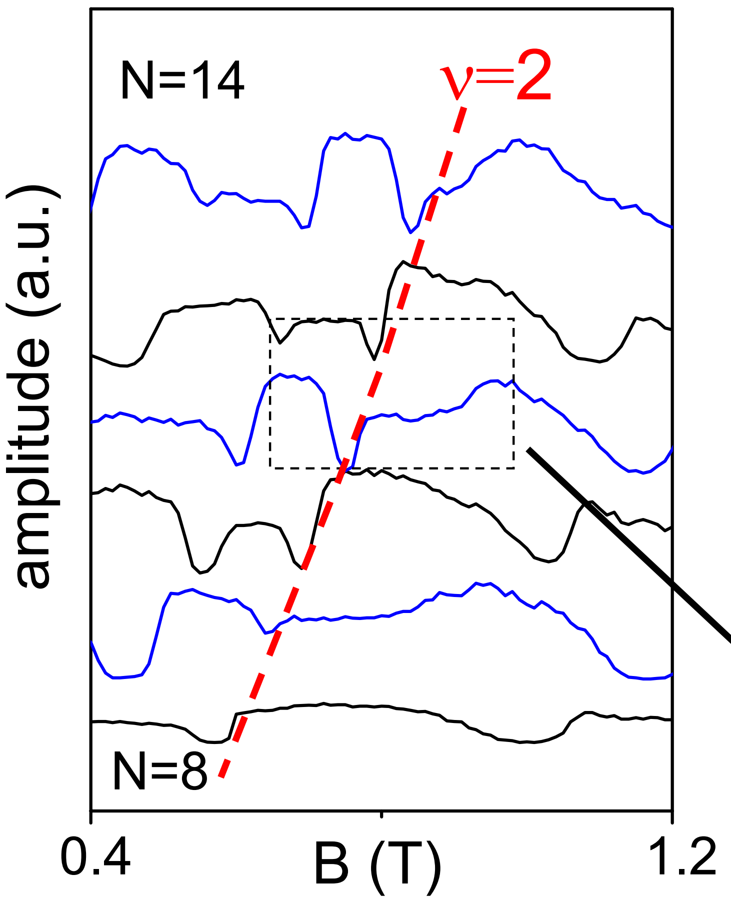
♦ A. Wójs & P. Hawrylak, PRB **53**, 1084 (1996)

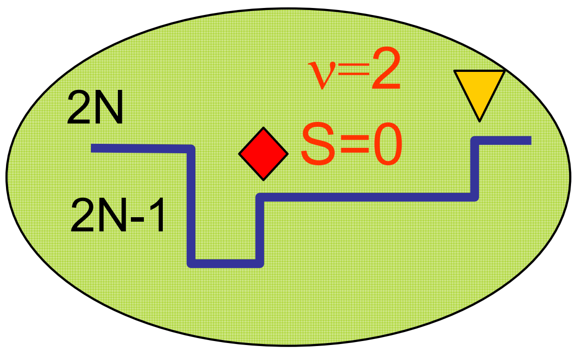
Experimental observation:

♦ S. Tarucha *et al*., PRL. **84**, 2485 (2000)- CB spectrum

♦M. Ciorga *et al*.,Physica E **11**, 35 (2001)- CB and SB

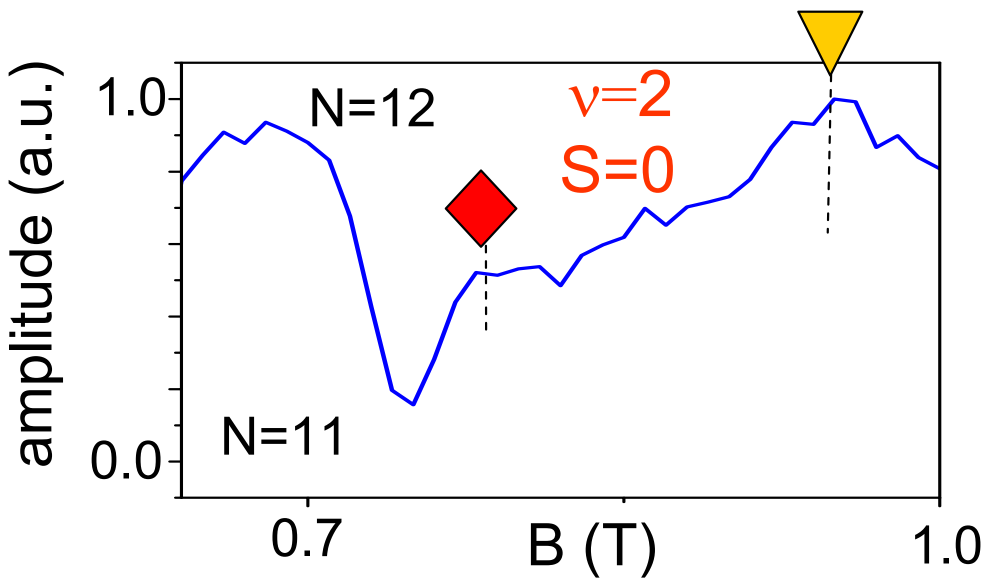
Current detection of spin transitions in the vicinity of ν=2





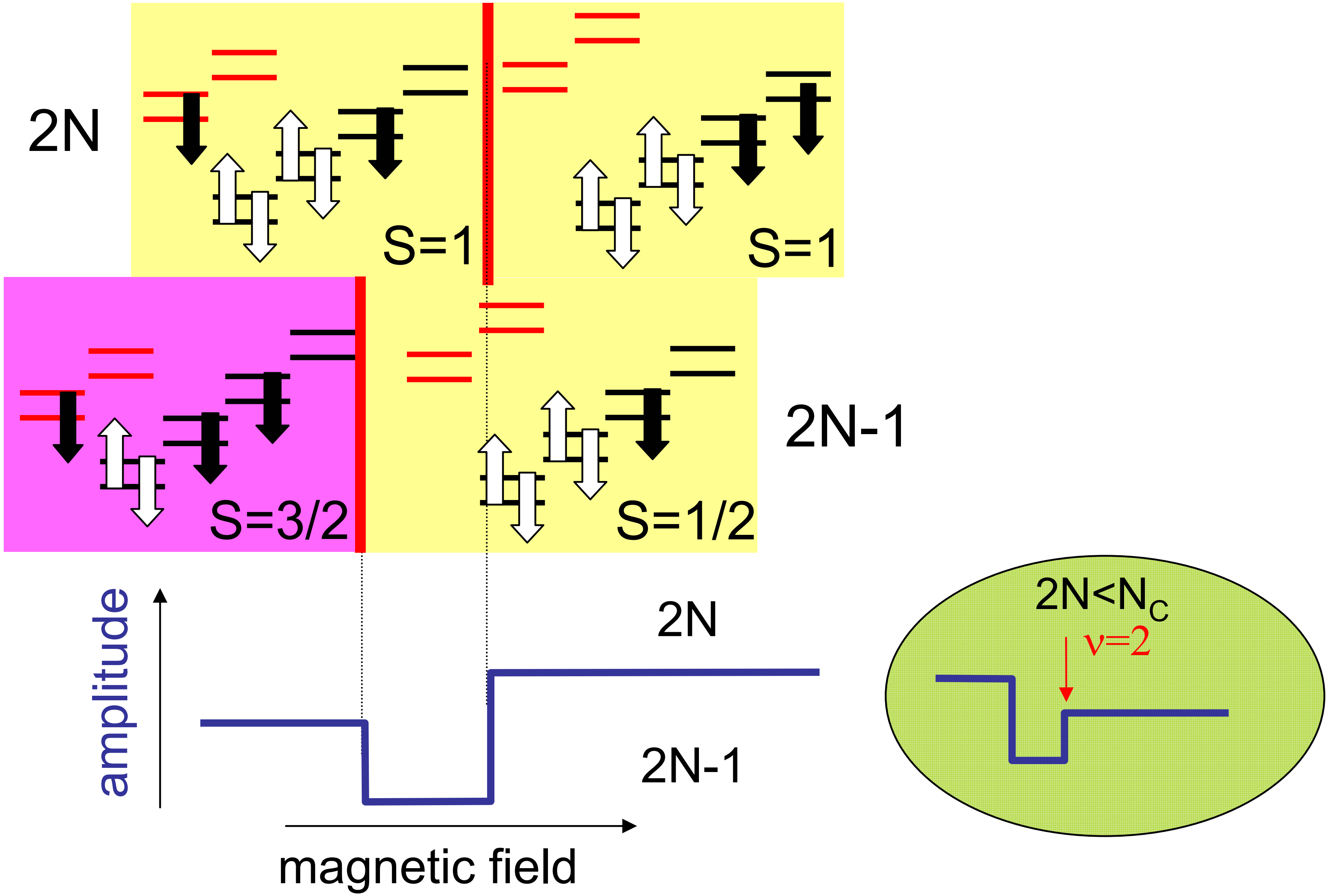
T-S transition at ν=2 boundary (S-T to the center of the dot)

S-T transition, 1st spin flip at the edge of the dot



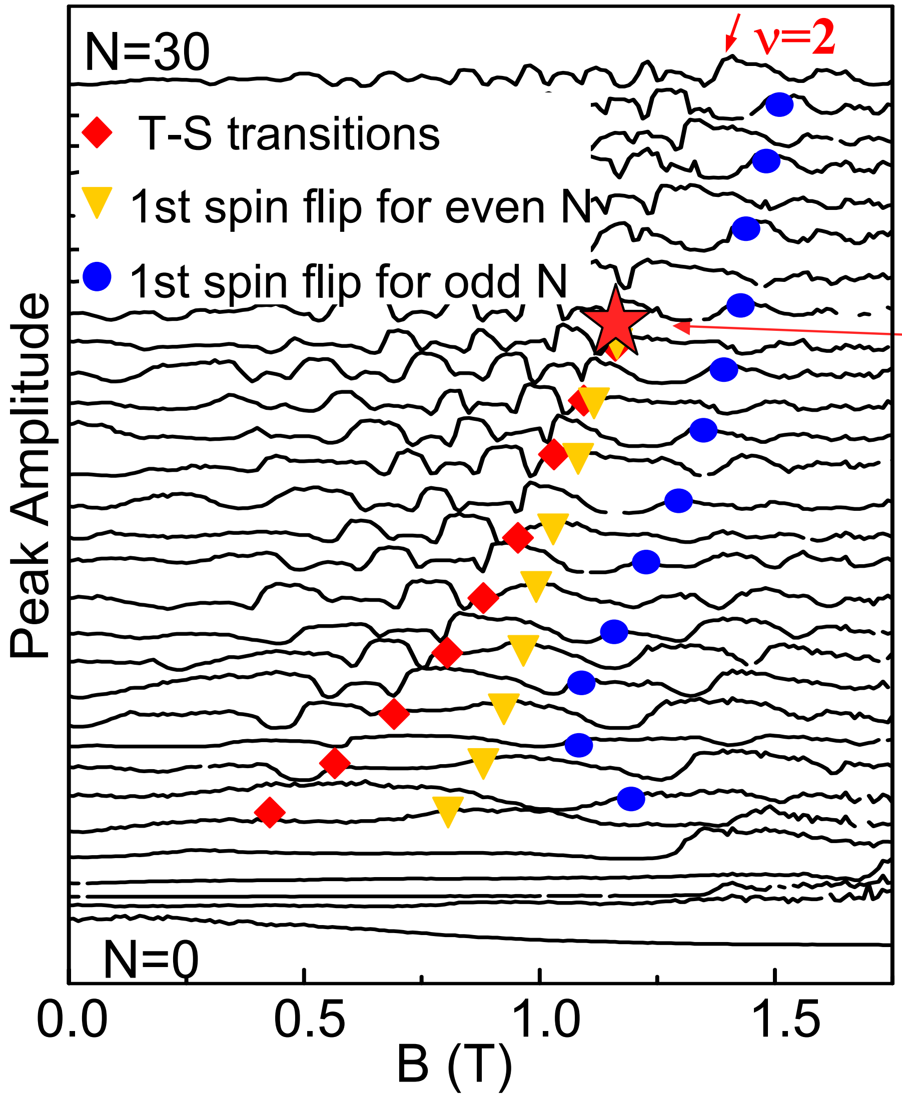
Spin transitions for $2N>N_C$

NO SPIN SINGLET PHASE!

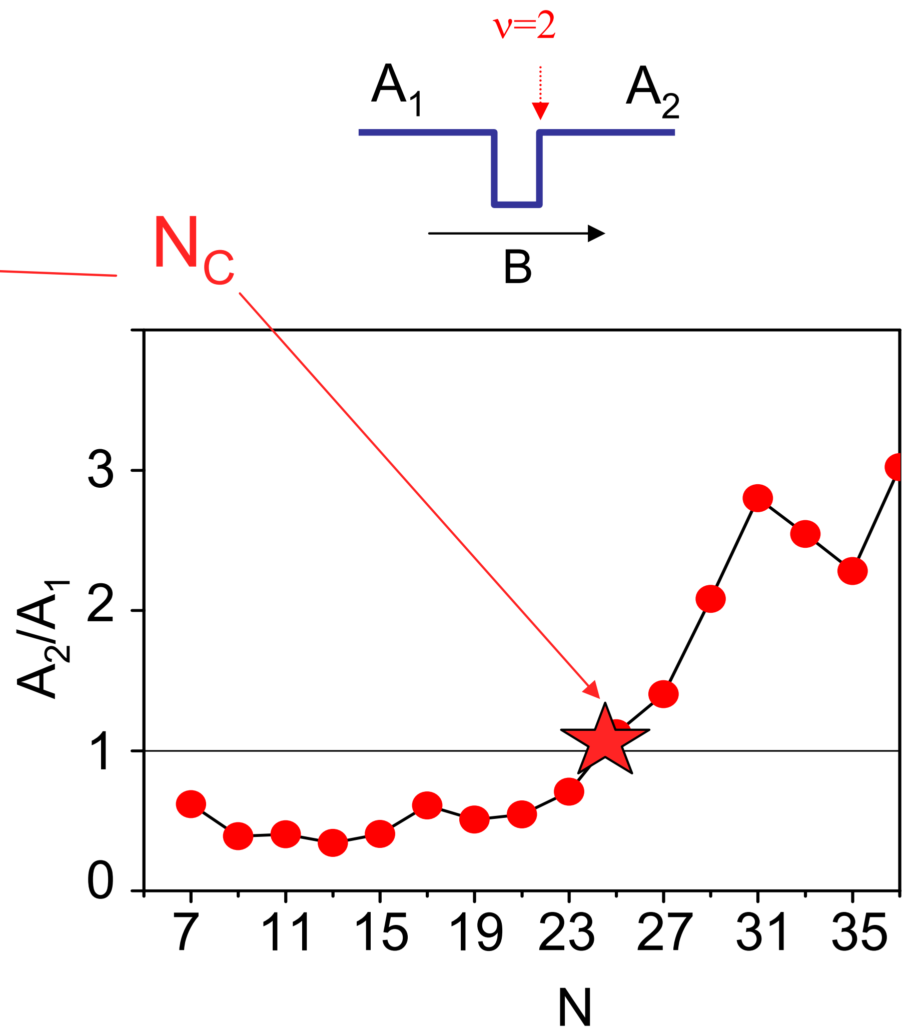


A. Wensauer, M. Korkusiński, and P. Hawrylak, PRB **67**, 035325 (2003)

Current detection of the collapse of the ν=2 Spin Singlet Phase



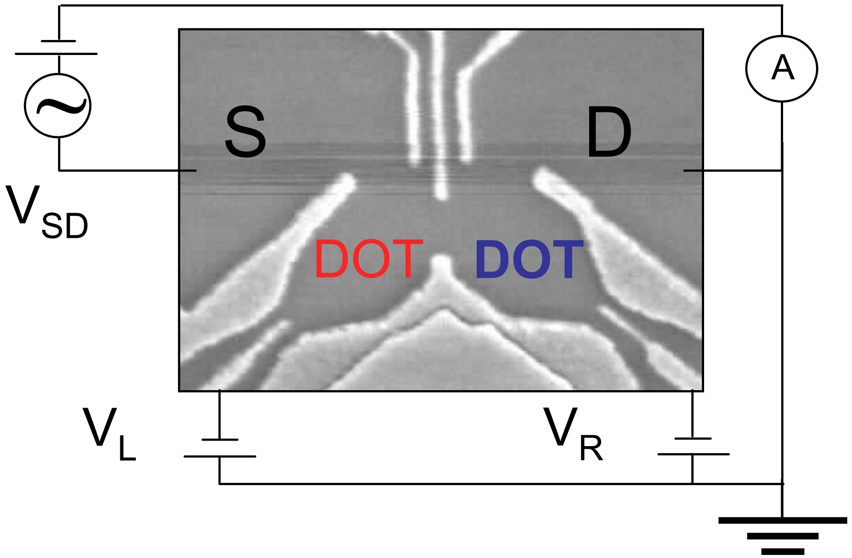
Experimental parameter: amplitude ratio A_2/A_1

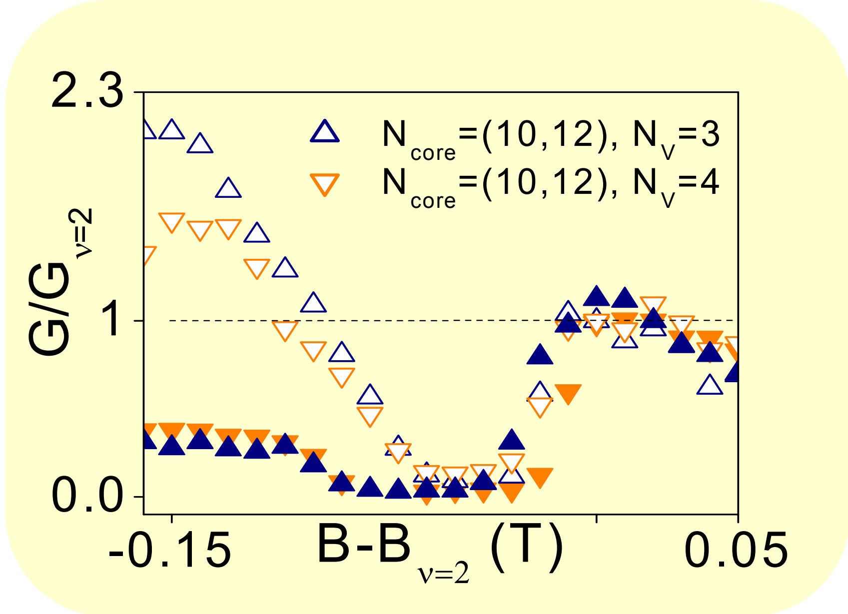


M. Ciorga *et al*. PRL **88**, 256804 (2002)

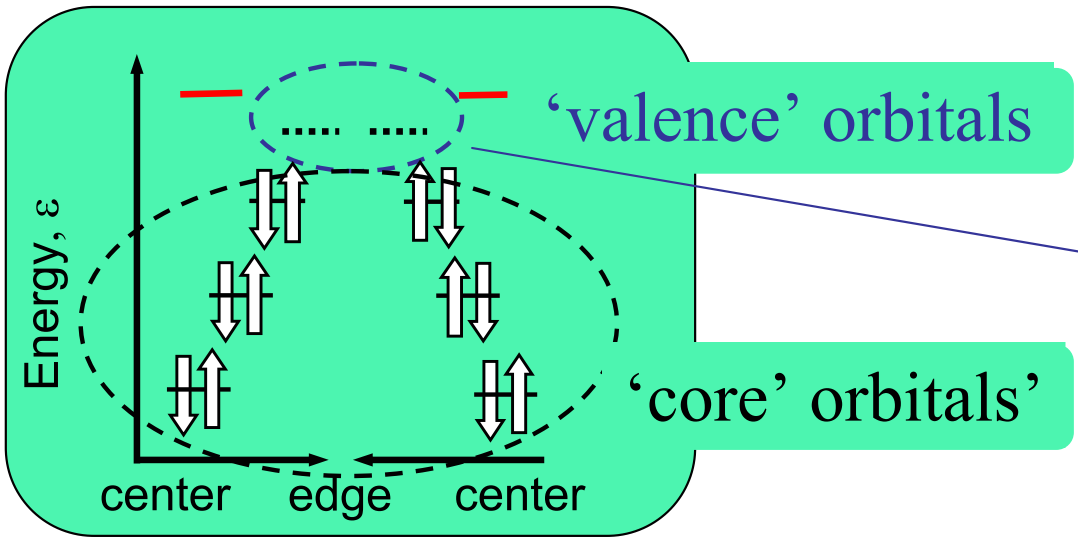
Spin Blockade in Quantum Dot Molecules

M.Pioro-Ladriere et al. Phys. Rev. Lett. 91, 026803 (2003)

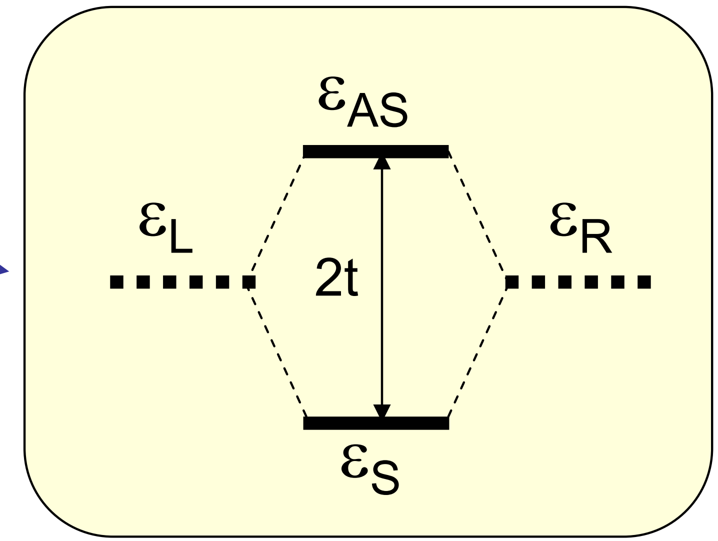




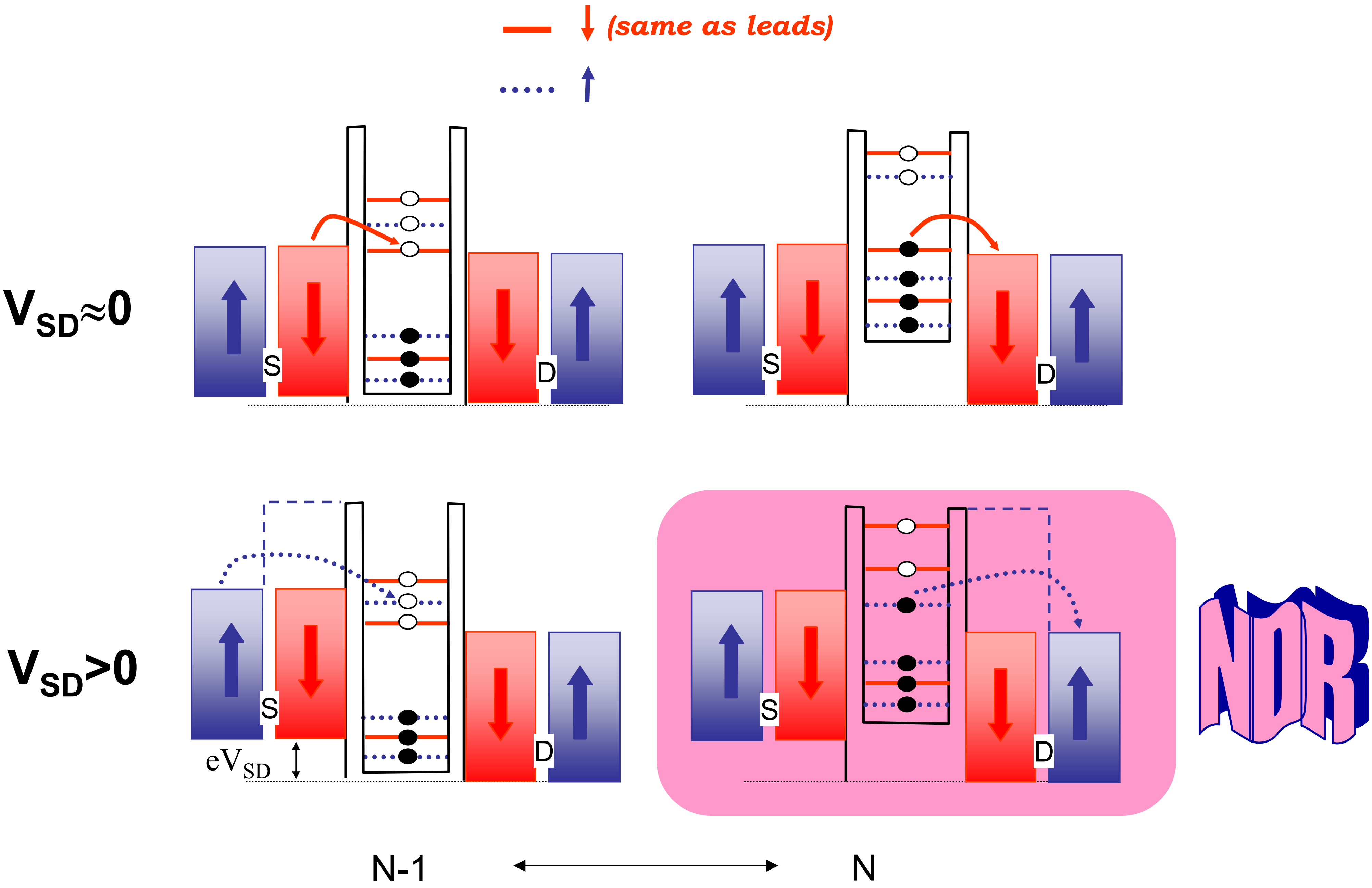
Two dots



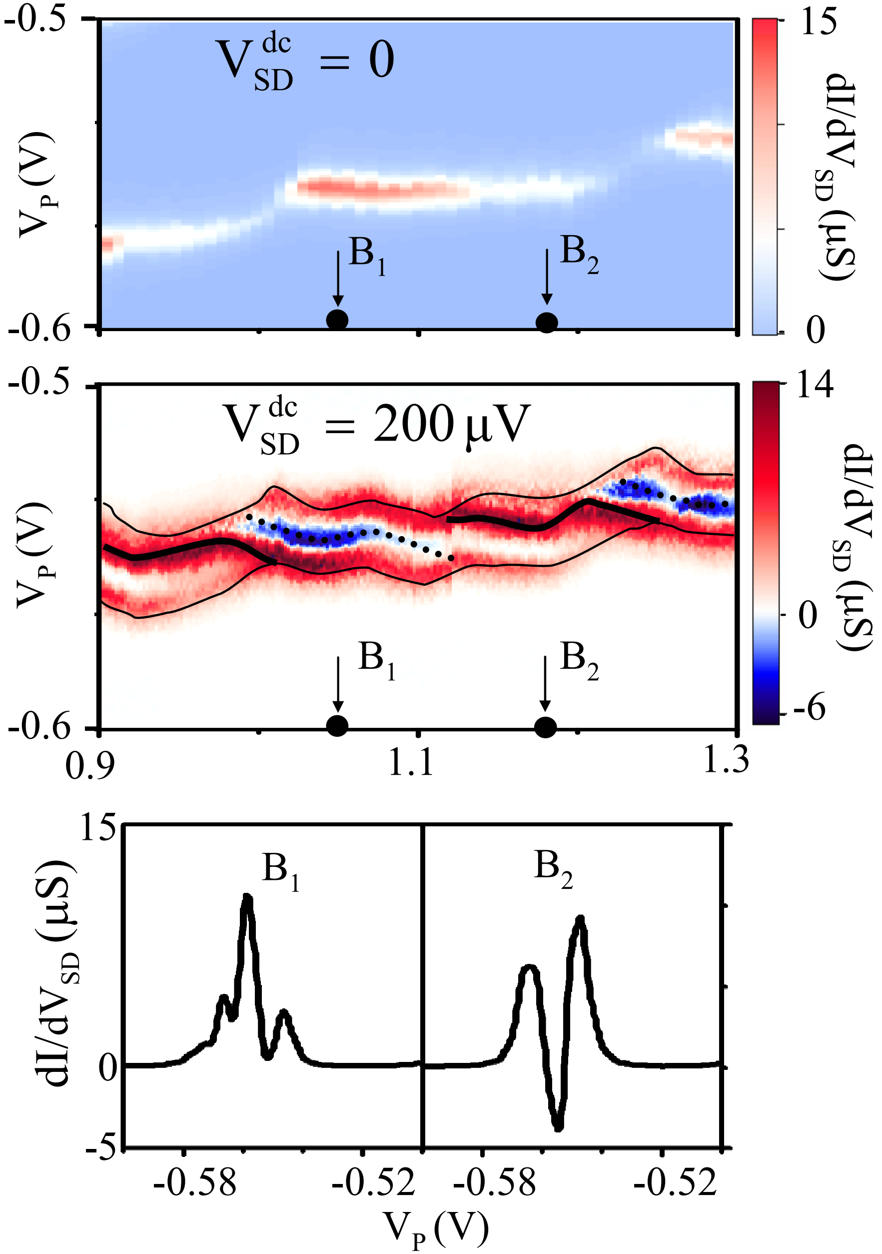
A two-level molecule



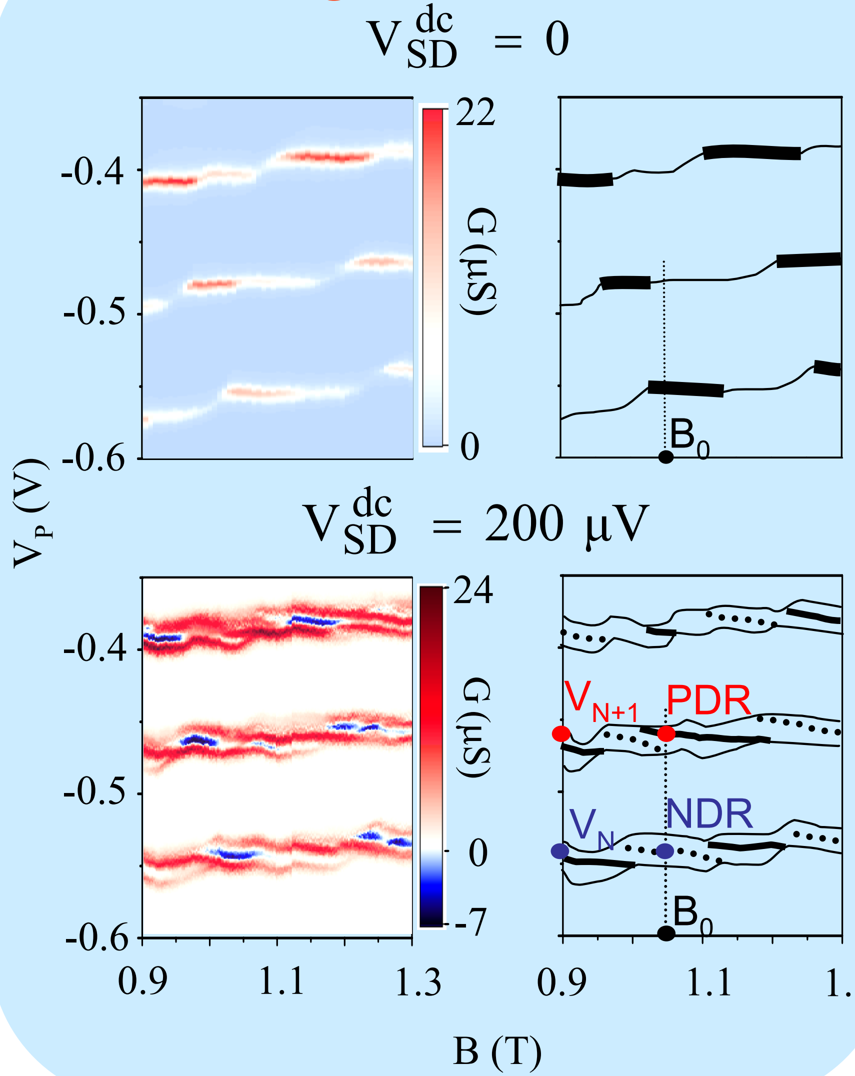
NDR as a result of a spin polarized detection



Tunable Negative Differential Resistance



Tuning NDR and PDR



M.Ciorga et al. APL. 80, 2177 (2002)

Summary

Spin selectivity in QPCs

- *Parallel magnetic field – Zeeman splitting*
- *Transverse electron focusing experiments*
- *Plateaus in conductance also at B=0T*

Spin selectivity in Quantum Dots

- *Perpendicular magnetic field – spin resolved Landau levels*
  – magnetic edge states
- *Current readout of the spin of the system: singlet-triplet transitions*
- *Negative differential resistance*