Semiconductor few-electron quantum dots as spin qubits for quantum computing

"Delft Spin Qubit Team"

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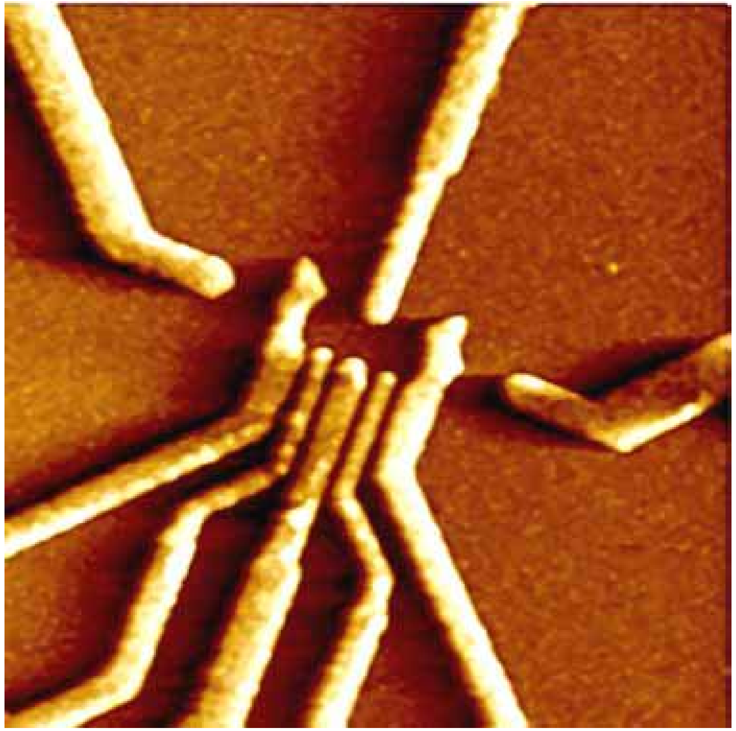


ERATO NTT DARPA FOM

Outline

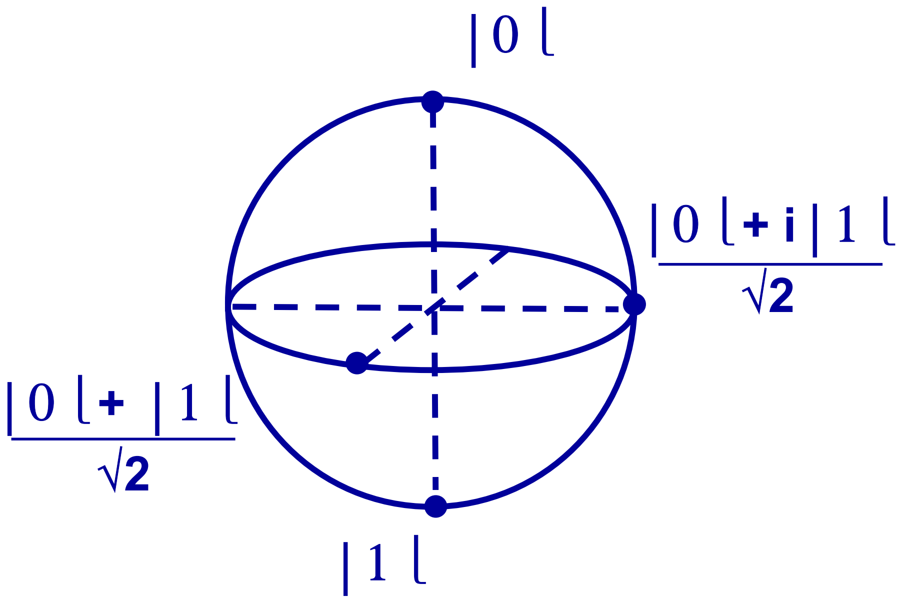
I. Introduction to quantum computing

II. Quantum dots and spin

III. One-electron quantum dots as spin qubits

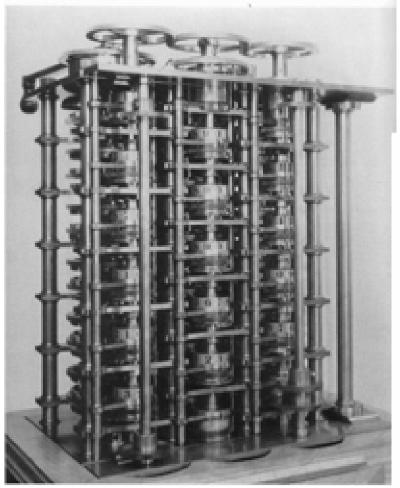
IV. Outlook

Part I.
Introduction to quantum computing



“Hard” problems

15	=	3	x	5		
91	=	...	x	...	?	
437	=	...	x	...	?	
	???					



Courtesy IBM Corporation

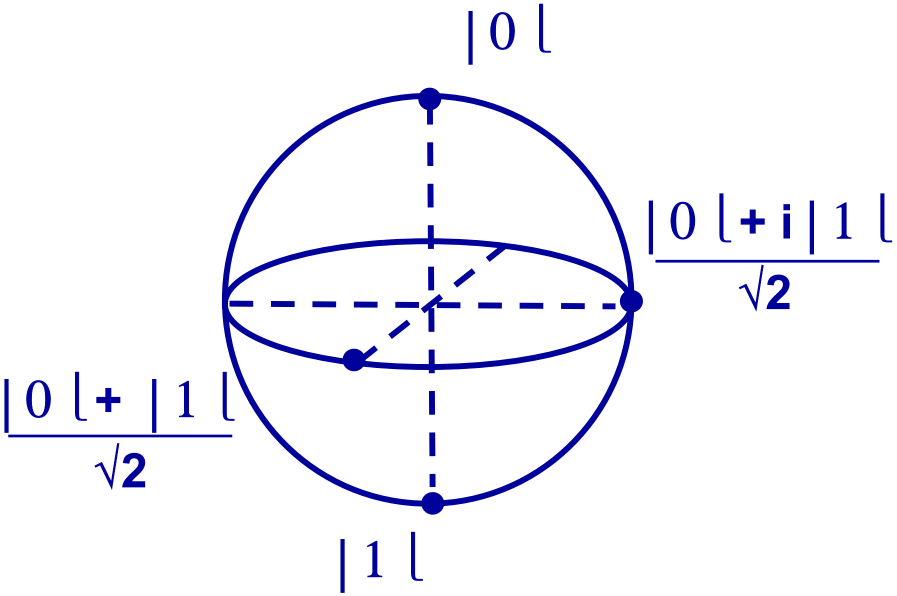
No classical algorithm is known to *efficiently* factor integers

⬇

factoring takes exponential effort

“Hard” problems are beyond the reach of any machine relying on the classical laws of physics

Complexity of Quantum Systems



n coupled quantum bits

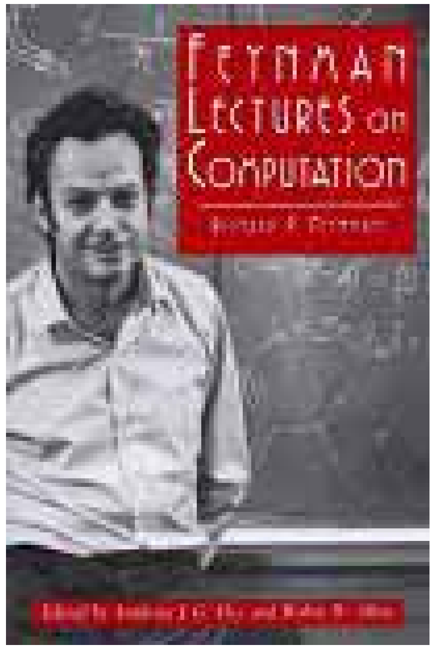
⇓

~~n spheres~~

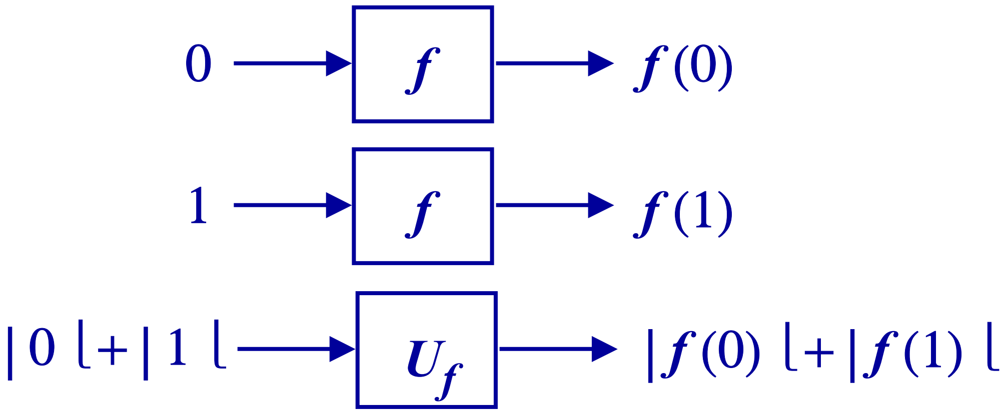
2^n degrees of freedom!

Could a quantum computer *efficiently* simulate quantum systems ?

Could it be used to solve hard problems ?



Quantum Parallelism

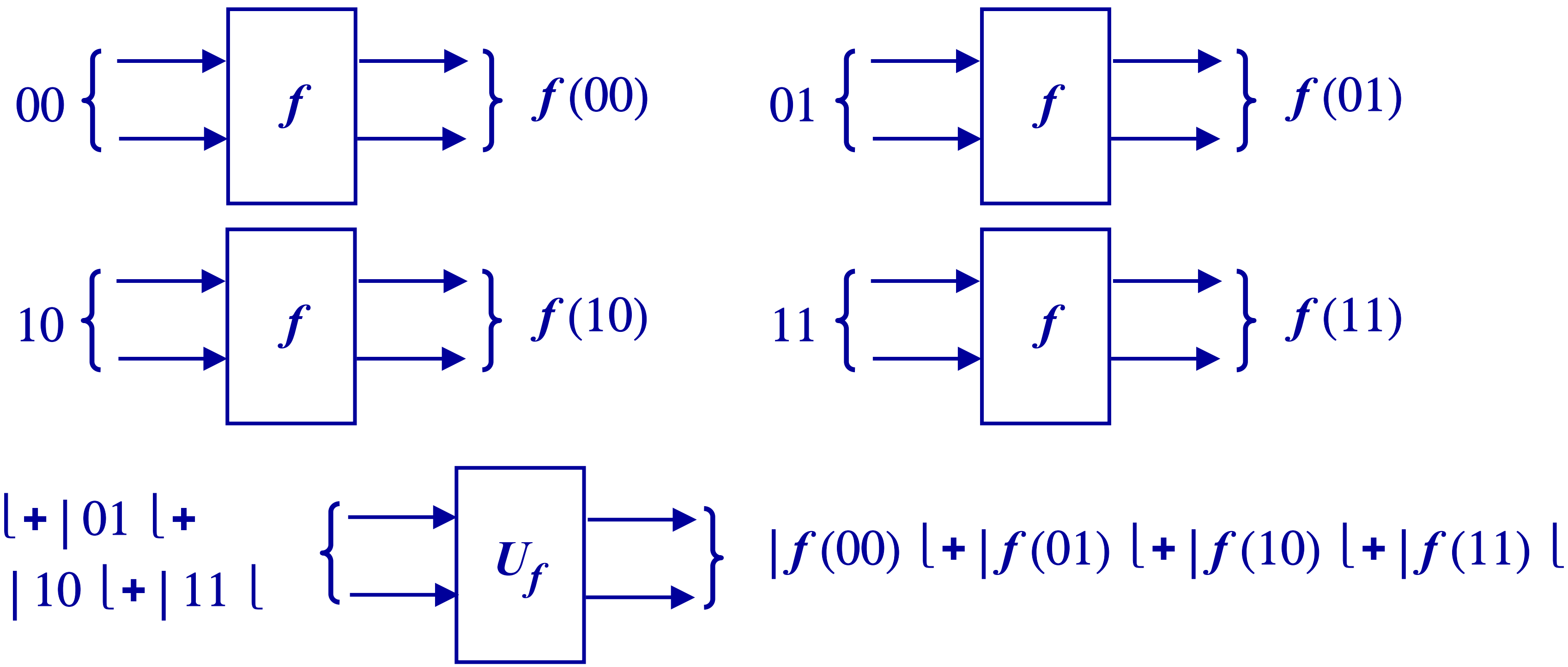


Computational power:

classically $\propto n$

quantum $\propto 2^n$

D. Deutsch, 1985



Quantum algorithms

Measurement of $|f(0)\rangle + |f(1)\rangle$ gives either $f(0)$ or $f(1)$

The exponential power appears inaccessible ...

Nevertheless: quantum algorithms make computational speed-ups possible !

- Exponential for factoring integers (P. Shor 1994)
- Quadratic for unstructured searches (L. Grover 1996)
- Exponential for quantum simulations (S. Lloyd 1996)

Quantum error correction

Decoherence destroys quantum parallelism

↓

The exponential power appears limited in time ...

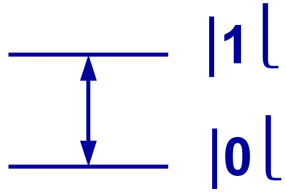
Nevertheless: quantum error correction makes arbitrarily long quantum computations possible !

- Quantum error correction (P. Shor 1996, A. Steane 1996)
- Accuracy threshold (D. Aharonov 1997, A. Kitaev 1997, ...): $\sim 10^{-4}$

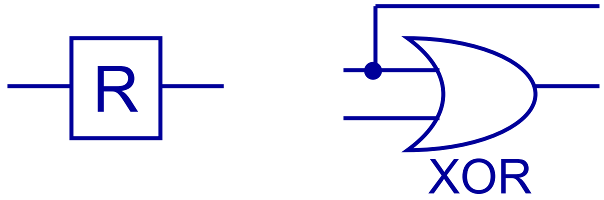
Implementation of quantum computers

D. DiVincenzo

1. Well-defined qubits



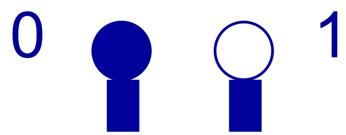
2. Universal set of quantum gates



3. Initialization to a pure state

$|00 \ldots 0\rangle$

4. Qubit-specific measurement



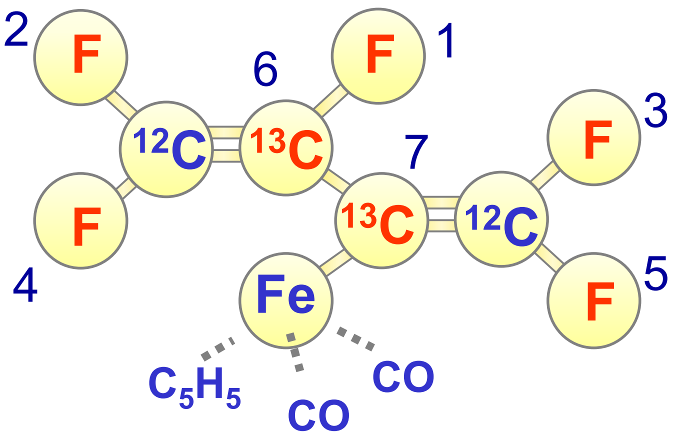
5. Long coherence times

$|0 \ldots 0\rangle + |1 \ldots 1\rangle$

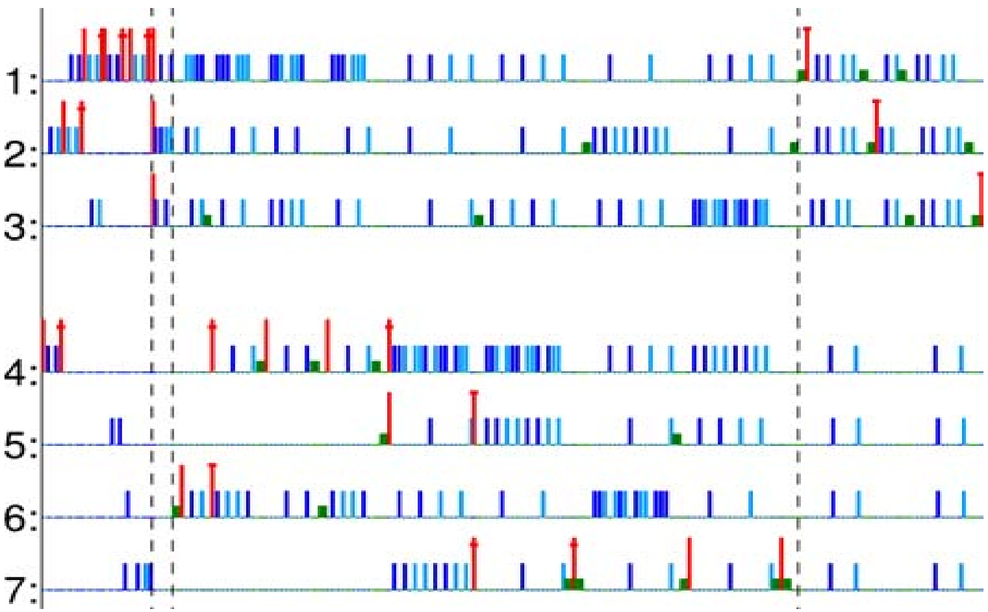
Key challenge: combine access to qubits (initialization, control, readout) with high degree of isolation (coherence)

Factoring 15 with nuclear spins

Vandersypen *et al.*, *Nature* 414, 883 (2001)



15 = 3 x 5



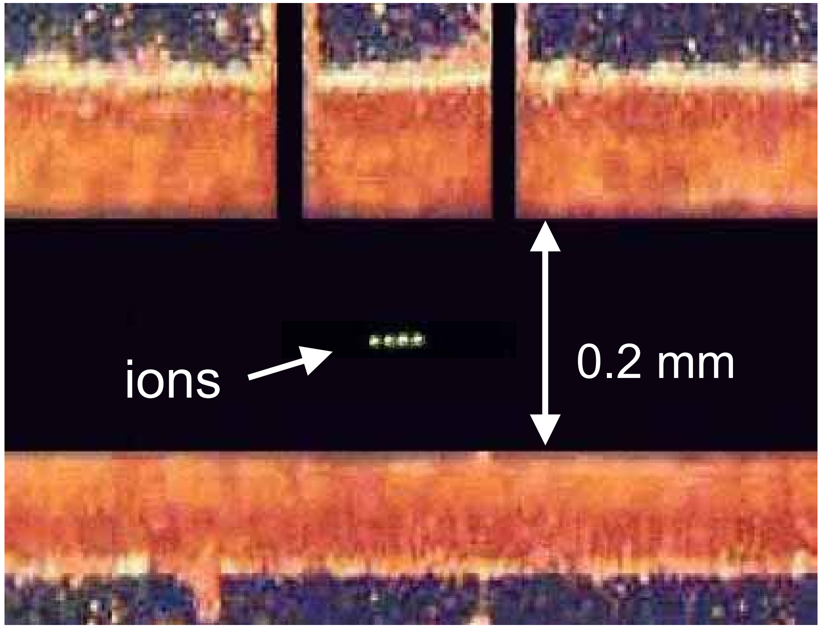
Proof-of-principle of quantum computing

But:

No practical path for scaling liquid NMR to many more qubits

Other techniques

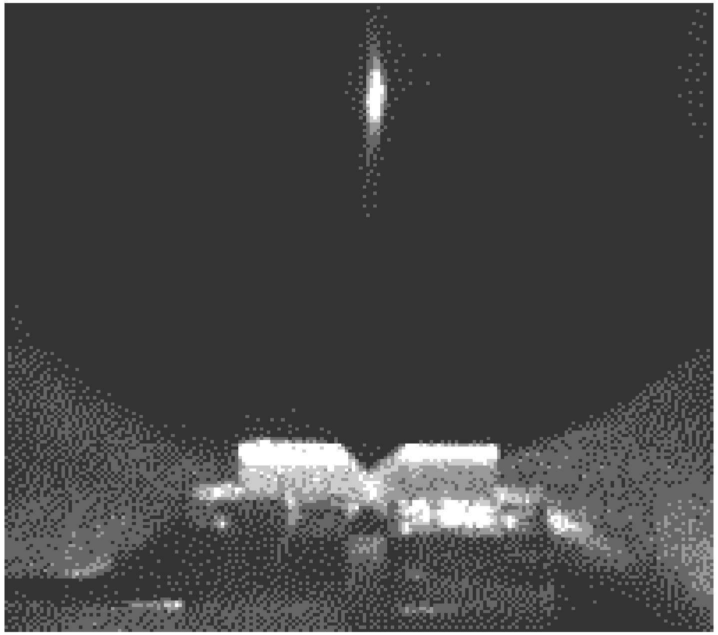
Trapped ions



Courtesy D. Wineland, NIST

Scalability is a big problem!

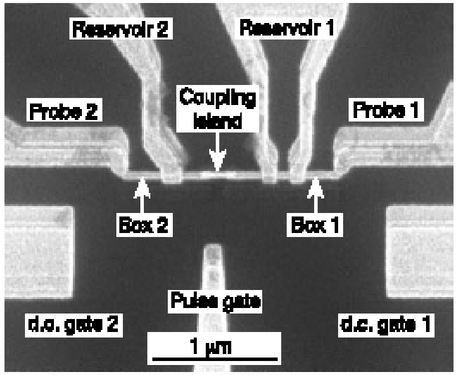
Neutral atoms in optical traps



Courtesy J. Kimble, Caltech

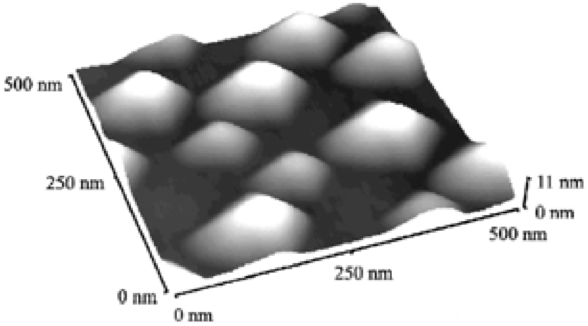
Charge quantum bits in the solid state

- ***Superconducting charge qubits***
  - One- and two-qubit operations
  - Single-shot read-out

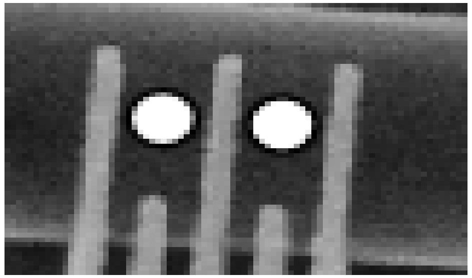


Courtesy Y. Nakamura, NEC

- ***Semiconductor quantum dots***
  - Excitons in self-assembled quantum dots
  - Double dot charge qubit

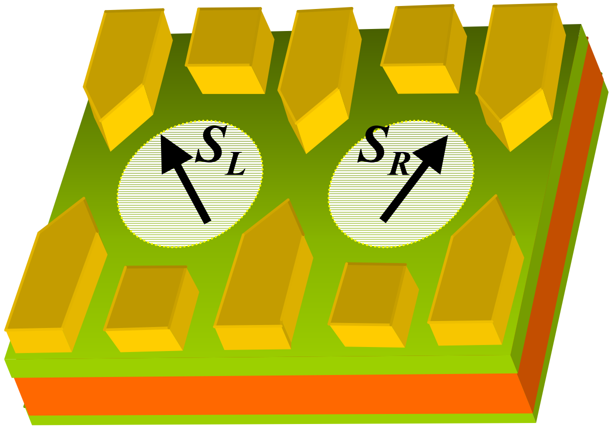


- **Charge easy to manipulate and read out**
- **But coherence time only ~ ns**



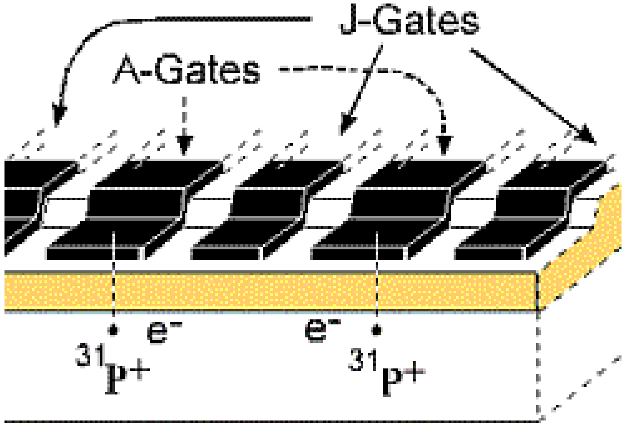
"Scalable" single-spin qubit proposals

Electron spin in gated quantum dots (electrical)



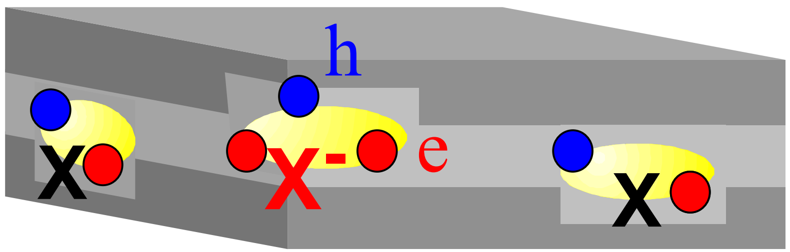
Loss & DiVincenzo, PRA 1998

Nuclear spin of P donors in Si



Kane, Nature 1998

Electron spin in self-assembled quantum dots (optical)



Gammon *et al.*
Imamoglu *et al.*, PRL 1999

Electron spin in a lateral quantum dot

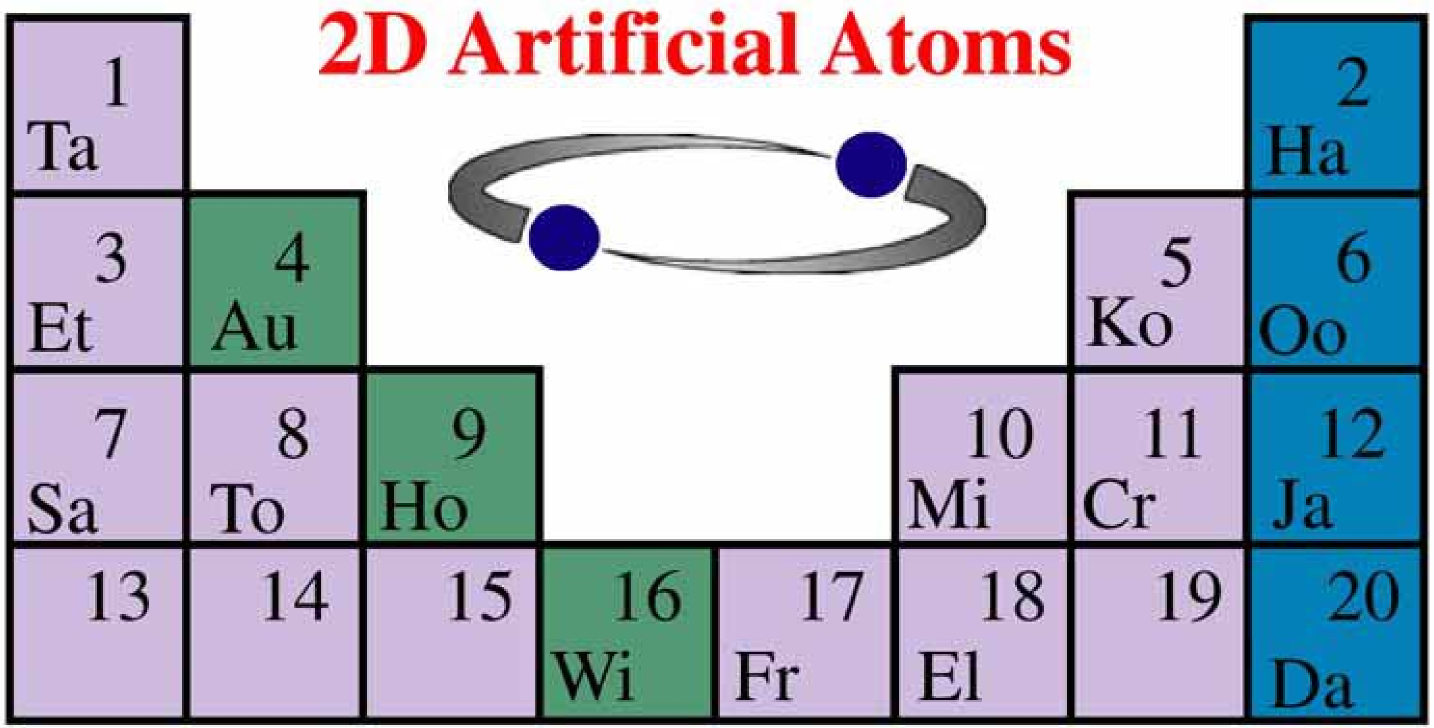
Why electron spin in a lateral quantum dot?

- Electron spin is a natural 2-level system
- Well isolated from environment ♥ long coherence times expected
- Lateral quantum dots are very flexible and controllable systems, should be scalable

Of course, not only application-driven:

- Spin physics at the fundamental quantum limit: 1 spin !

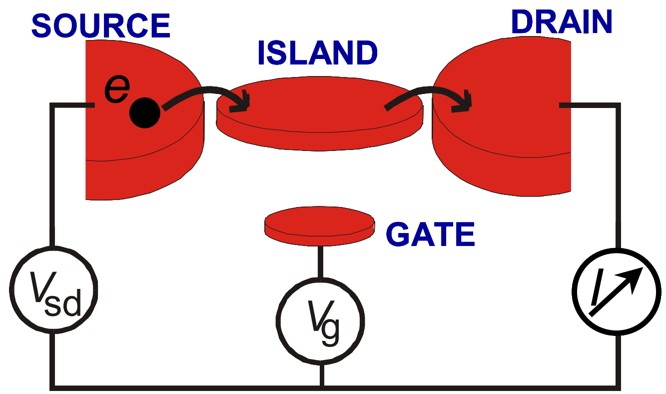
Part II:
Quantum dots and spin



Quantum dots

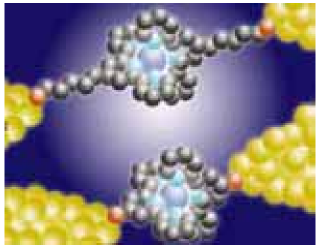
- Small box occupied by electrons (holes)
- Coupled via tunnel barriers to source and drain reservoirs
- Coupled capacitively to gate electrode(s)
- Box (island) has discrete energy spectrum

♥ **artificial atom!**

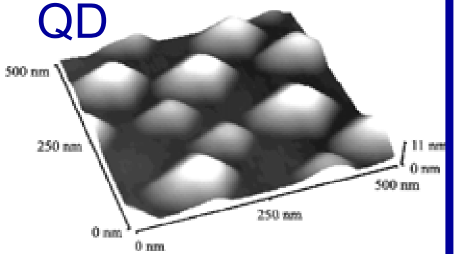


control & flexibility

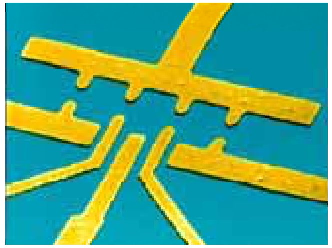
single molecule



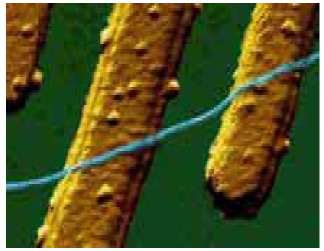
self-assembled QD



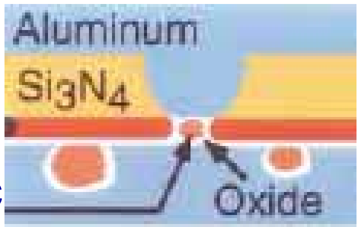
lateral QD



nanotube

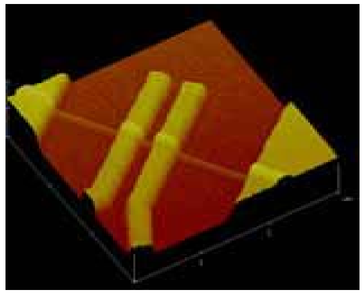


1 nm | 10 nm | 100 nm | 1 μm



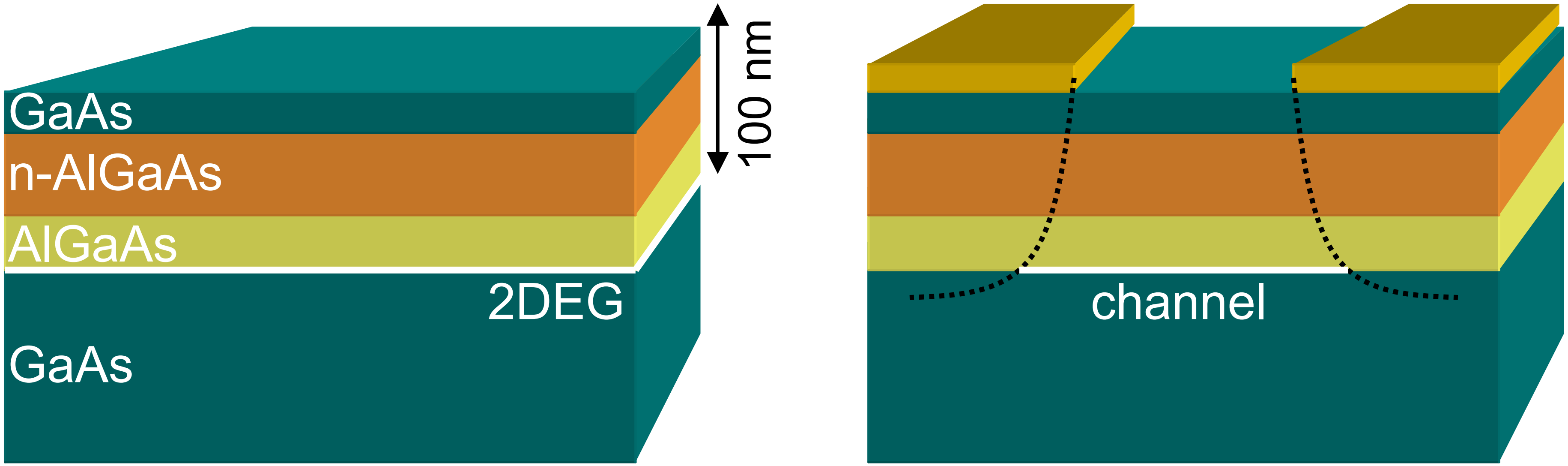
metallic (superconducting) nanoparticle

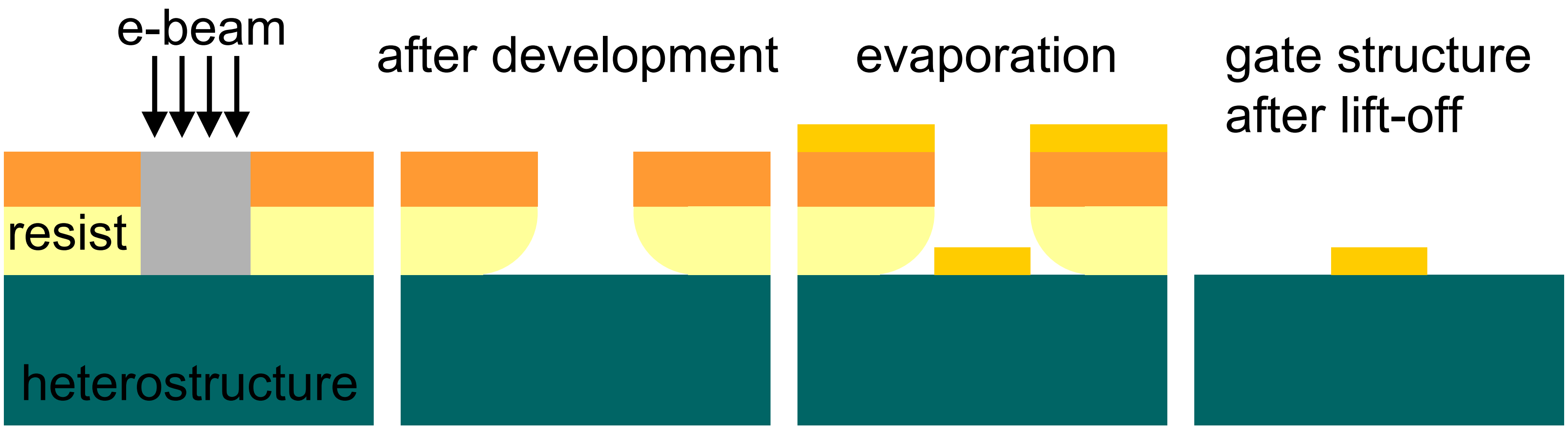
vertical QD



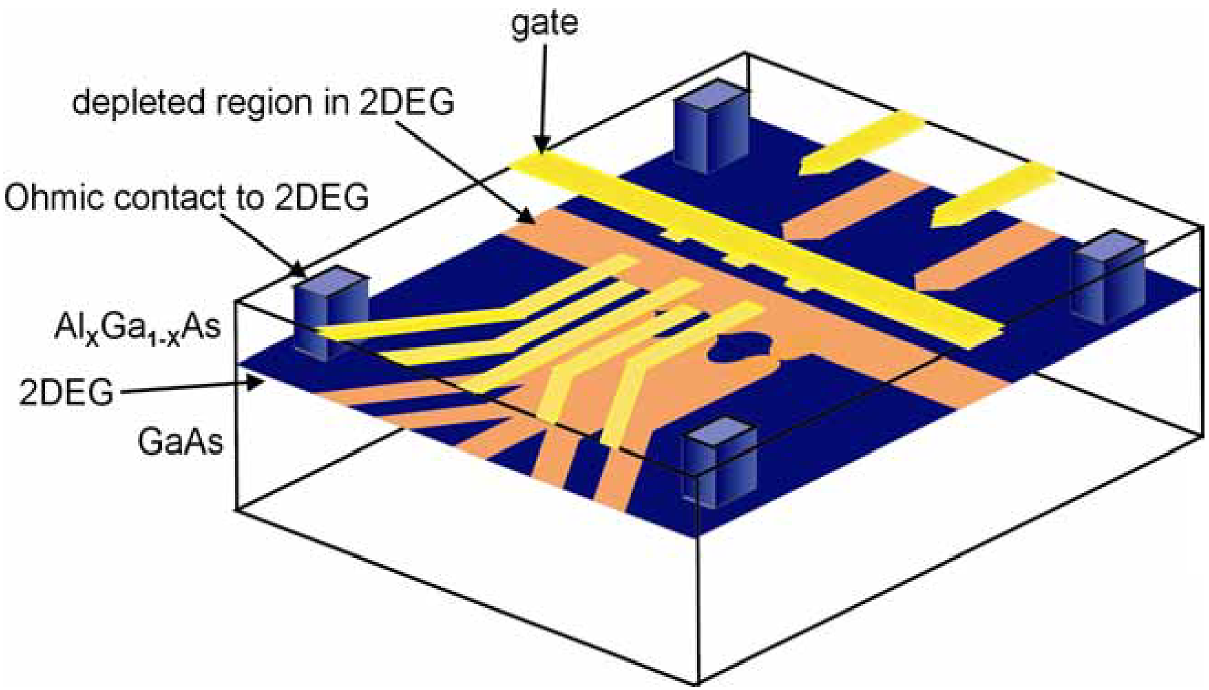
nanowire

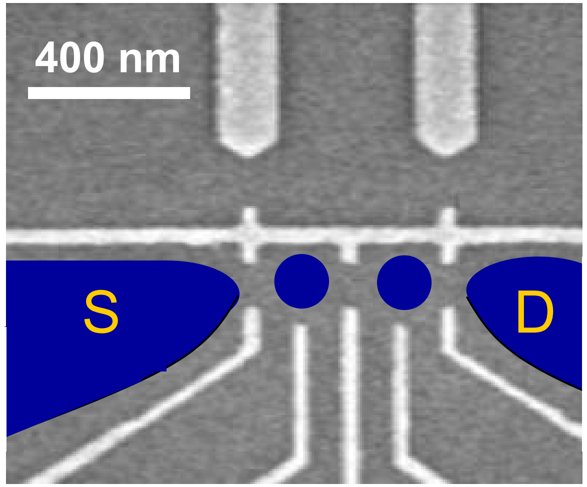
Heterostructure processing



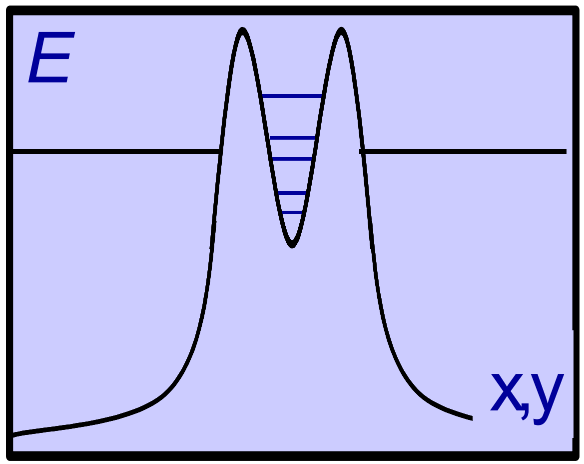


Lateral QD fabrication



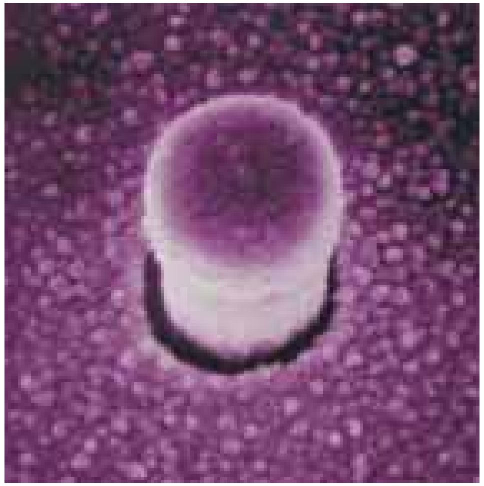


- High-mobility 2DEG (~10^6 cm^2/ Vs)
- Density ~10^{15} m^{-2} ♥ λ_F ~ 30 nm
- Resolution gate structure ~20 nm
- Dot size ~ 100 nm
- Comparable to electron wavelength
  ♥ discrete energy spectrum

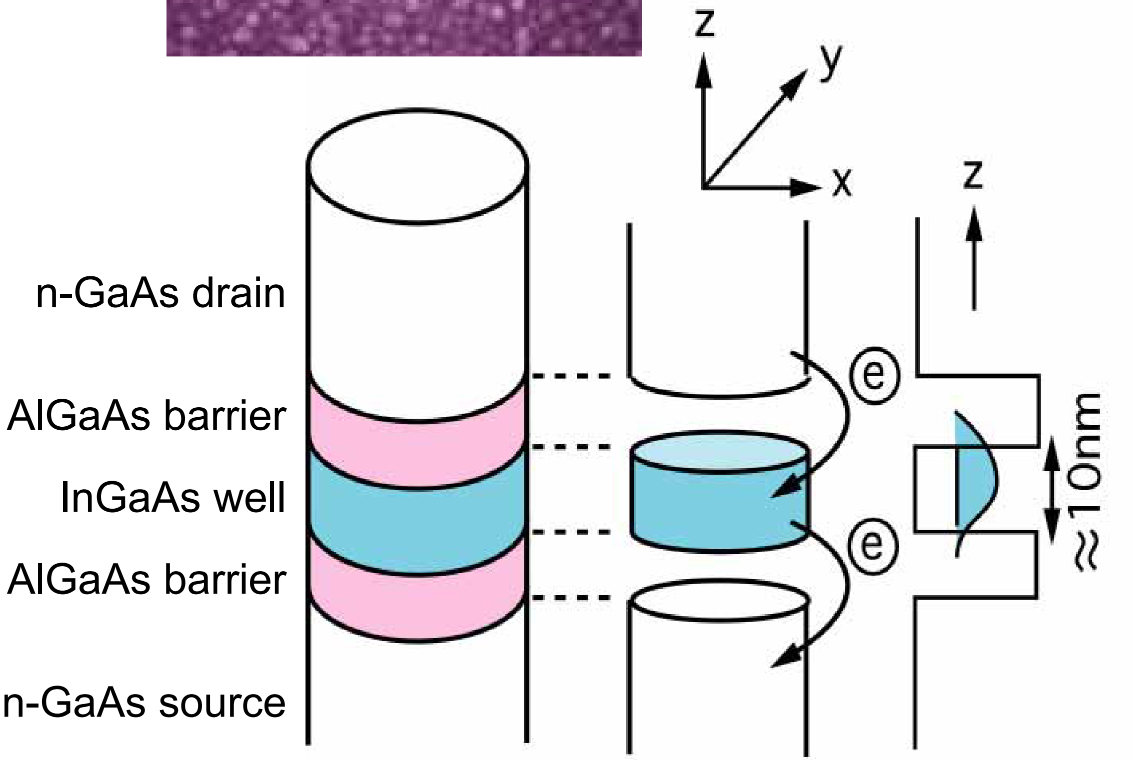


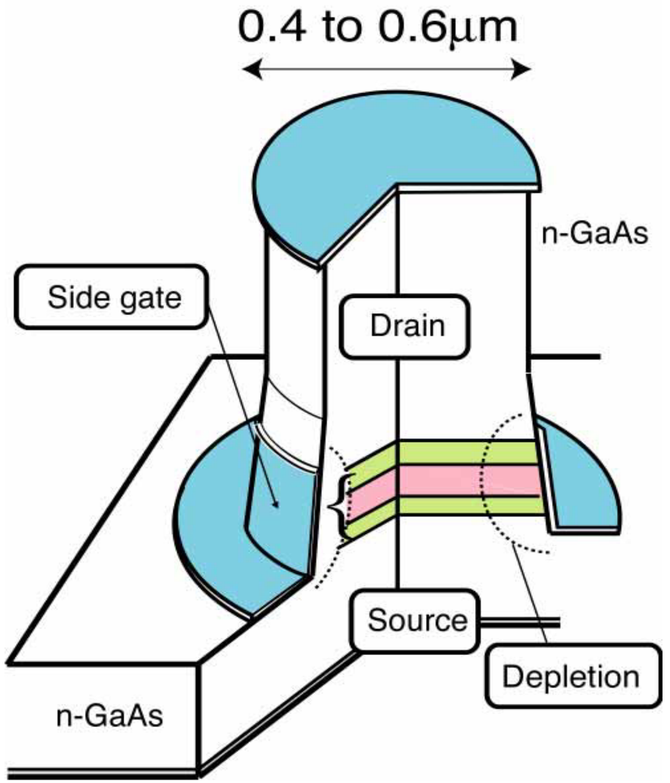
Vertical QD fabrication

Tarucha PRL 77, 3613 (`96)

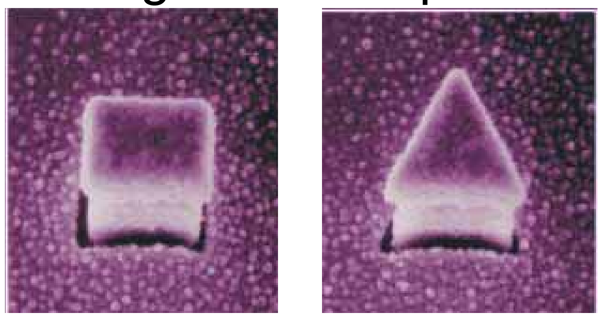


Circular pillar made from double barrier structure by dry and wet etching

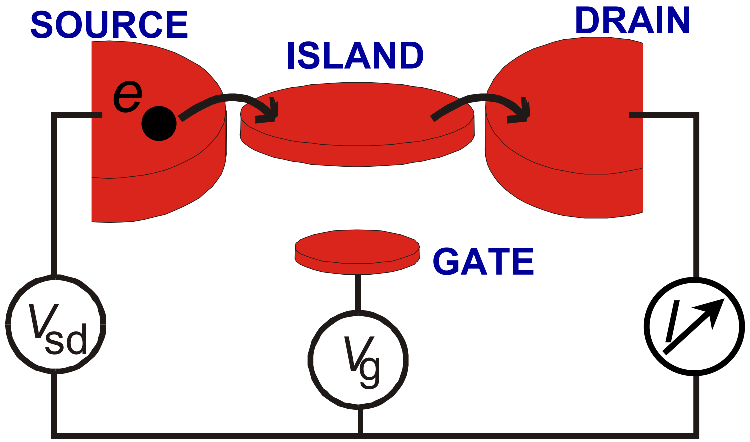


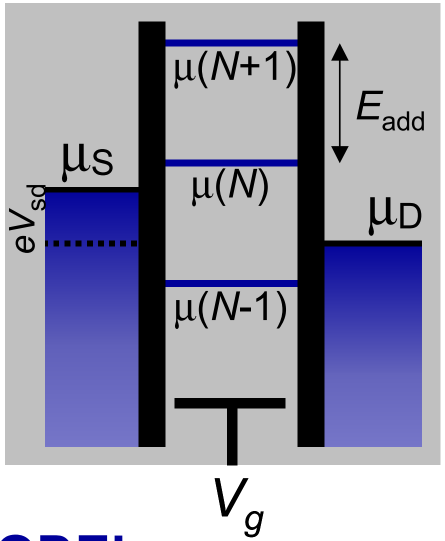


Other geometries possible



Coulomb Blockade in transport





charging energy:
$E_C = e^2/C_\Sigma$

$C \propto R$,
R (radius) 100 nm
♥ $E_C \sim$ few meV

CONSTANT INTERACTION MODEL

$$U(N) = \frac{(-Ne + C_g V_g + q_0)^2}{2C_\Sigma} + E_{int}(N) \qquad C_\Sigma = C_L + C_R + C_g$$

$$\mu(N) \equiv U(N) - U(N-1) = E_C\,[(N - ½ - q_0/e) - C_g V_g/e] + E_N \qquad E_C = e^2/C_\Sigma$$

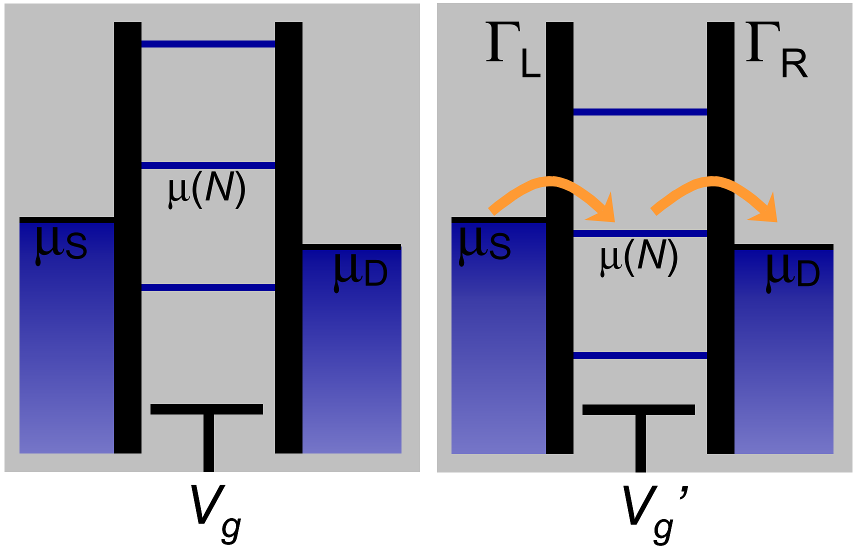
$$E_{add} \equiv \mu(N+1) - \mu(N) = E_C + \Delta E$$

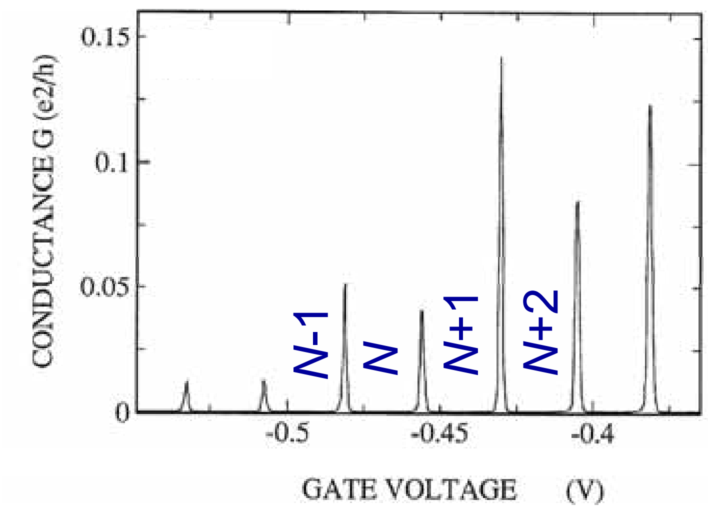
- Transport when $\mu(N) = \mu_S, \mu_D$
- Small C_Σ ♥ large addition energy
- At low T, small V_{sd}, energy not available

→ **CURRENT = 0 (*COULOMB BLOCKADE*)**

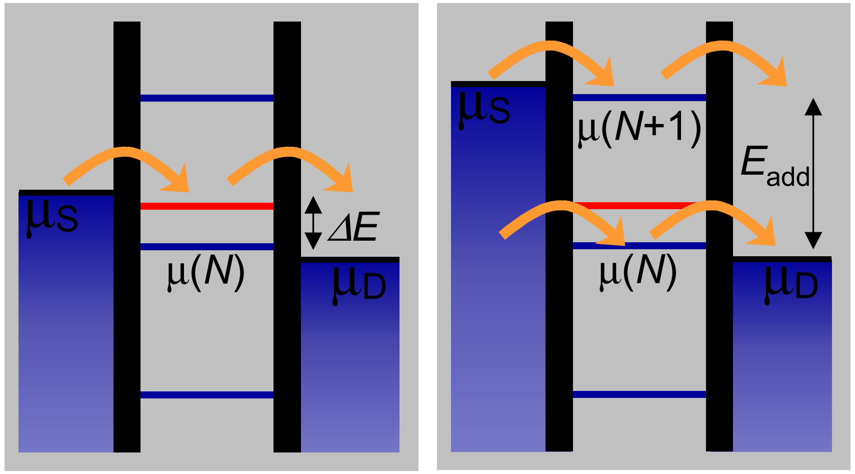
Single electron tunneling

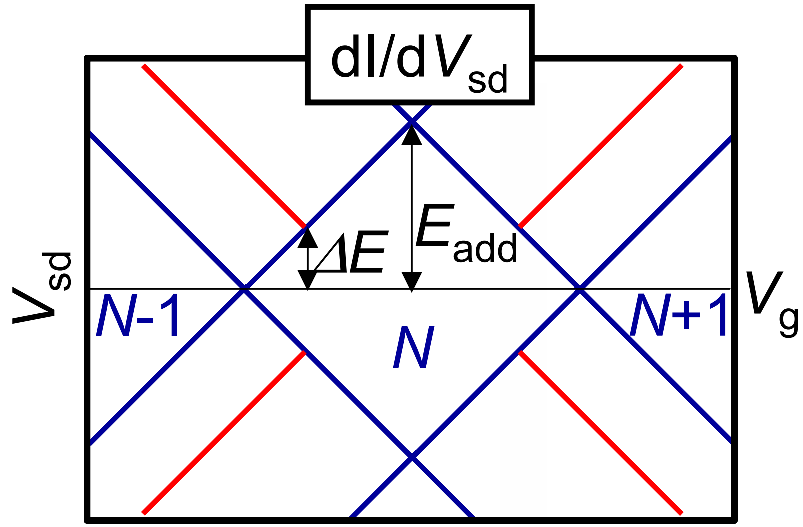
Linear response





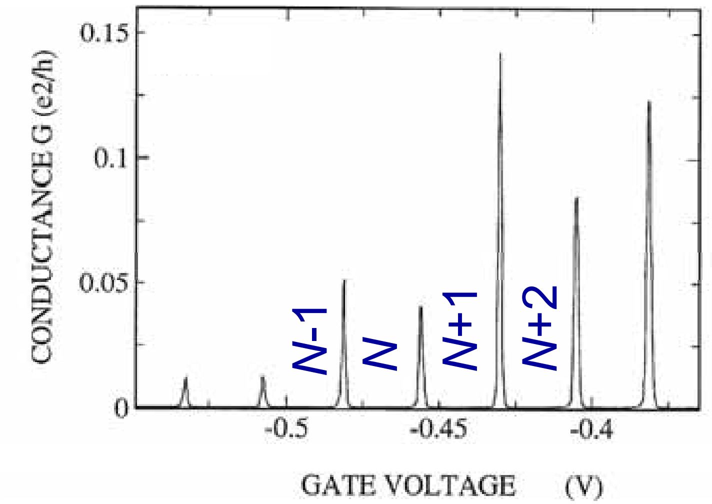
Non-linear transport





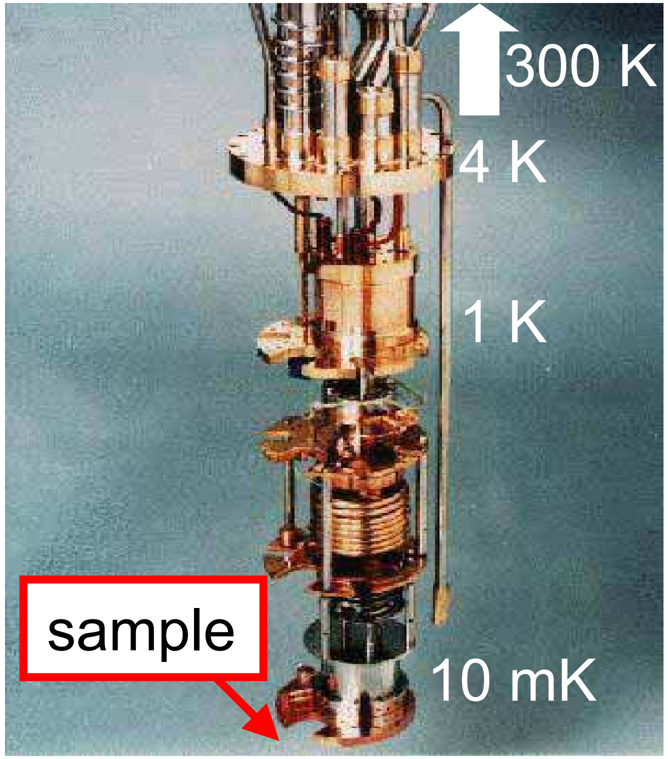
Large-bias spectroscopy!

Experimental set-up



- Resonance width: lifetime ($h\Gamma$), V_{sd}, temperature, noise
- Peak spacing: charging + single-particle spacing
- E_C ~ few meV
- ΔE ~ few 0.1 meV
- 3 fA / Hz^{½} ♥ 1 e/50 μs

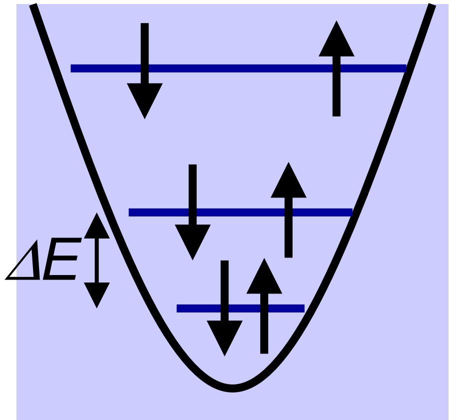
Dilution refrigerator:
10 mK (~few μeV)



~ 1m

low-noise amplifiers
+
filtering

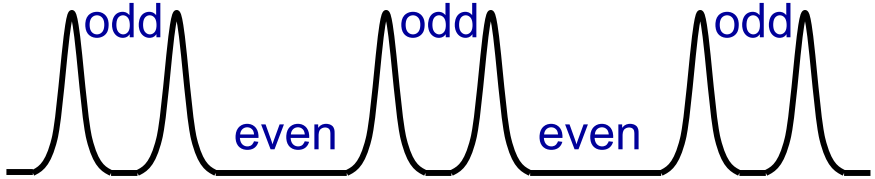
Single-particle levels & shell structure



orbitals 2-fold degenerate ♥ expect even/odd effects in peakspacing

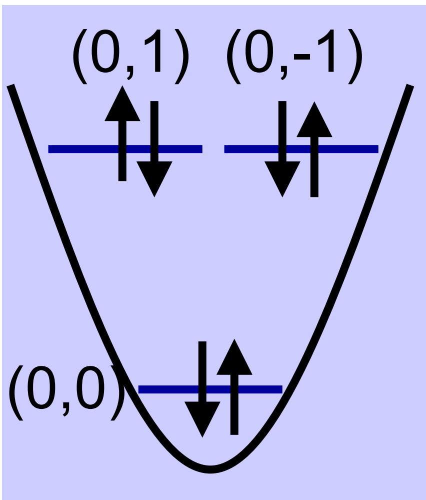
$$U(N) = \frac{(-Ne + C_g V_g + q_0)^2}{2C_\Sigma} + E_{int}(N)$$

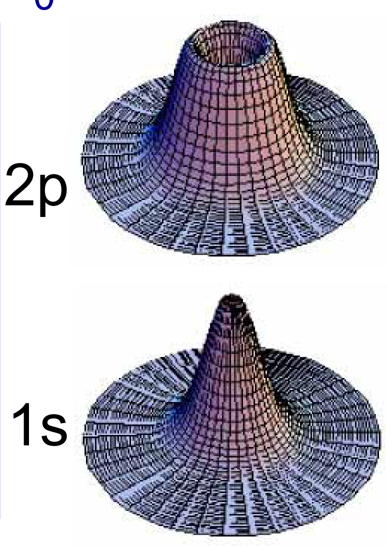
$$E_{add} = E_C + \Delta E$$



B = 0 T:

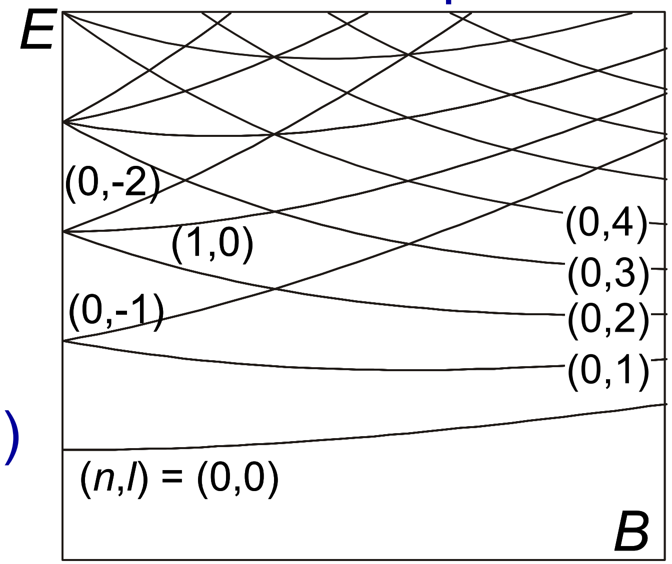
$$E_{nl} = (2n+|l|+1)\hbar\omega_0$$





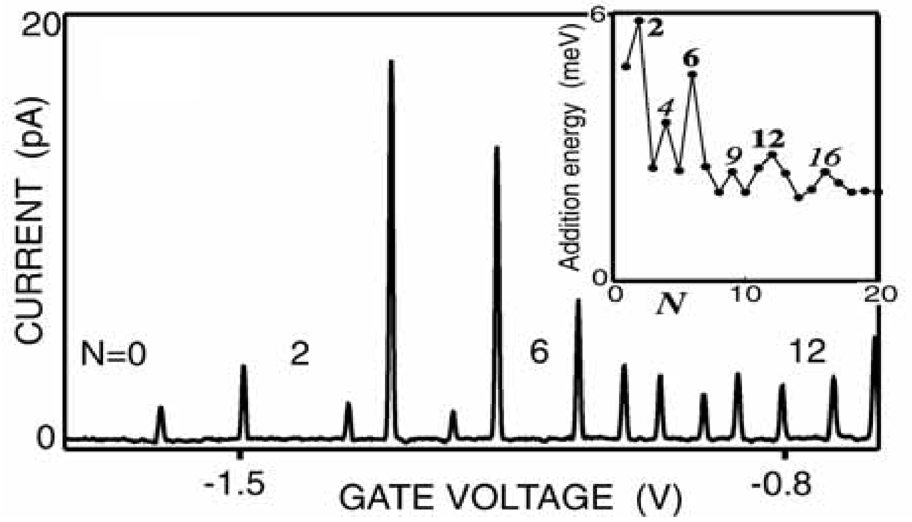
N=2,6,12 full shell (noble elements)

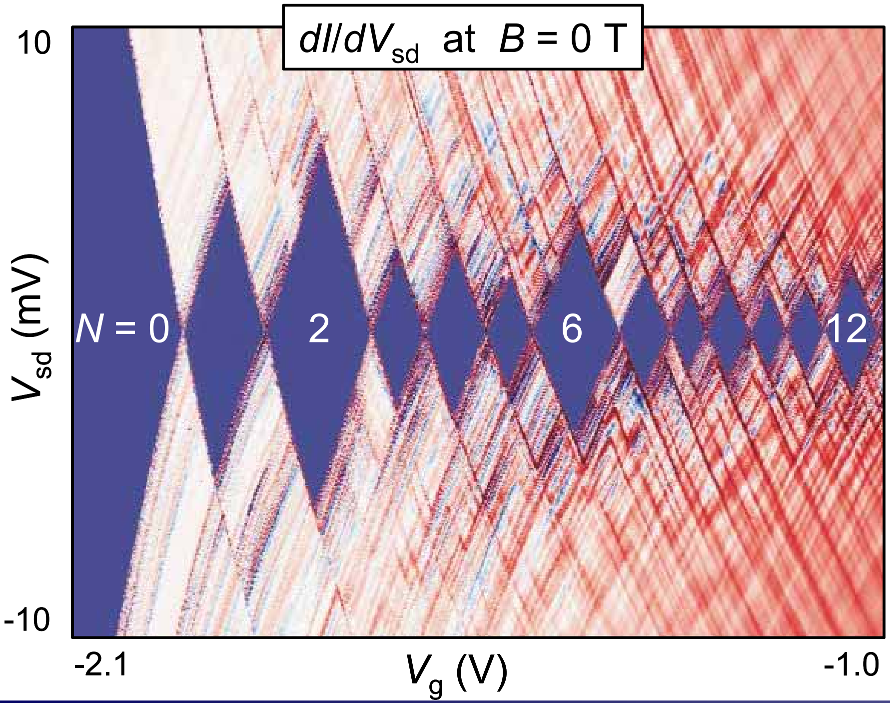
2D harmonic potential: Darwin-Fock spectrum

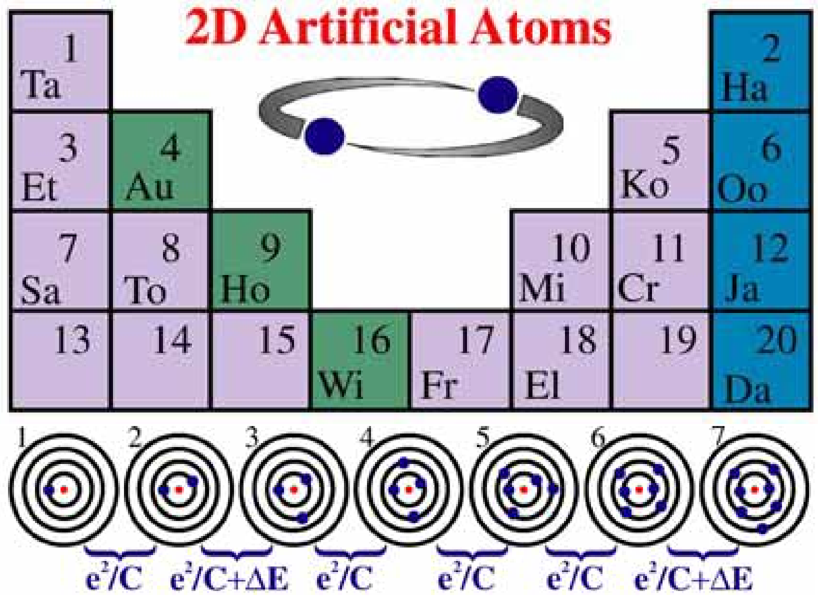


Artificial atoms

Kouwenhoven *et al.*, Science 278, 1788 (`97)

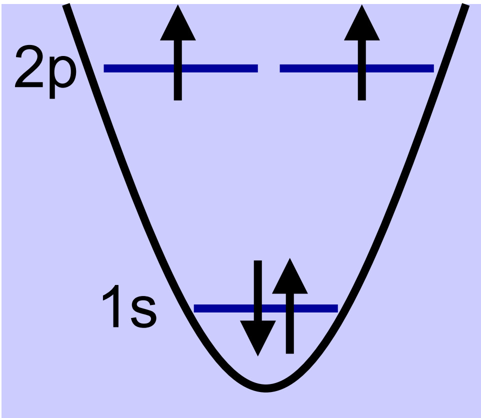






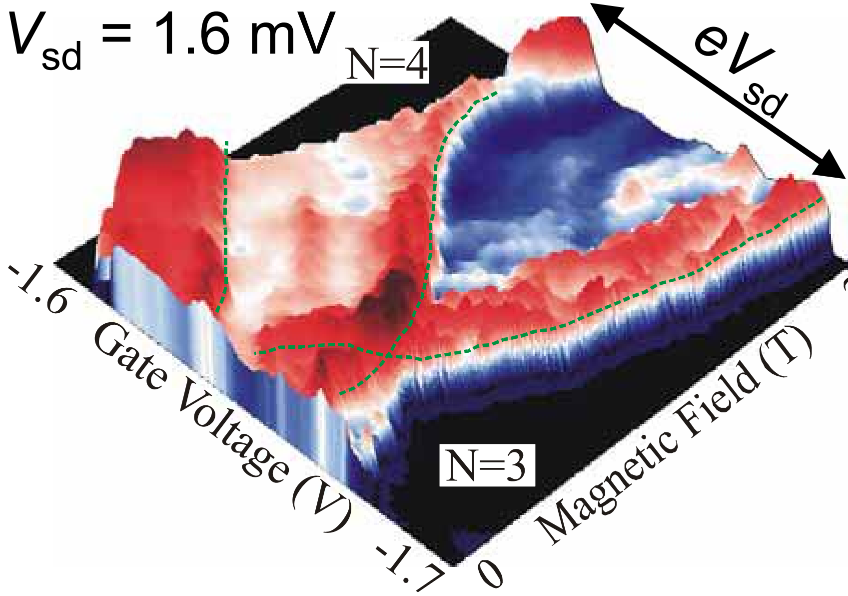
- Few-electron QDs are *artificial atoms*
- Change element by tuning V_g
- Full shell N = 2,6,12,20… (noble elements)
- Half-full shell N = 4,9,16…

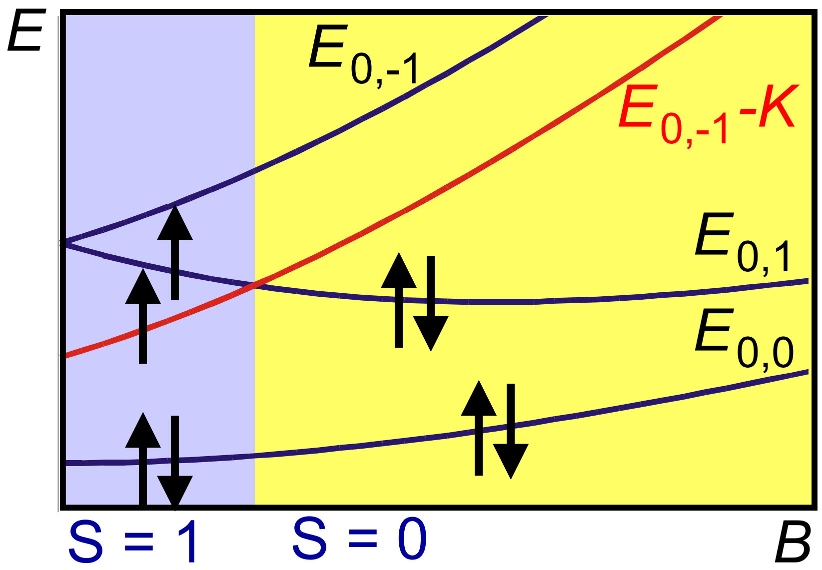
Hund's rule for N = 4



Half-filled shell for N=4,9,16,..

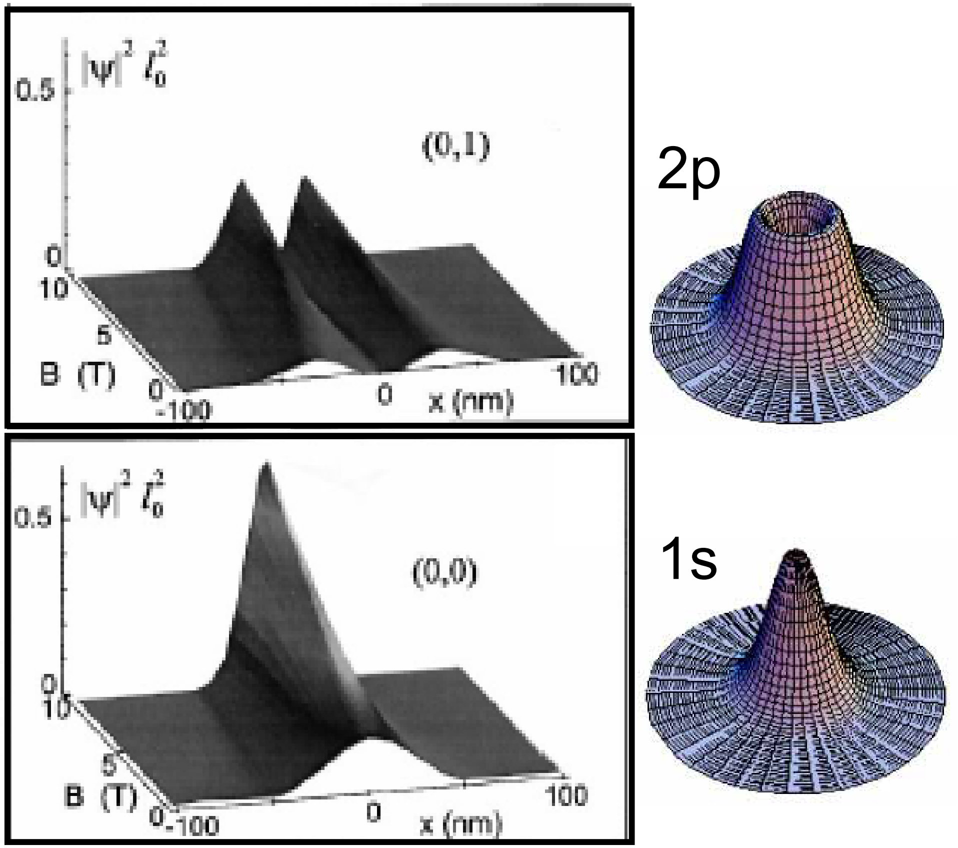
♥ total spin maximized (exchange)

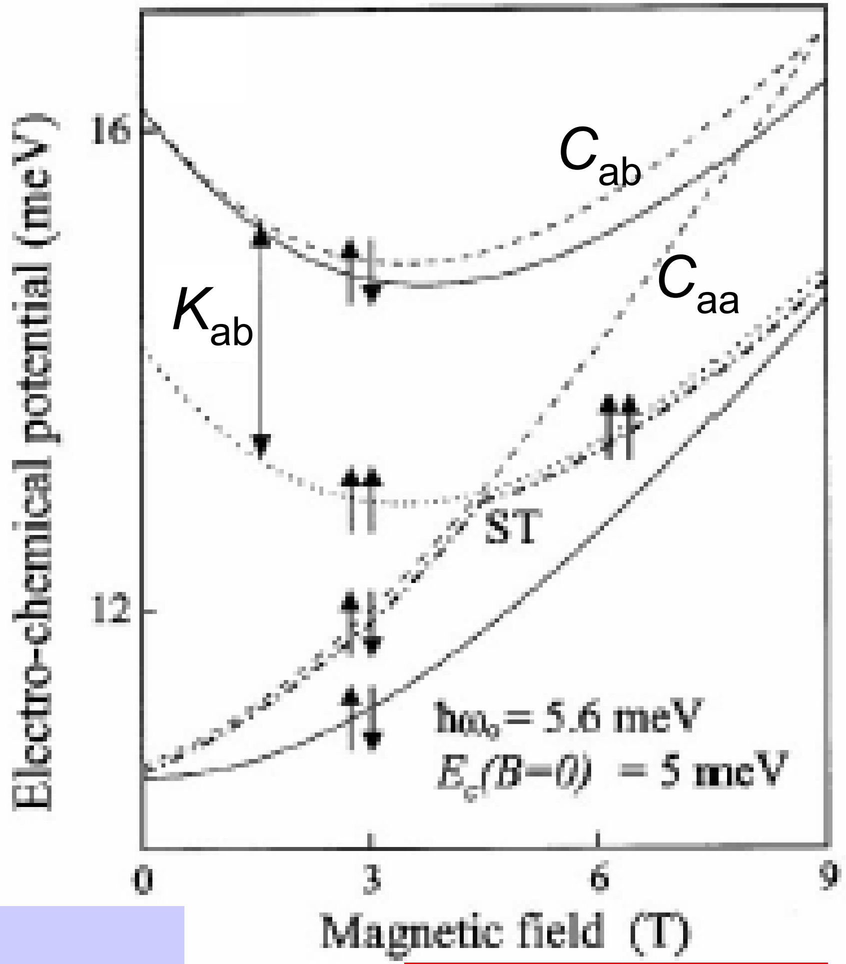




- Transition in angular momentum (l) accompanied by spin transition
- Exchange energy ~0.8 meV
- Spin states well described by 2-electron states (S and T)

Singlet-triplet transition for N = 2

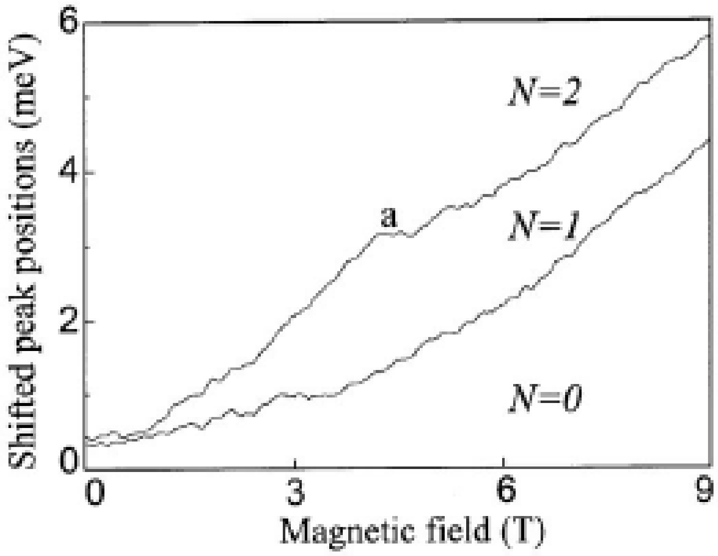




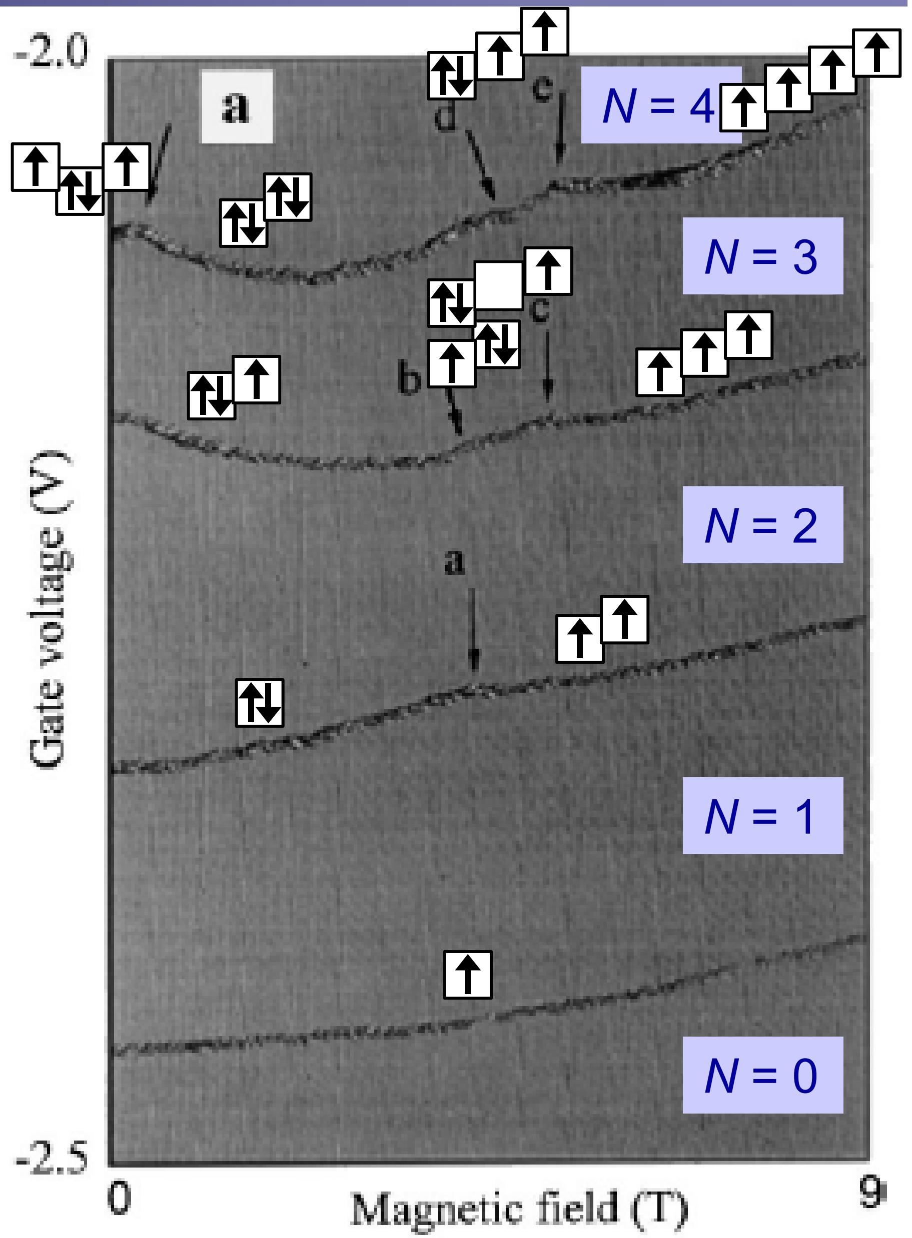
- $B_\perp$ shrinks wavefunction ♥ increases Coulomb interaction
- C_{aa} grows faster than C_{ab}
- Exchange interaction favors parallel spins

→ 2nd electron in 2p orbital to form triplet

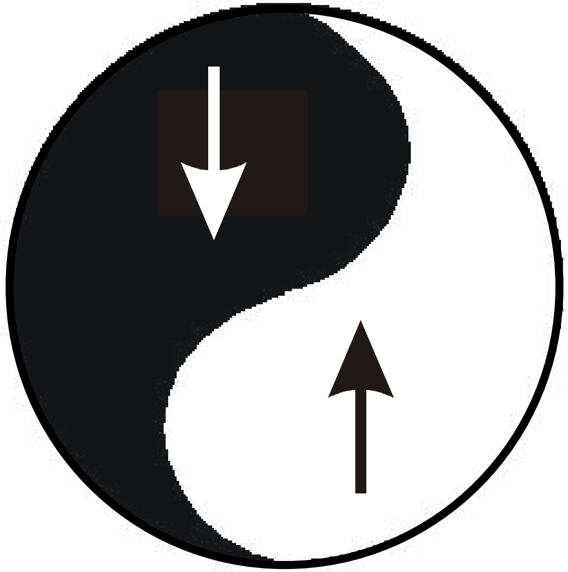
Spin transitions vs. B



- Spins gradually polarized as *B* increases
- Spin states more complicated as *N* increases
- ***Single-spin state (N = 1) always simple!***

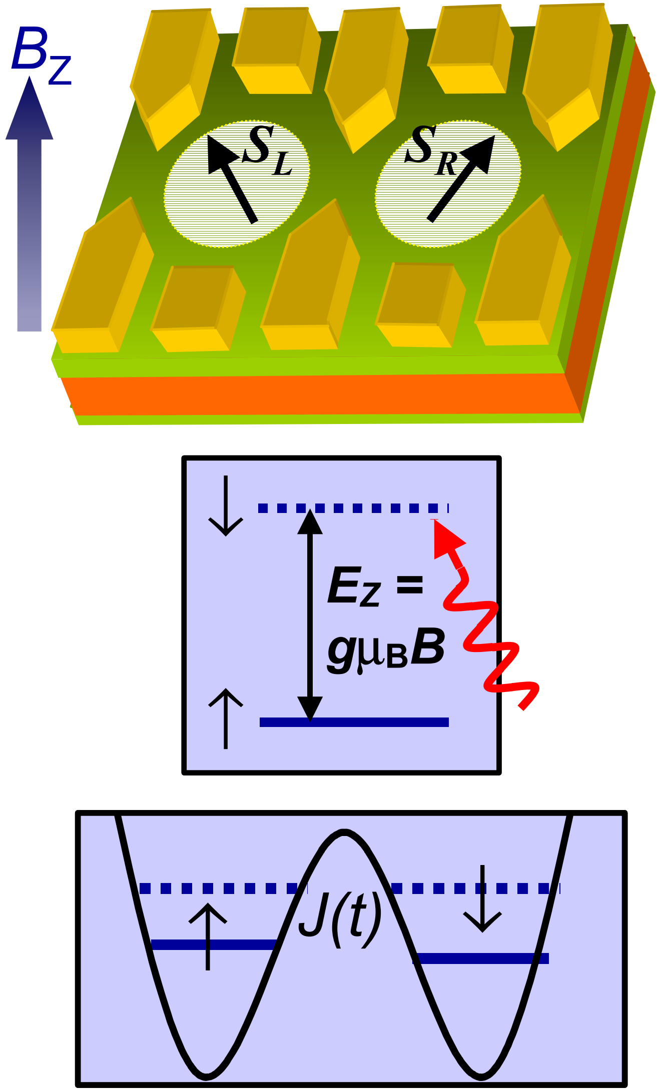


Part III: One-electron quantum dots as spin qubits



Spin qubits

Loss & DiVincenzo, PRA 57, 120 (1998)

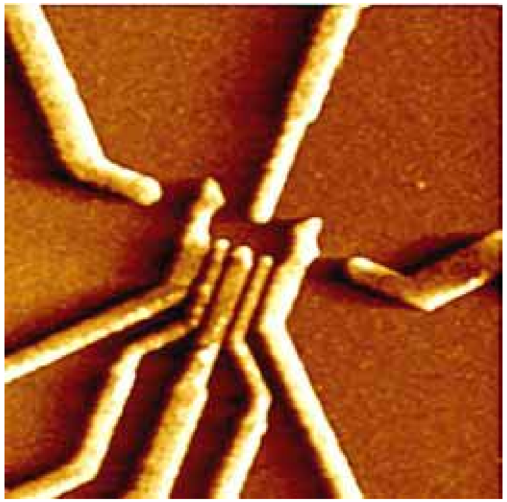


$$H_s(t) = J(t)\, \mathbf{S}_L \cdot \mathbf{S}_R$$

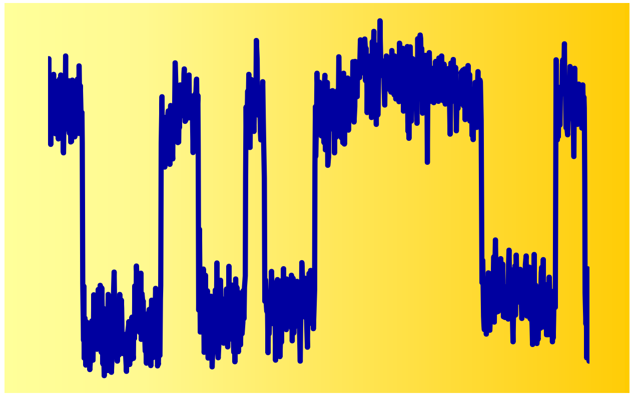
- Qubit defined by Zeeman-split levels of *single electron* in quantum dot
- 1-qubit control:
    - magnetic (ESR-field)
    - electric (modulate effective g-factor)
- 2-qubit coupling: electric (exchange interaction between dots)
- ***Read-out of the qubit state!***

We need…

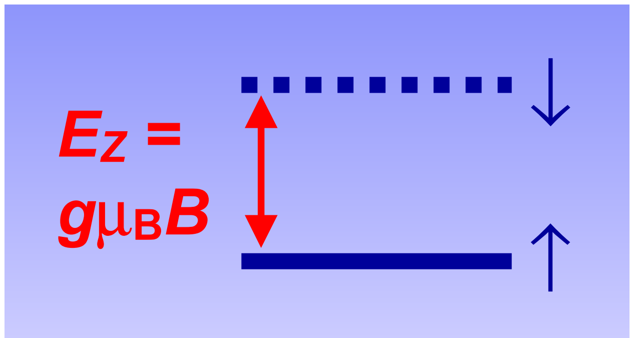
one-electron
double dots…



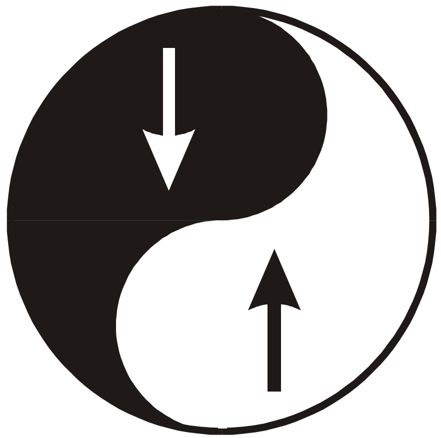
…fast charge
detection…



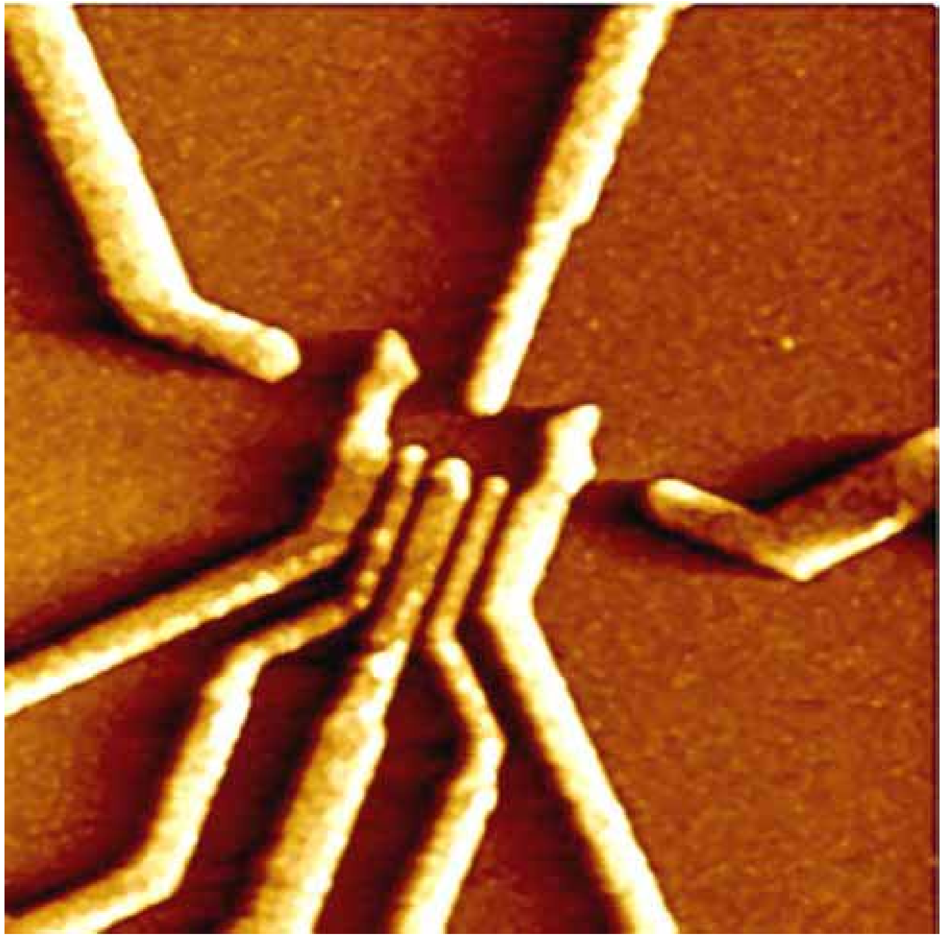
…two-level
system…



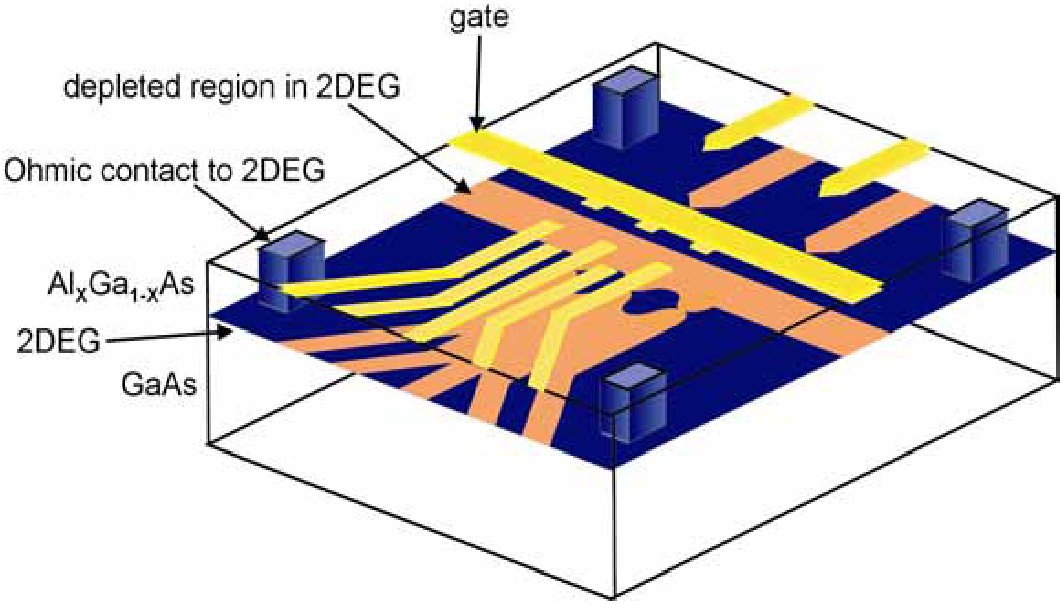
**….single spin
measurement!**

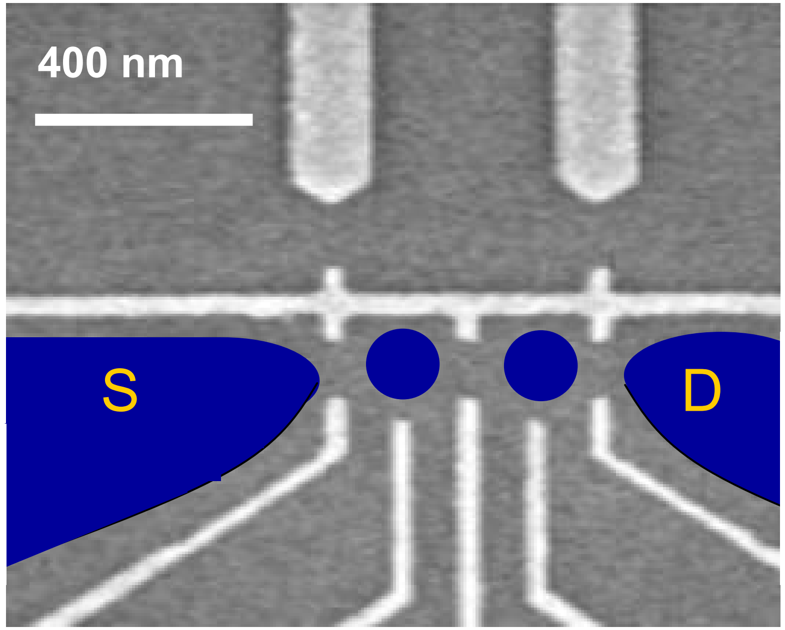


Few-electron quantum dot circuit with integrated charge detector



N = 1 in lateral quantum dots?





- High-mobility 2DEG (~10^6 cm^2/ Vs)
- Density ~10^{11} cm^{-2} ♥ λ_F ~ 30 nm
- Smallest gate structure ~ 40 nm
- Dot size ~ 200 nm

♥ discrete energy spectrum

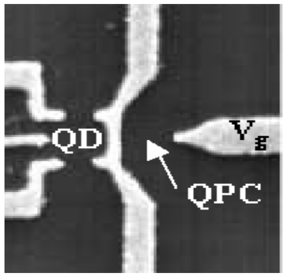
BUT: Barriers close as dot is depleted ♥ current too small to measure!

Lateral few-electron double dot

few-electron single dot

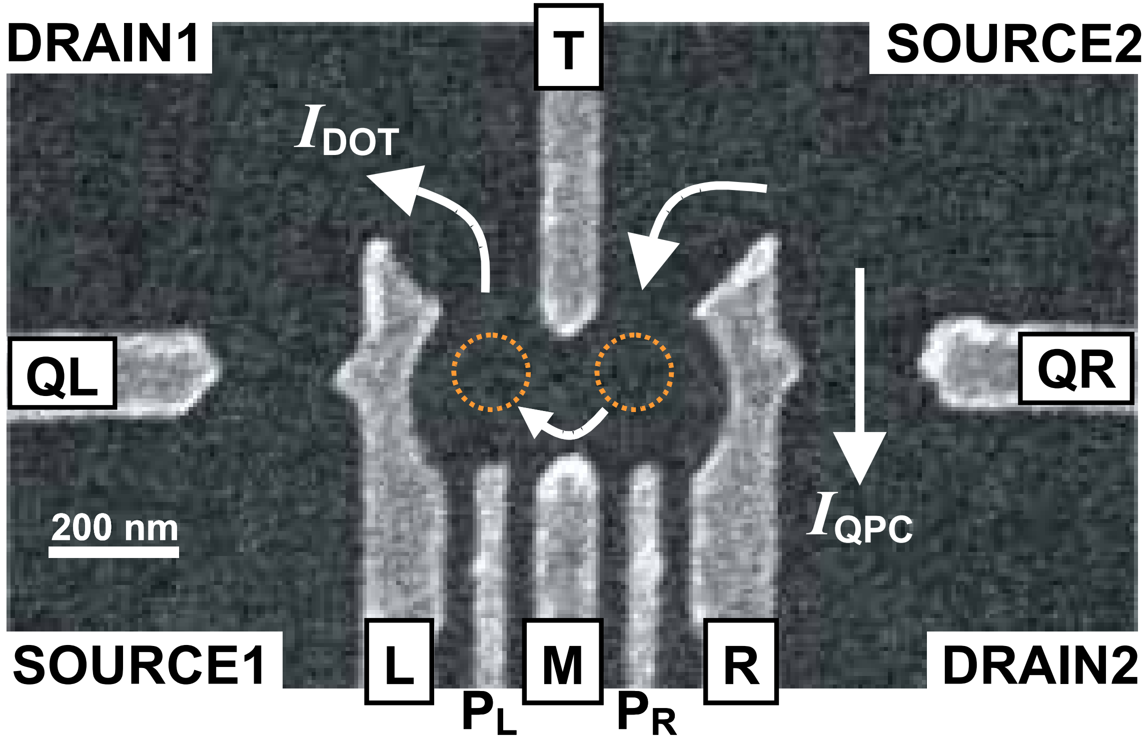
Ciorga '99

QPC charge detector



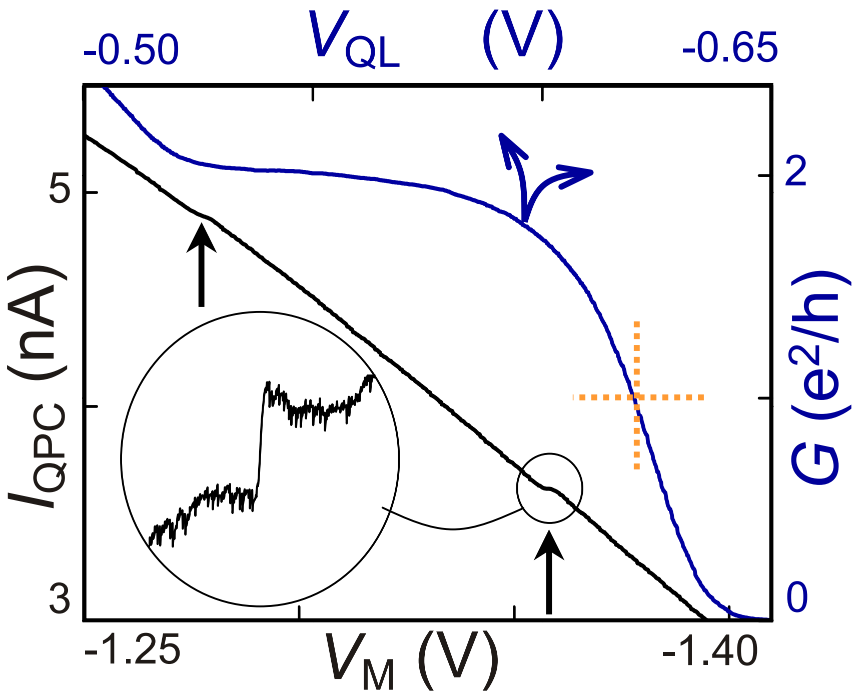
Field '93
Sprinzak '01

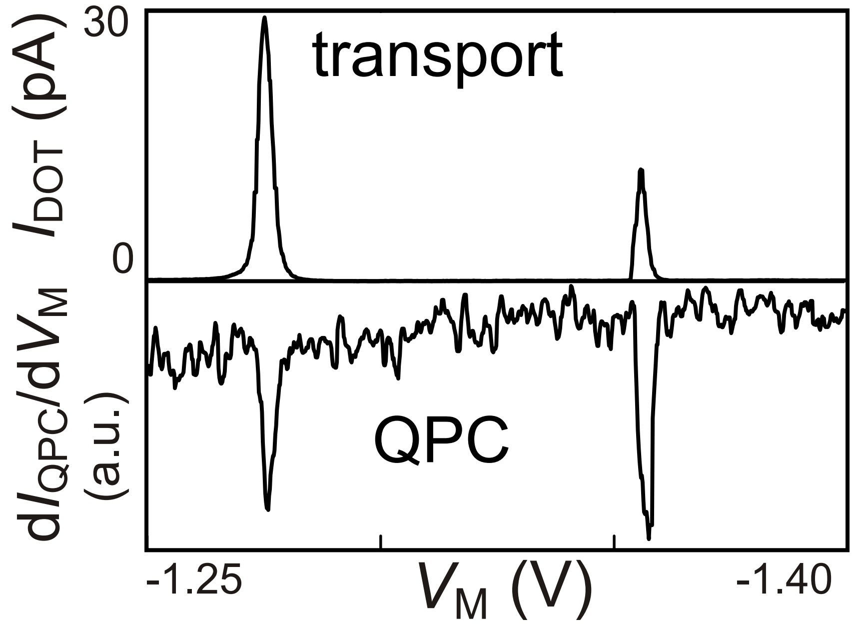
GaAs/$Al_{0.27}Ga_{0.73}As$ heterostructure
2DEG 90 nm deep, $n_s = 2.9 \times 10^{11}$ cm^{-2}



Design: barriers don't close as DQD is depleted

QPC - detector for single dot

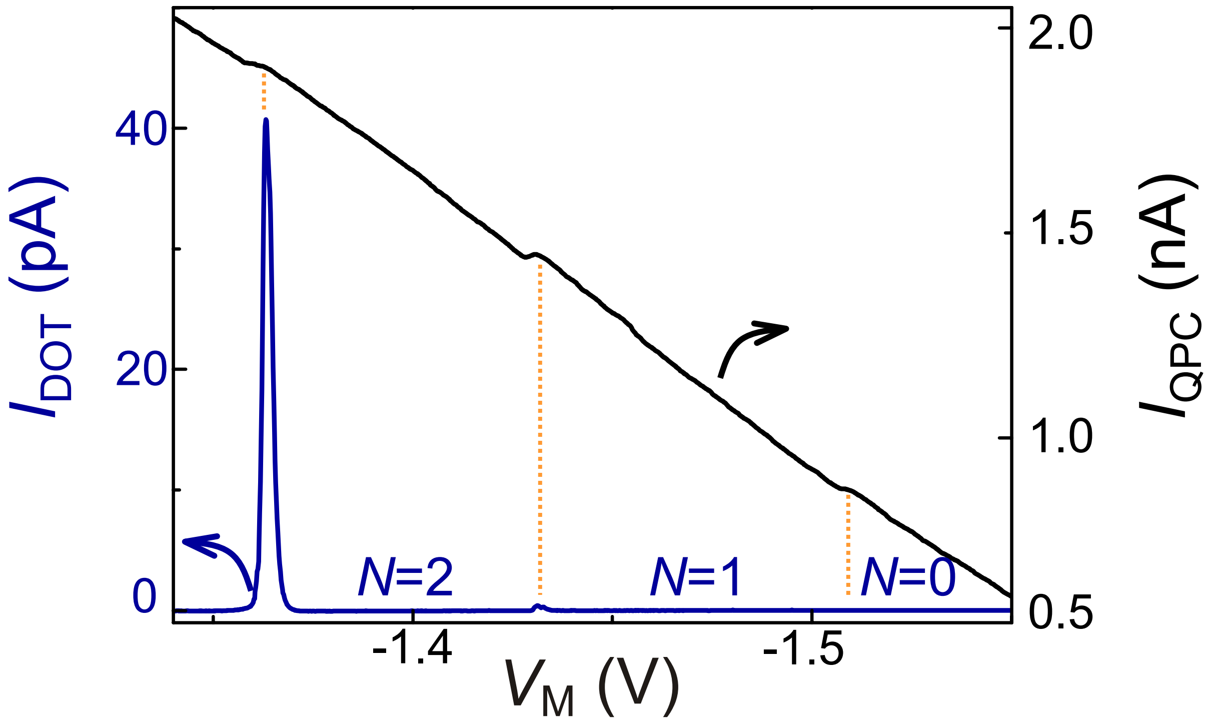




- Tune to steepest point ($G \sim e^2/h$)
- Jumps in I_{QPC} ♥ change in electron number

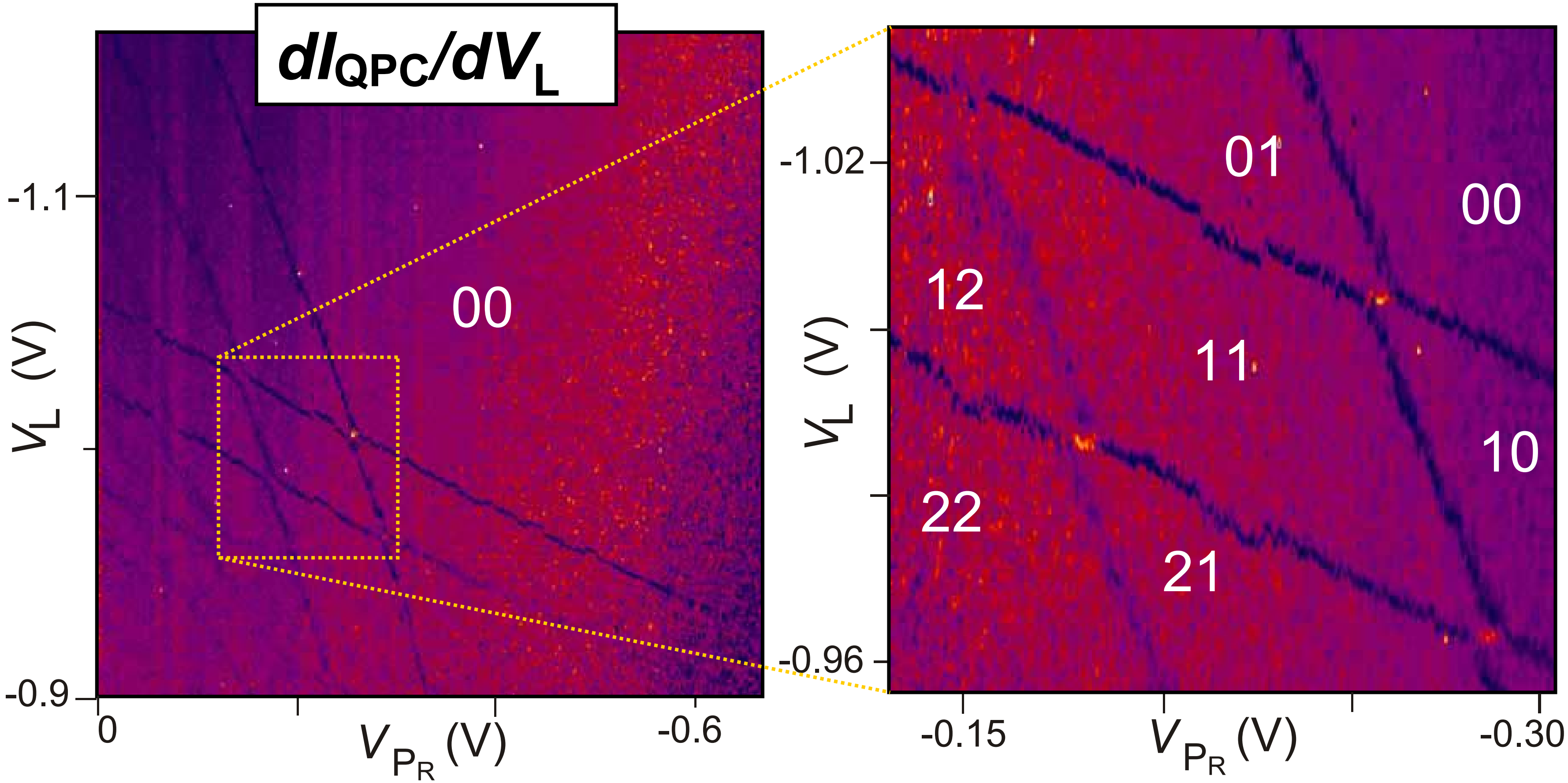
- Modulate V_M with lock-in
  ♥ measure dI_{QPC} / dV_M
- **Dips in QPC-signal coincide with Coulomb peaks in transport!**
- Sensitivity ~0.1e (at 17 Hz)

QPC - detector for isolated single dot



QPC can detect charge transitions in *isolated* QD!

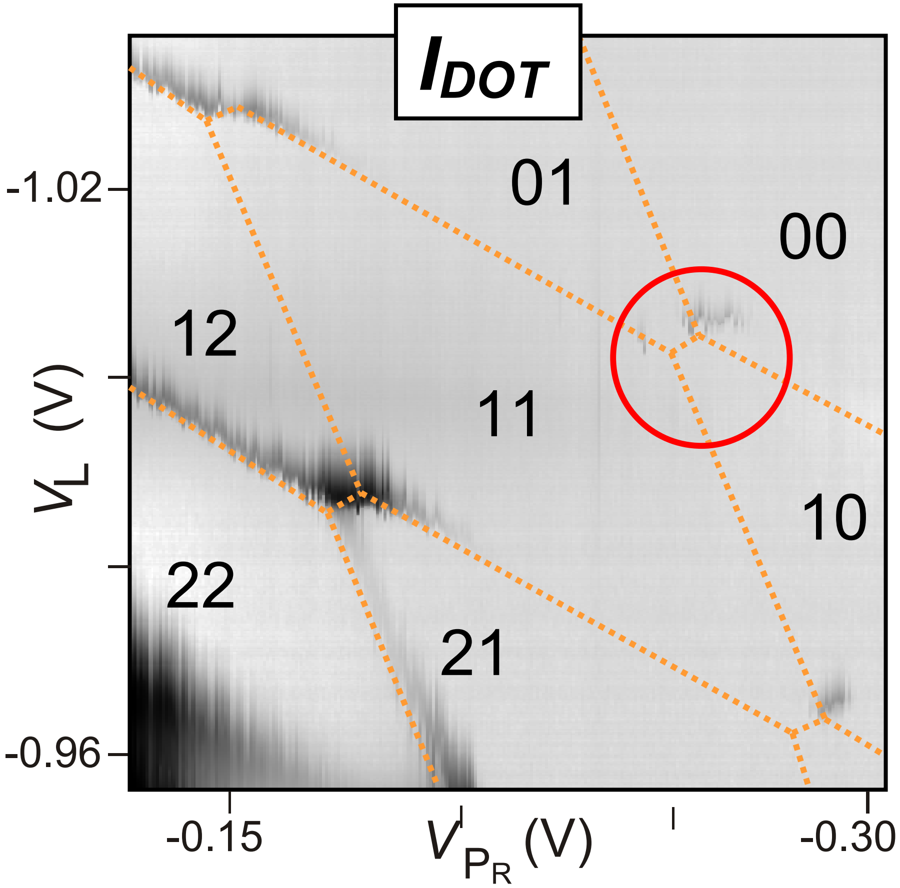
QPC - detector for double dot



- **Double dot emptied completely !**
- E_C = 4.5 meV

QPC detects *all* charge transitions, also between dots

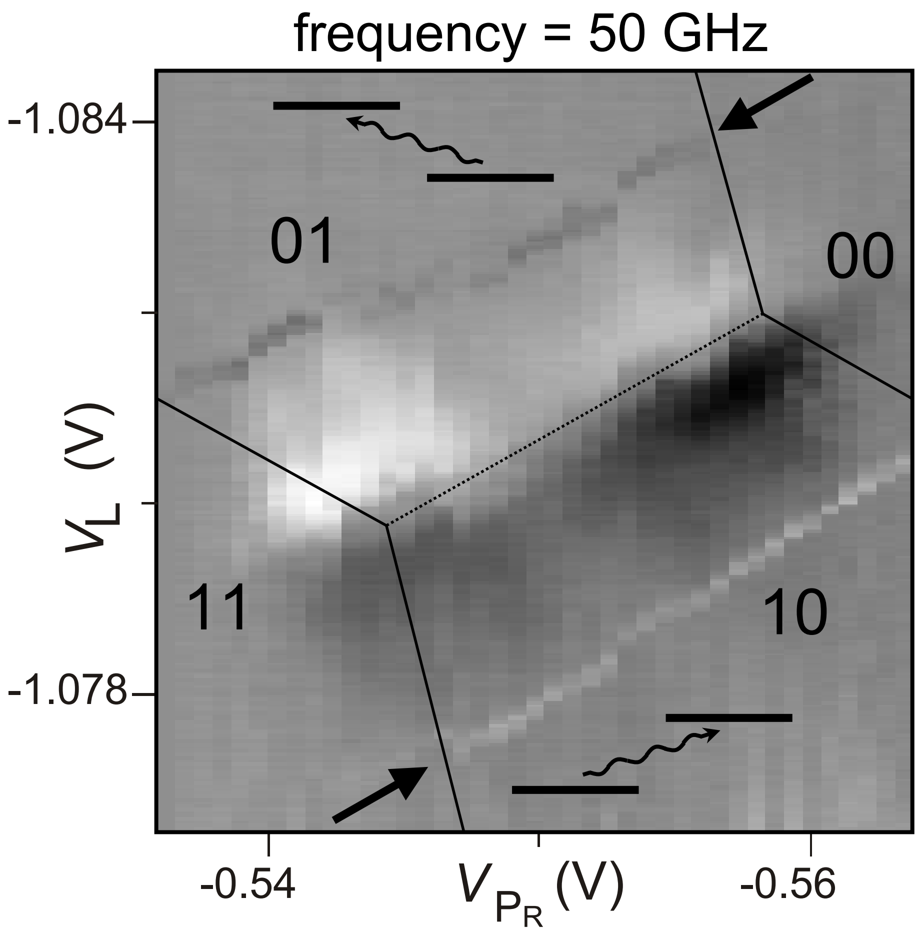
Tunable few-electron double dot

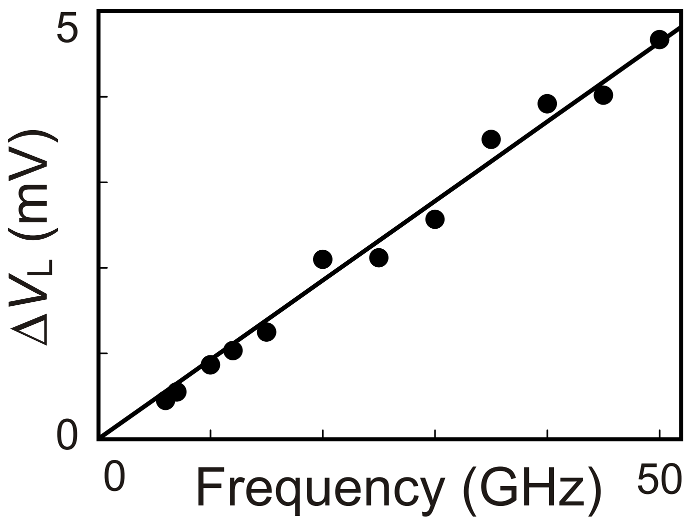


All triple points visible
♥ ***barriers still open***

Double dot
fully tunable!

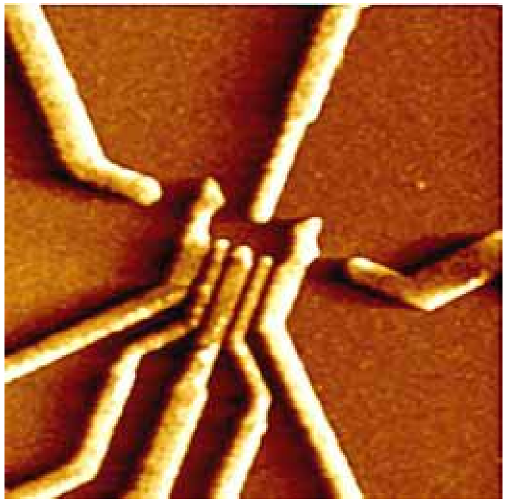
Photon-assisted tunneling





- Photon-assisted current visible for $f > 6$ GHz
- Always linear ♥ coherent coupling between two dots not visible

Summary…



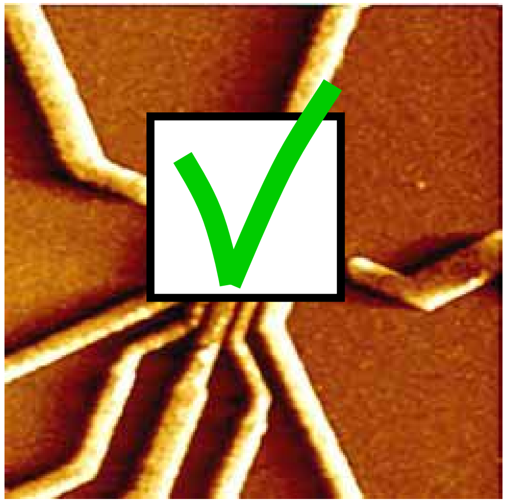
We can:

- **isolate *single electron spin* in (double) quantum dot**
- **study it using transport or charge detection**

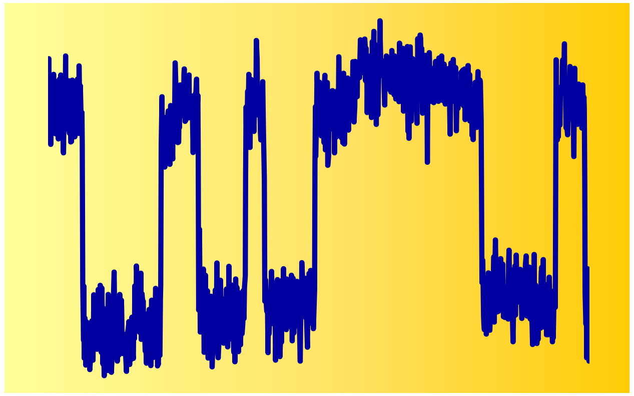
PRB 67, 161308(R) (2003)

We need…

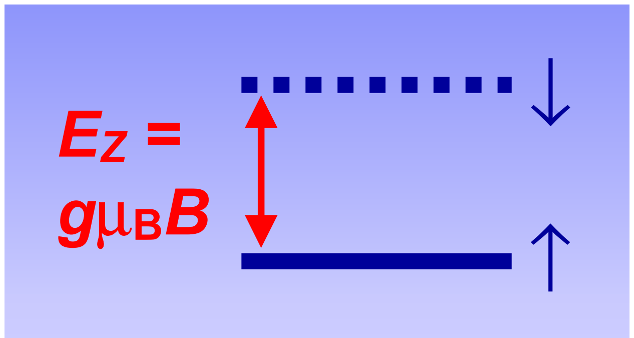
one-electron
double dots…



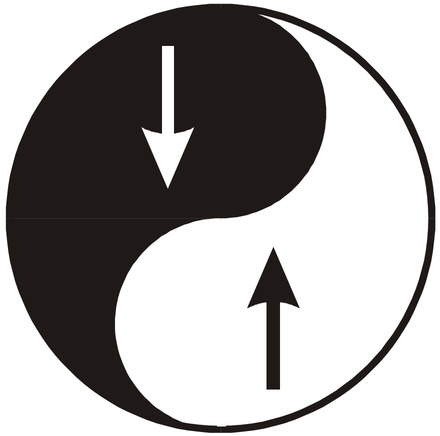
…fast charge
detection…



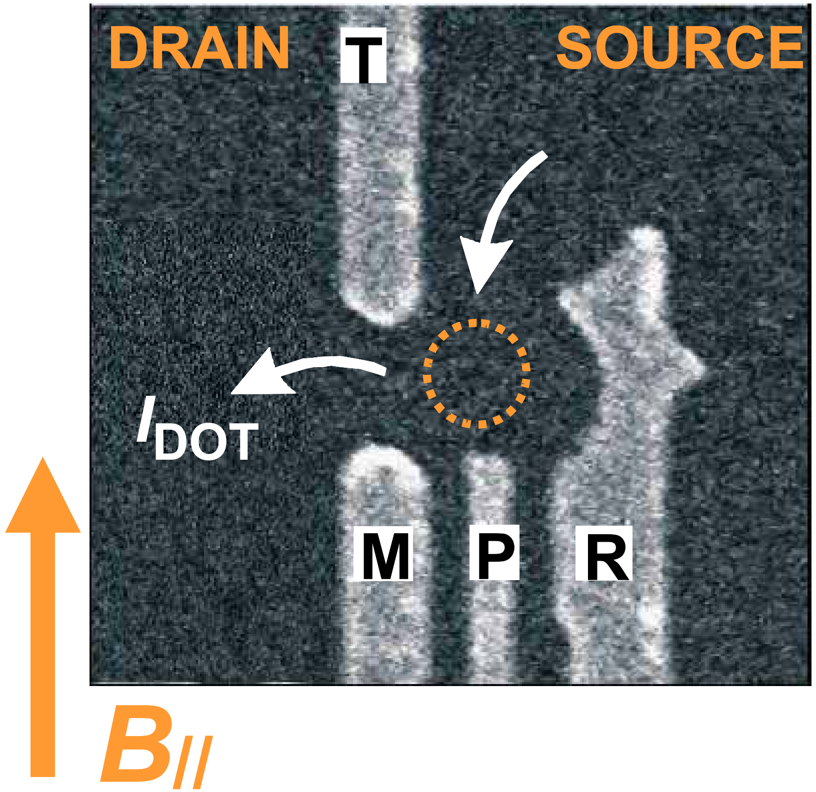
…two-level
system…



….single spin
measurement!

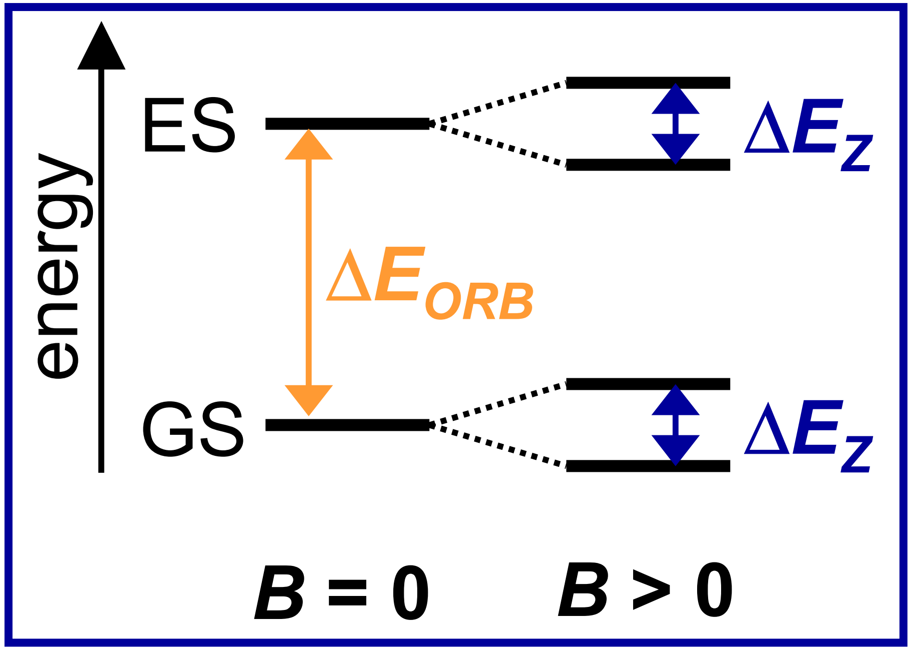


Zeeman splitting in an artificial Hydrogen atom

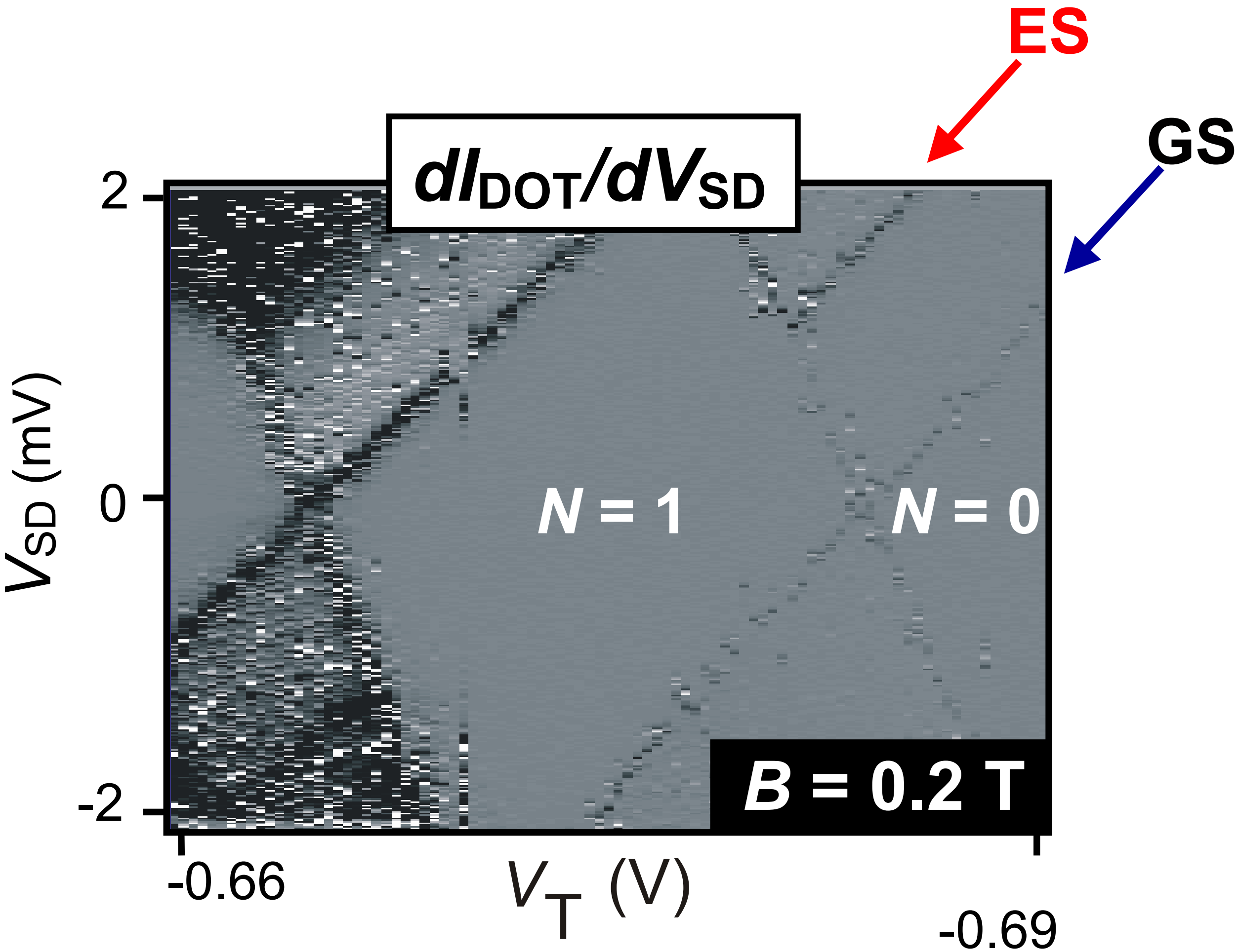


Similar double dot device: other gates grounded

magnetic field *parallel* to 2DEG

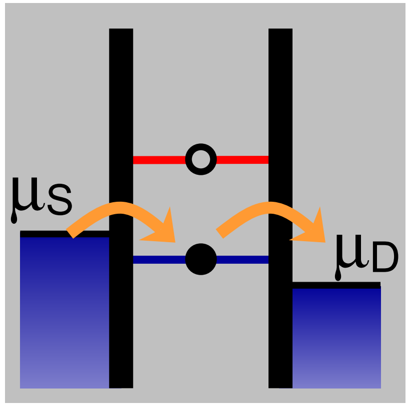


N = 1 Coulomb diamond

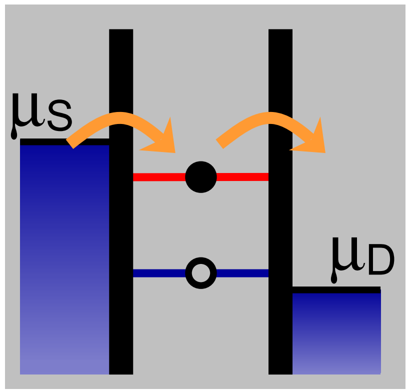


Large-bias spectroscopy reveals excited states

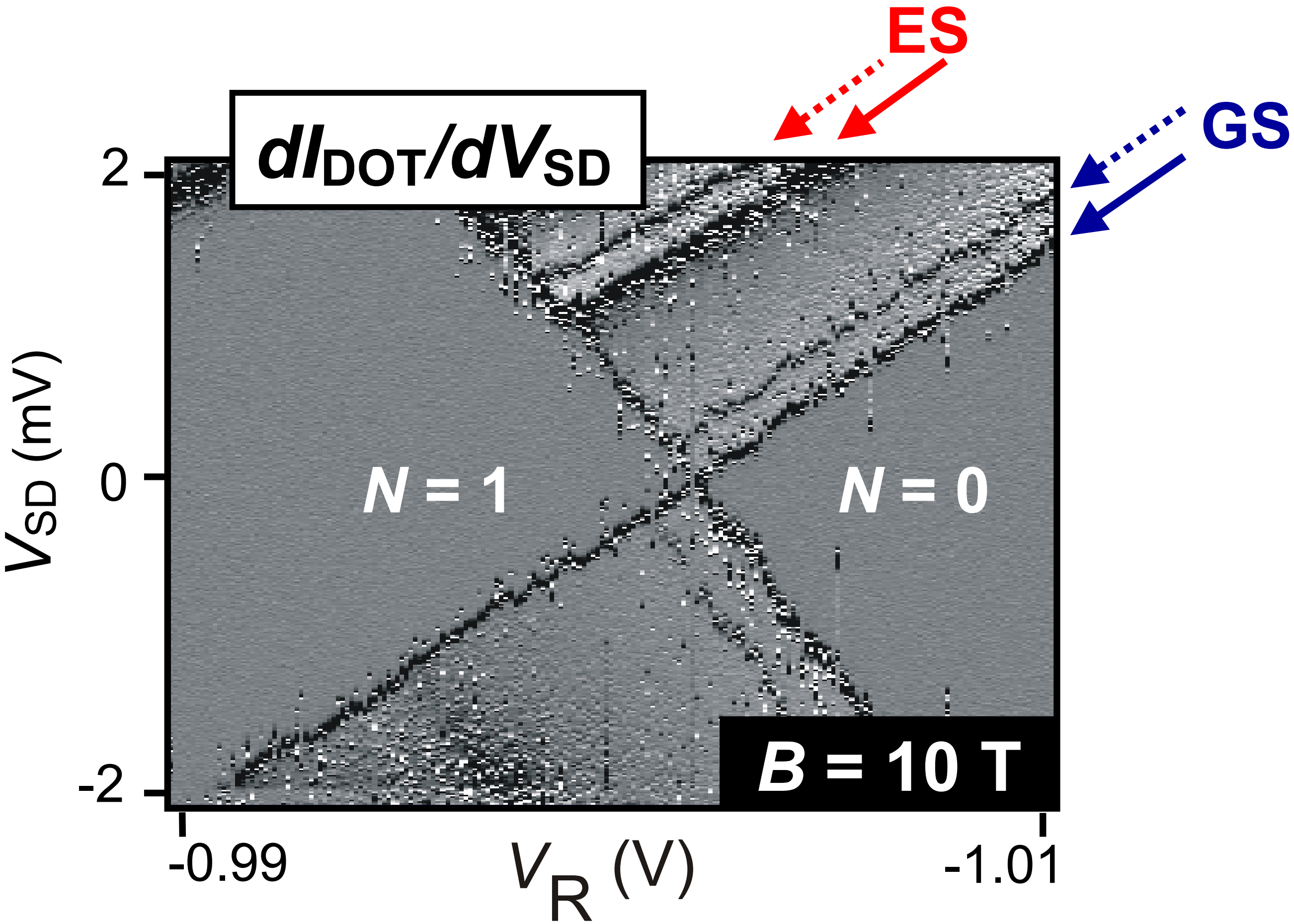
N = 1 orbital ground state

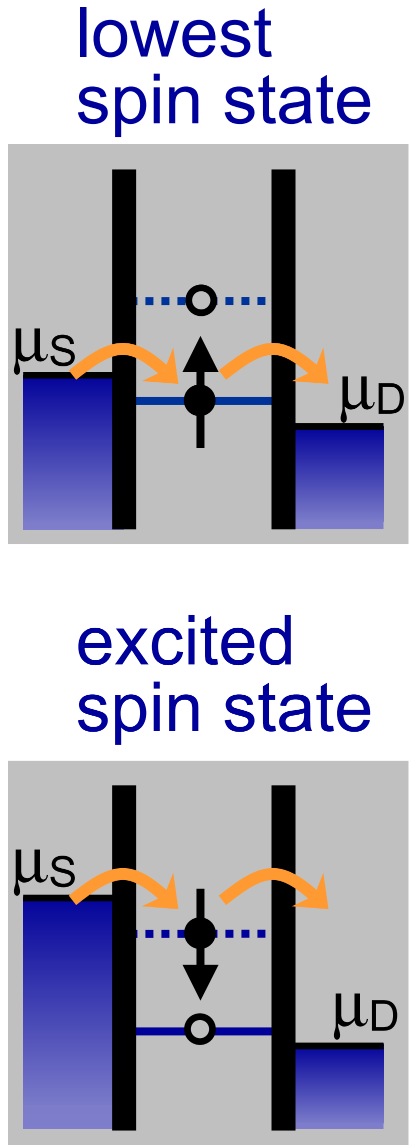


N = 1 orbital excited state



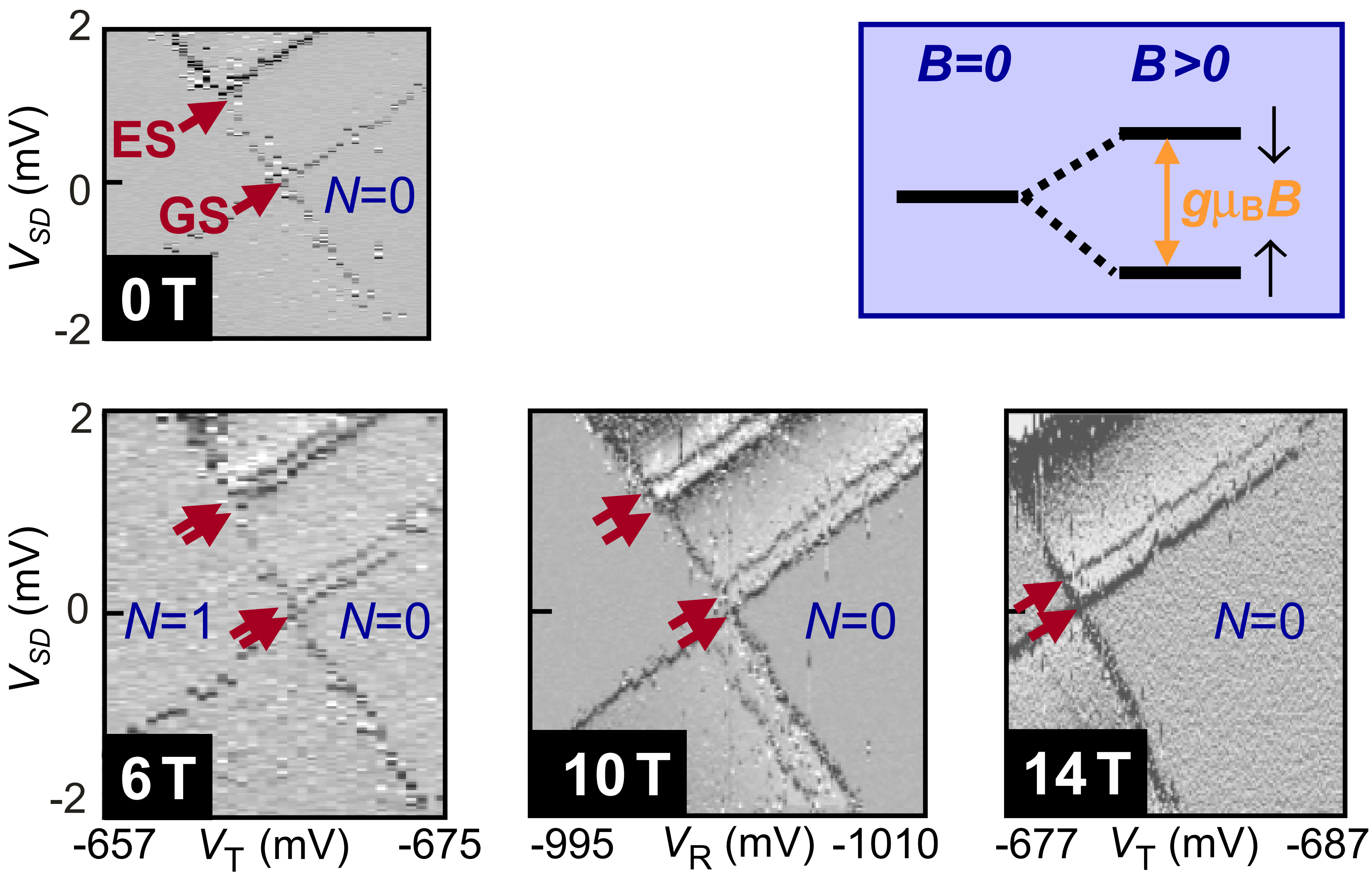
N = 1 Zeeman splitting in $B_{//}$



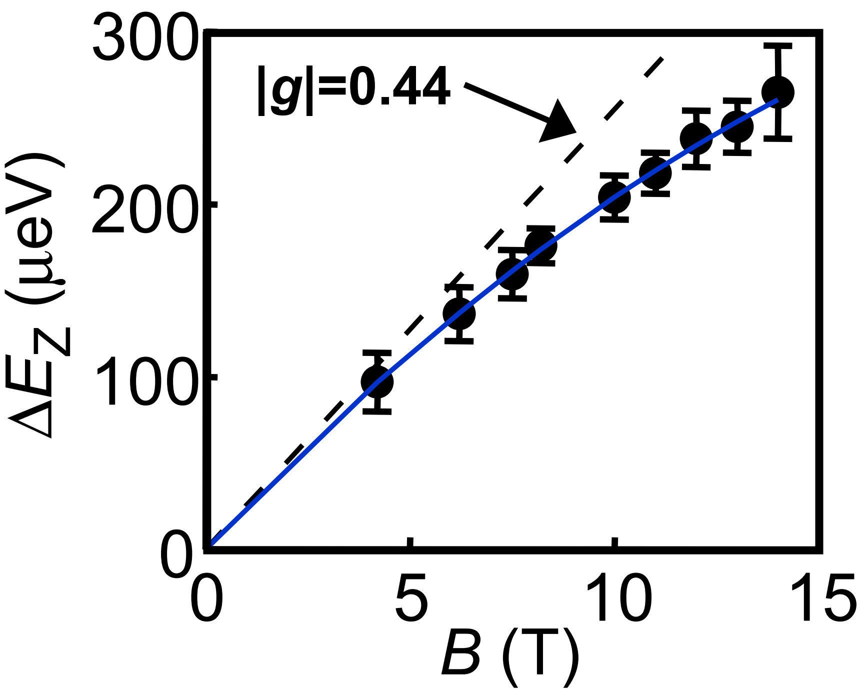


Zeeman splitting clearly visible for GS and ES !

N = 1 Zeeman splitting in $B_{//}$



Spectroscopy of qubit 2-level system

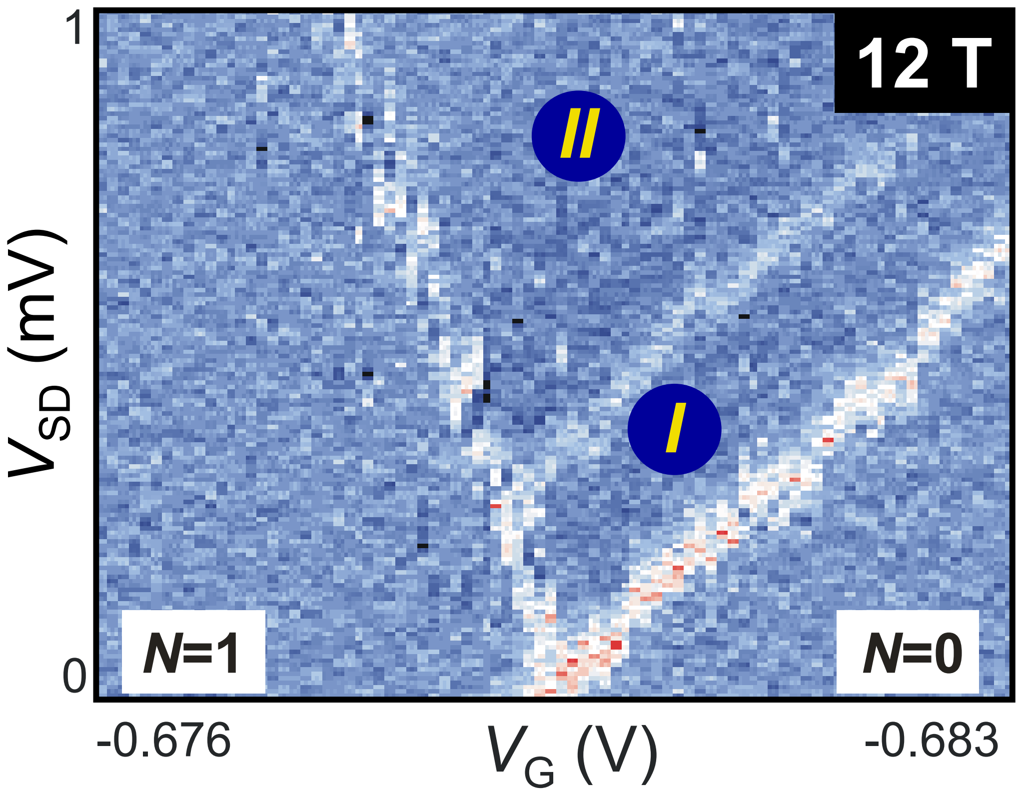


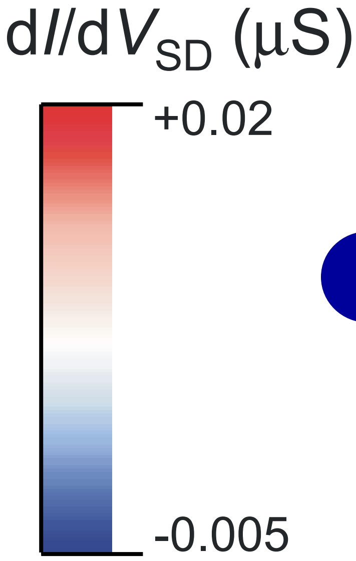
$E_Z = g\ \mu_B B_{//}$

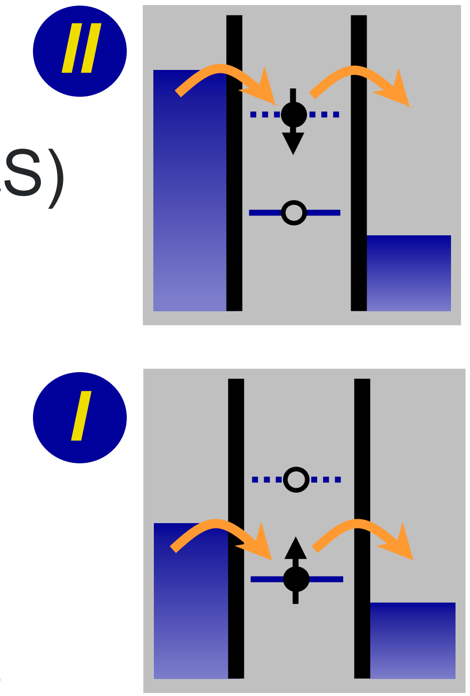
$|g| = 0.43 - 0.008B$

N = 1 dot as filter for spin-up

theory: Recher *et al.*, PRL 85,1962 (2000)



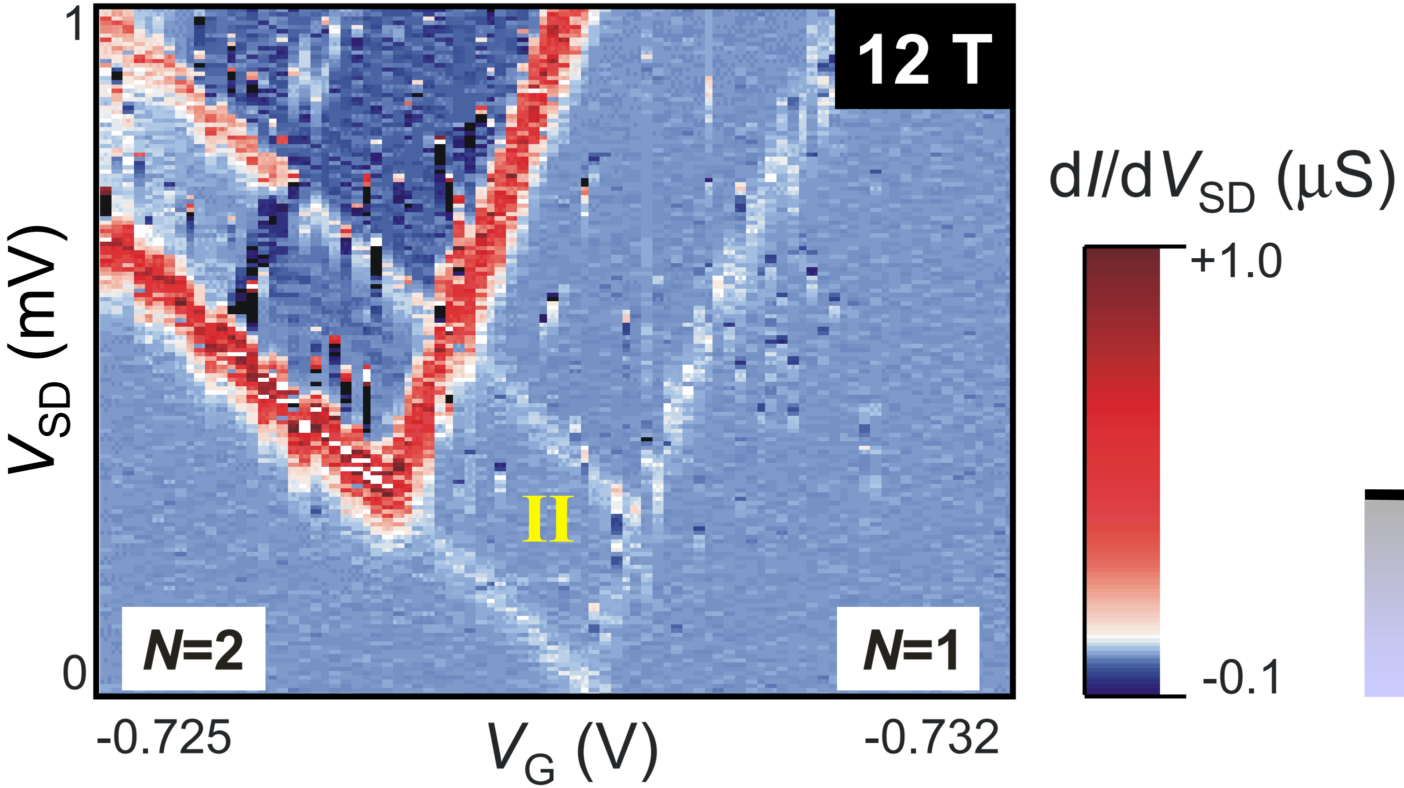


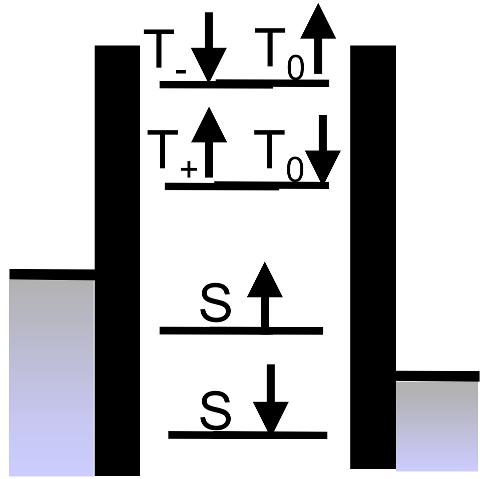


Quantum dot in region I acts as *spin filter*; only spin-up electrons can pass through

N = 2 dot as filter for spin-down

theory: Recher *et al.*, PRL 85,1962 (2000)





Quantum dot in region II acts as *spin filter*; only **spin-down** electrons can pass through

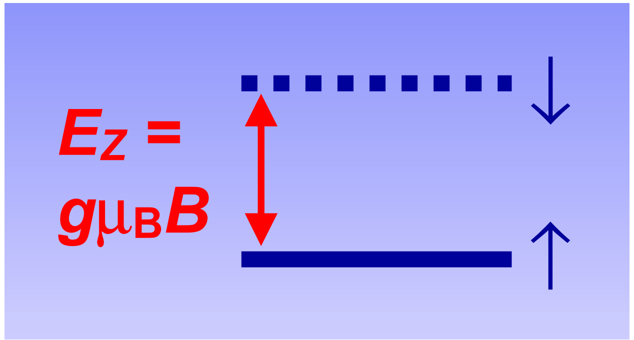
Summary…

We have:

- **identified (stable) two-level system**
- **(T_1 > 50 μs)**
- **bipolar spin filter**

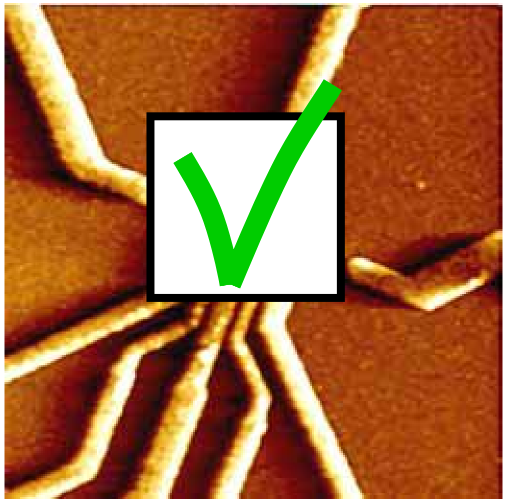
Hanson *et al.*, PRL 91, 196802 (2003)

Cond-mat/0311414

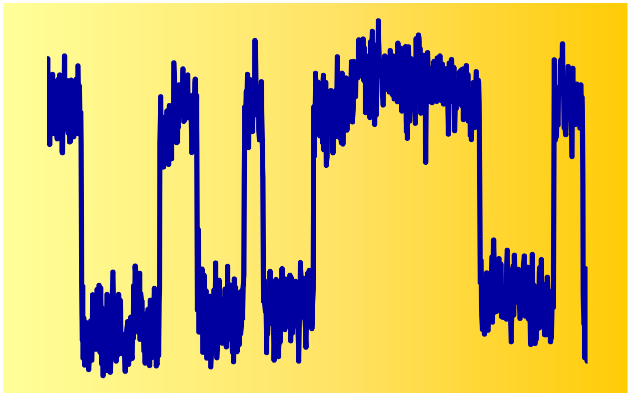


We need…

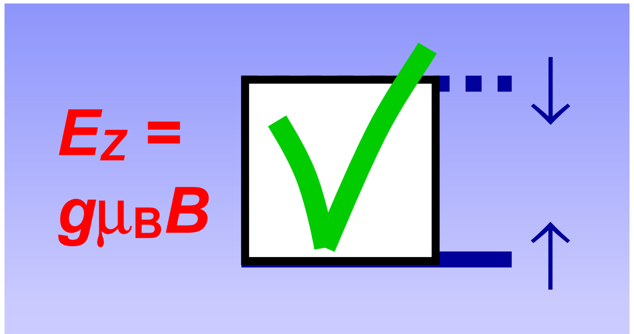
one-electron
double dots…



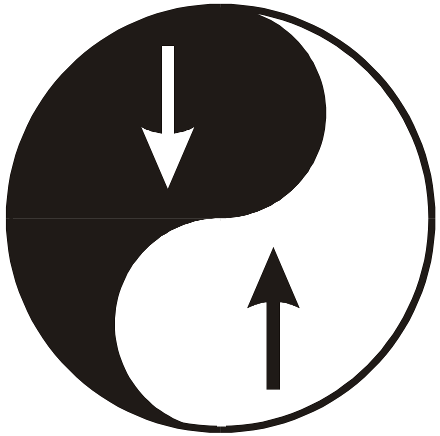
…fast charge
detection…



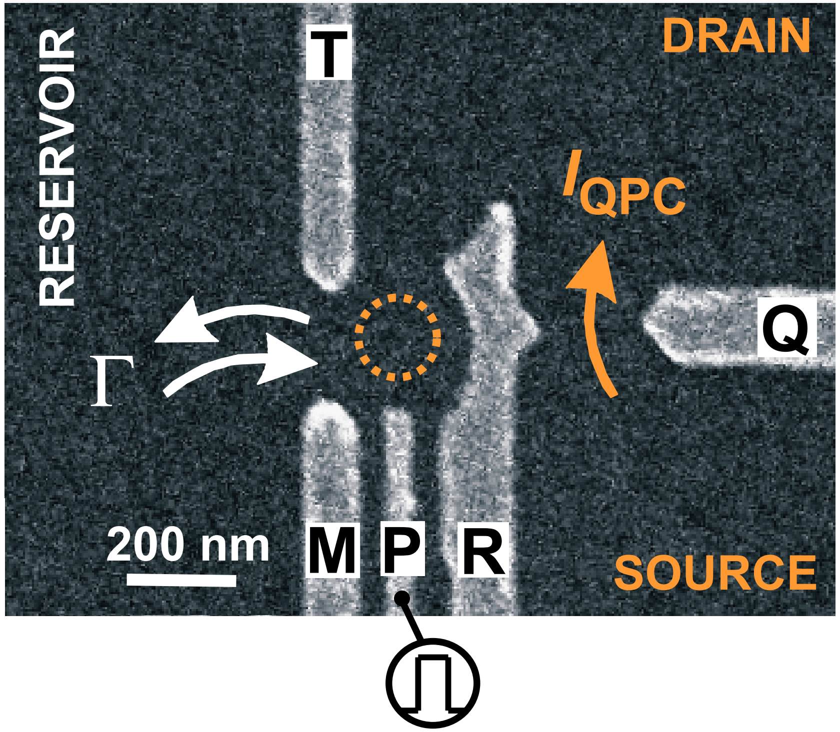
…two-level
system…

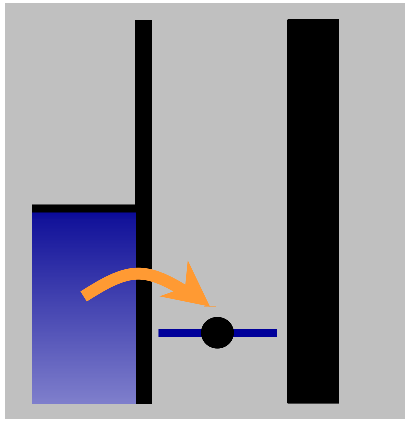


….single spin
measurement!



Quantum Point Contact as a fast charge detector

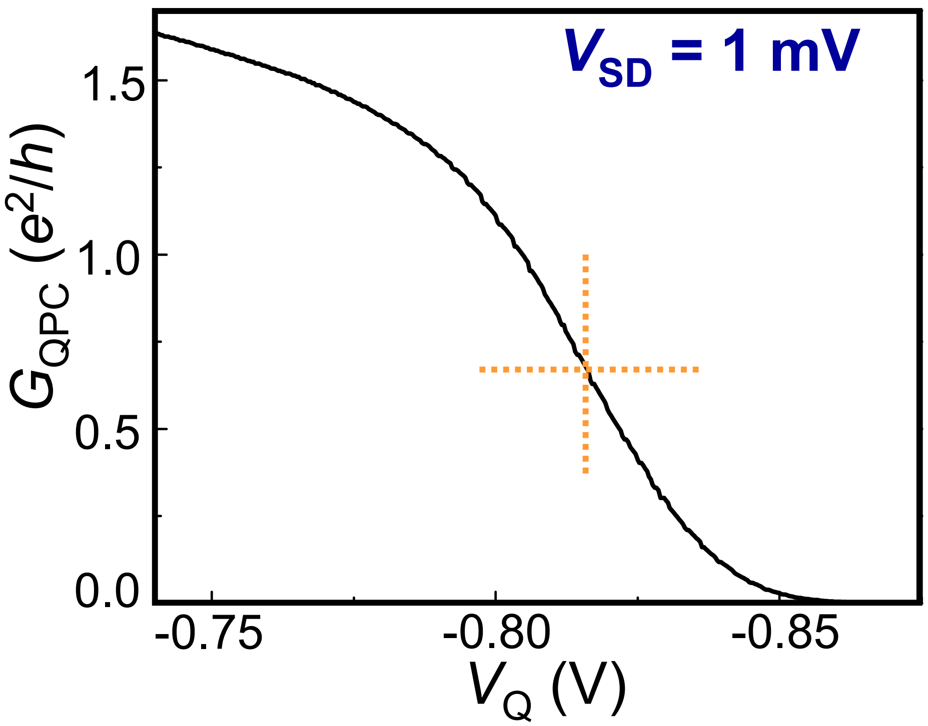


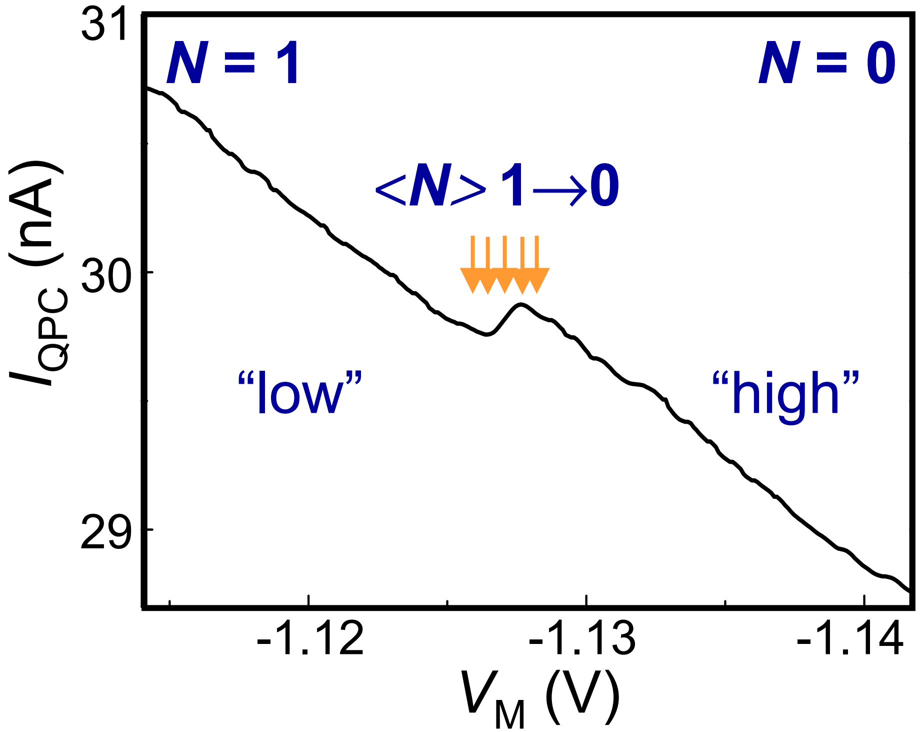


- Tunnel barrier to QPC-channel closed completely
- QD weakly connected to reservoir
- Detect individual tunnel events

- Fast IV-converter: 100 kHz, 0.8nV/Hz$^{1/2}$
- Fast ISO-amp: 300 kHz
- Operating bandwidth: 40 kHz
- Shot noise limit: 100 MHz

QPC average charge detection (dc)

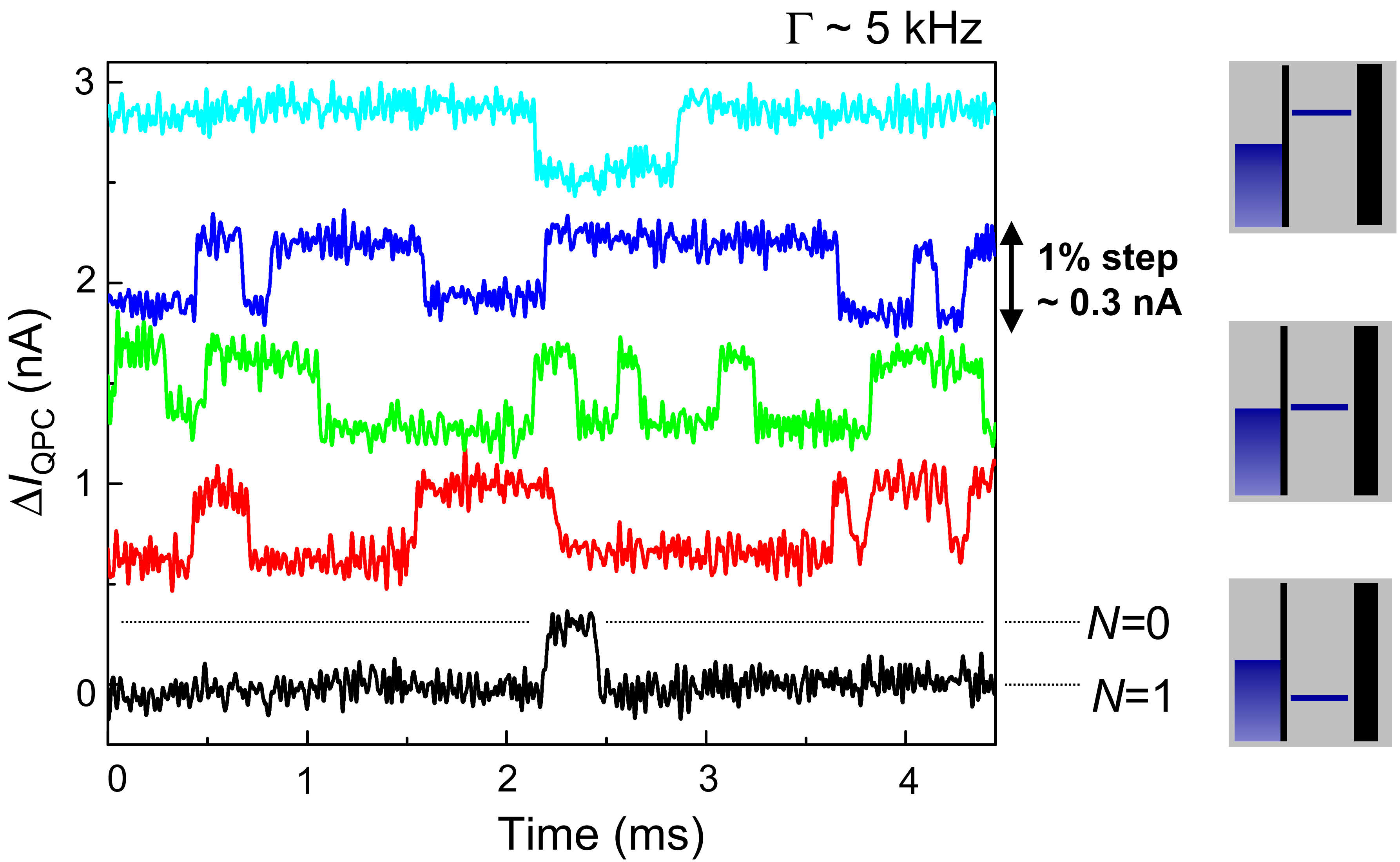




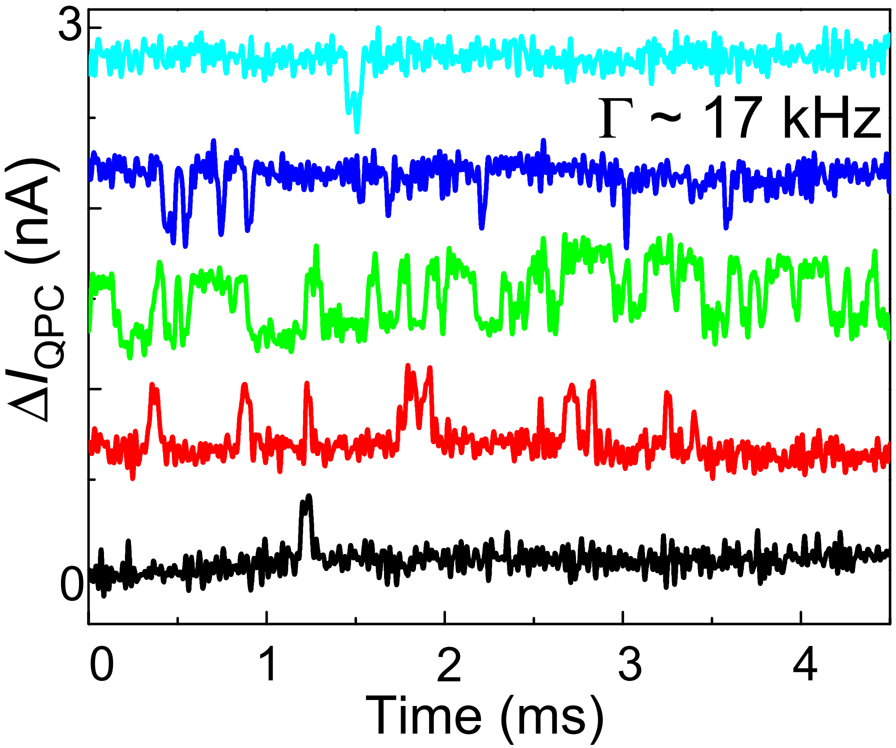
- $V_{SD} = 1$ mV
- $G_{QPC} \sim 0.5 - 1.0\ e^2/h$
- $I_{QPC} \approx 30$ nA

- Sweep dot-gate (V_M)
- I_{QPC} increases (~1%) when <*N*> from 1 to 0

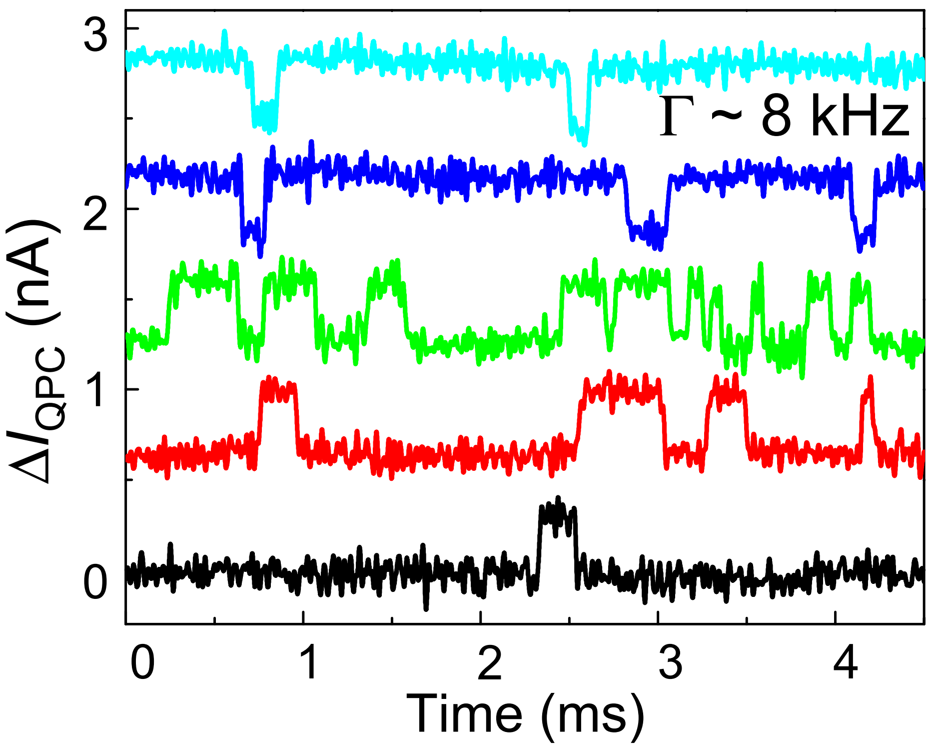
Real-time single-electron tunneling



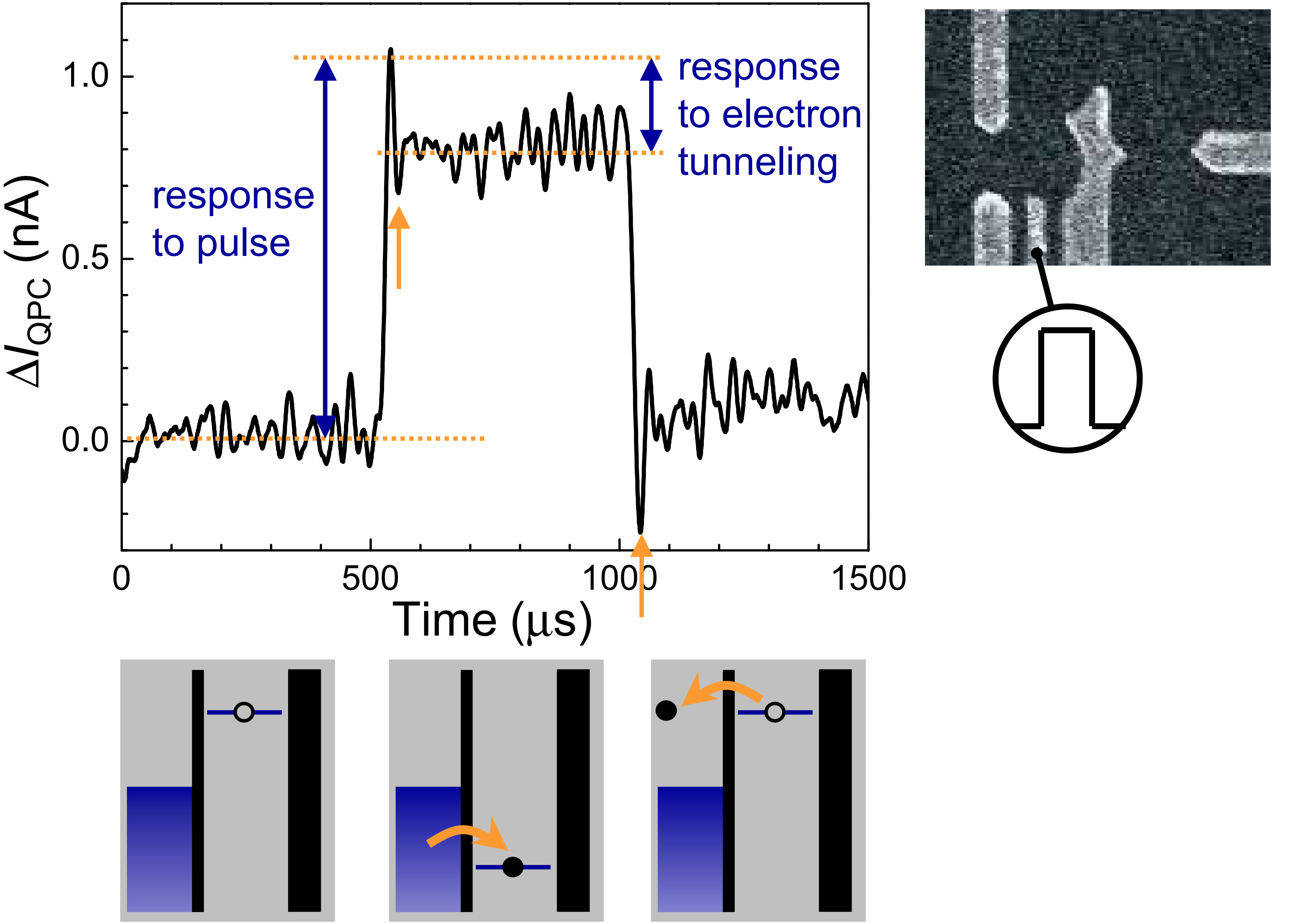
Real-time single-electron tunneling



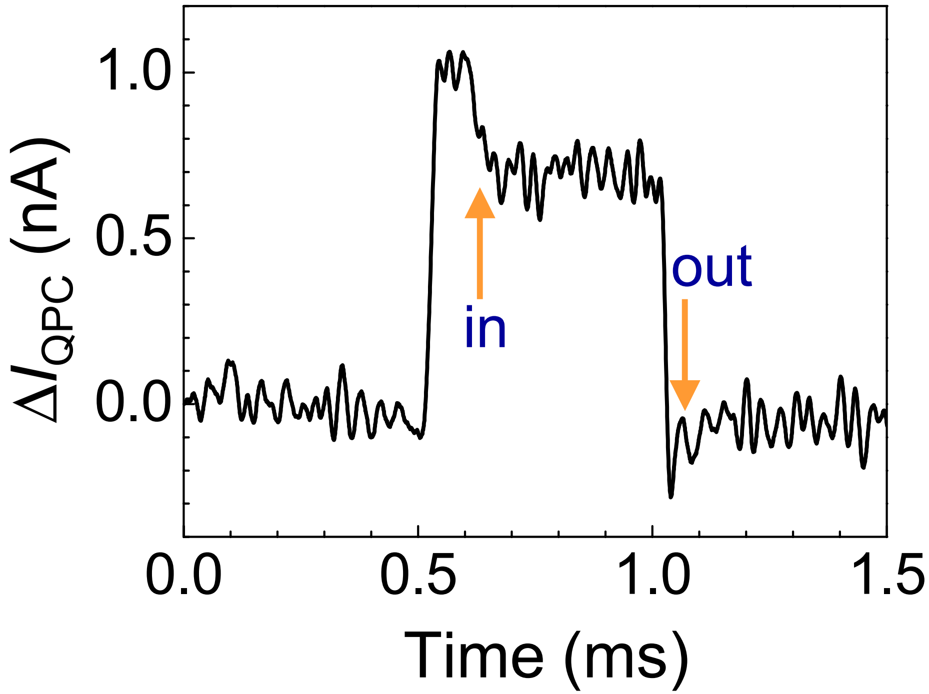
- V_{SD} = 1 mV
- I_{QPC} ~ 30 nA
- ΔI_{QPC} ~ 1%
- speed ~ 10 μs
- sensitivity ~ 10^{-3} e (Hz)$^{-1/2}$

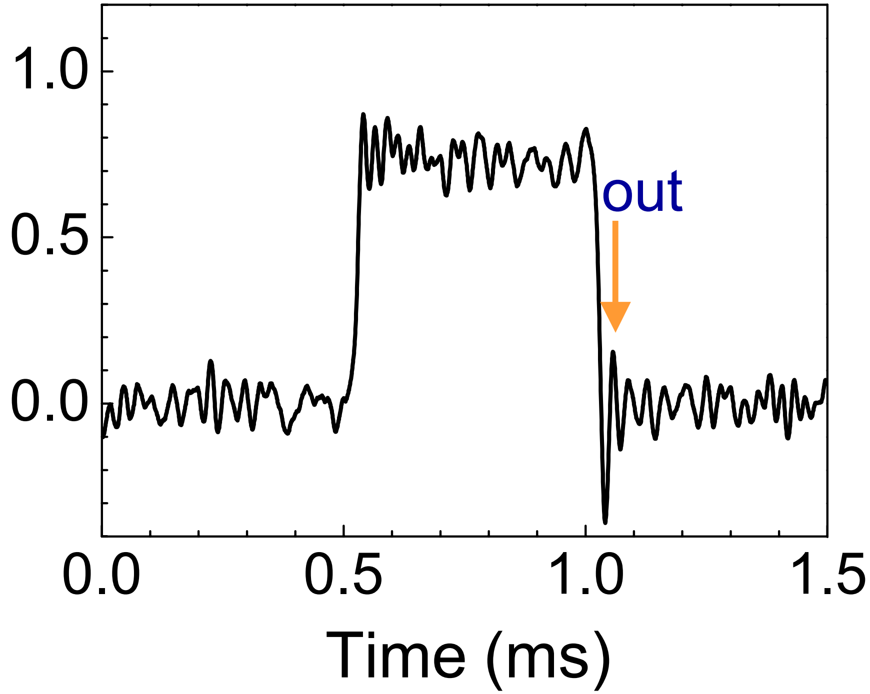


Tunneling induced by pulse



Tunnel-time is stochastic

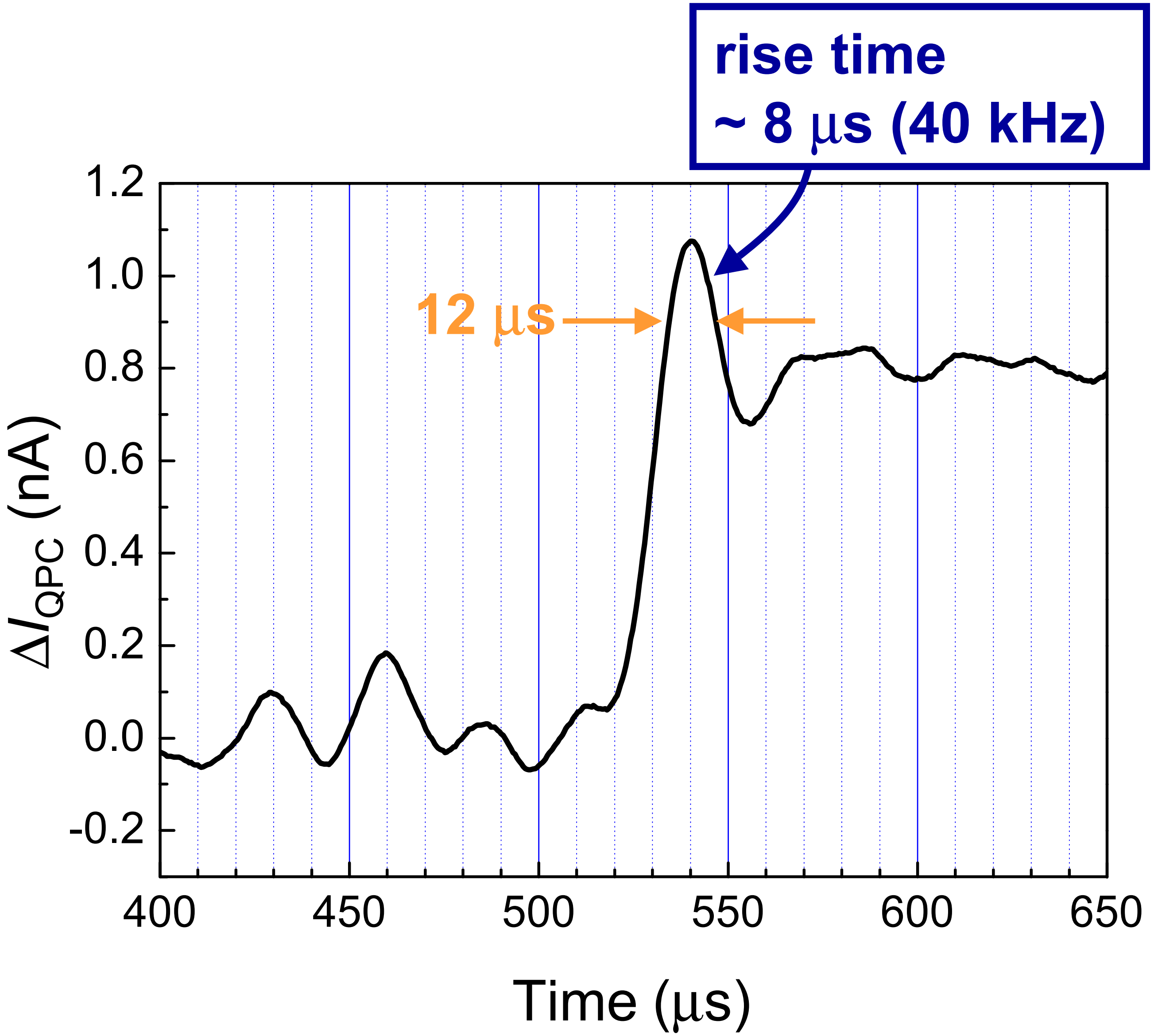




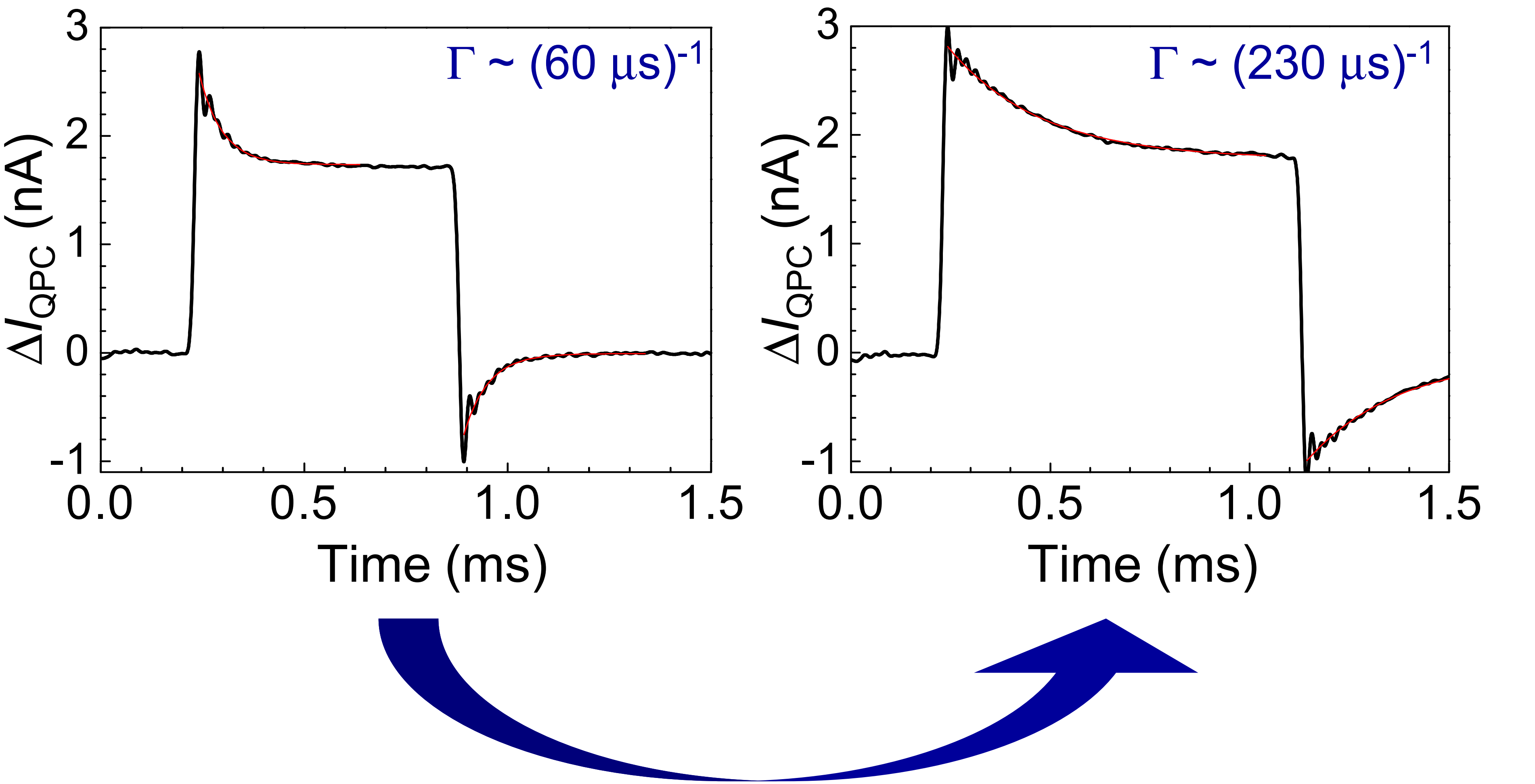
- Tunnel-in event visible
- Tunnel-out event very fast

- Tunnel-in event too fast
- Tunnel-out event visible

Fastest tunnel events



Histograms tunnel time

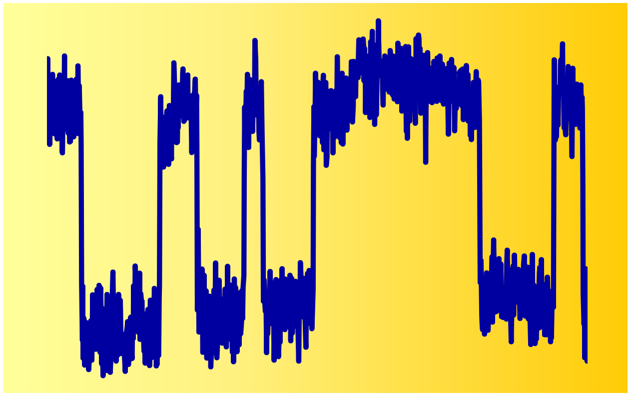


increase tunnel barrier

Summary…

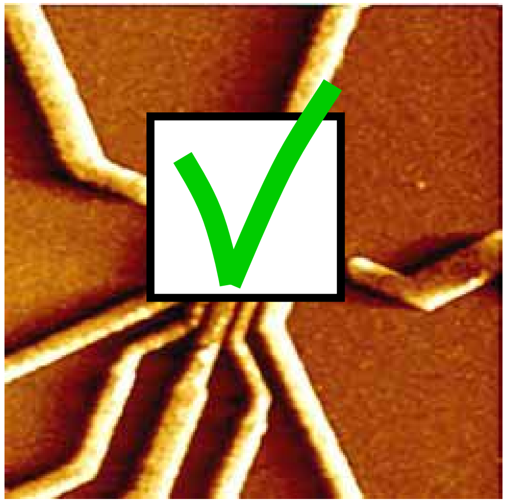
We can:

measure single-electron tunneling in *real-time* (~10 μs)

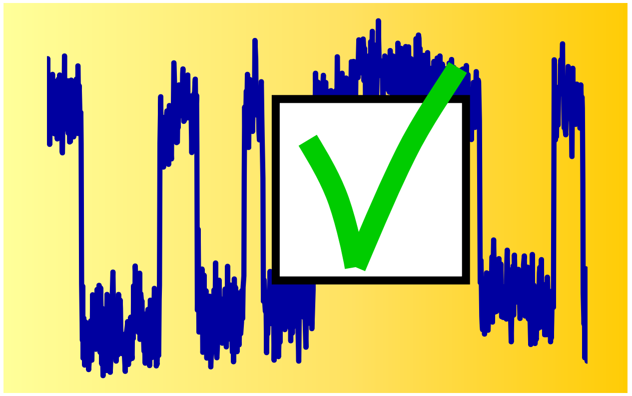


We need…

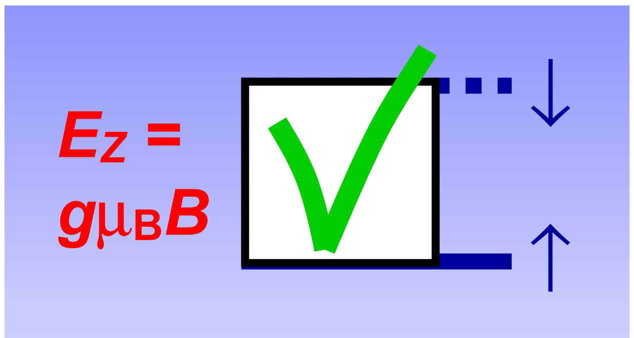
one-electron
double dots…



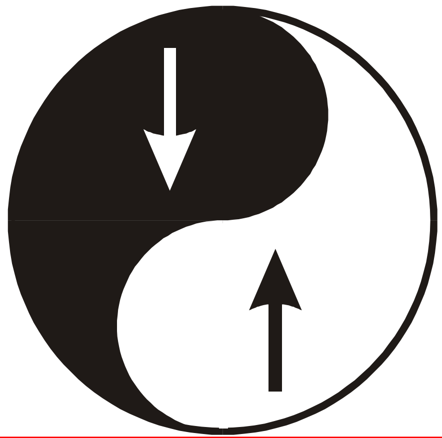
…fast charge
detection…



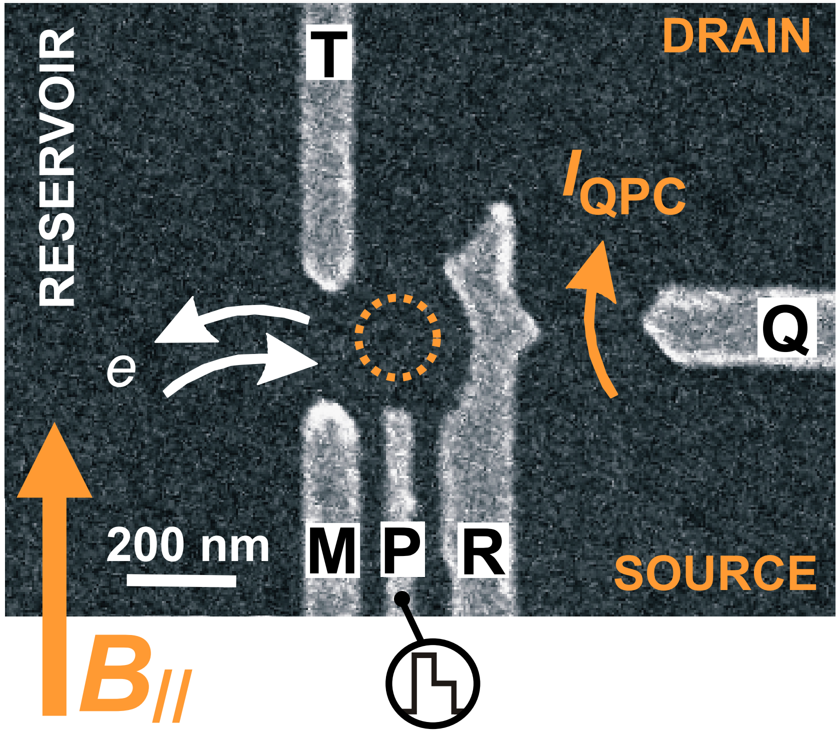
…two-level
system…

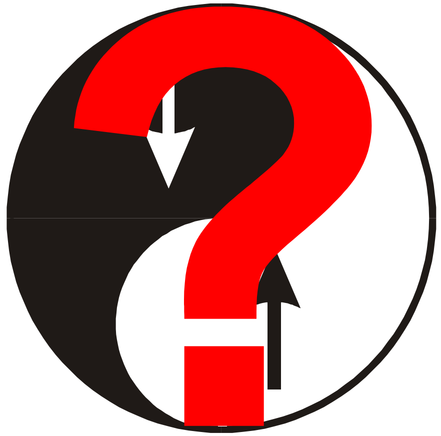


….single spin measurement!



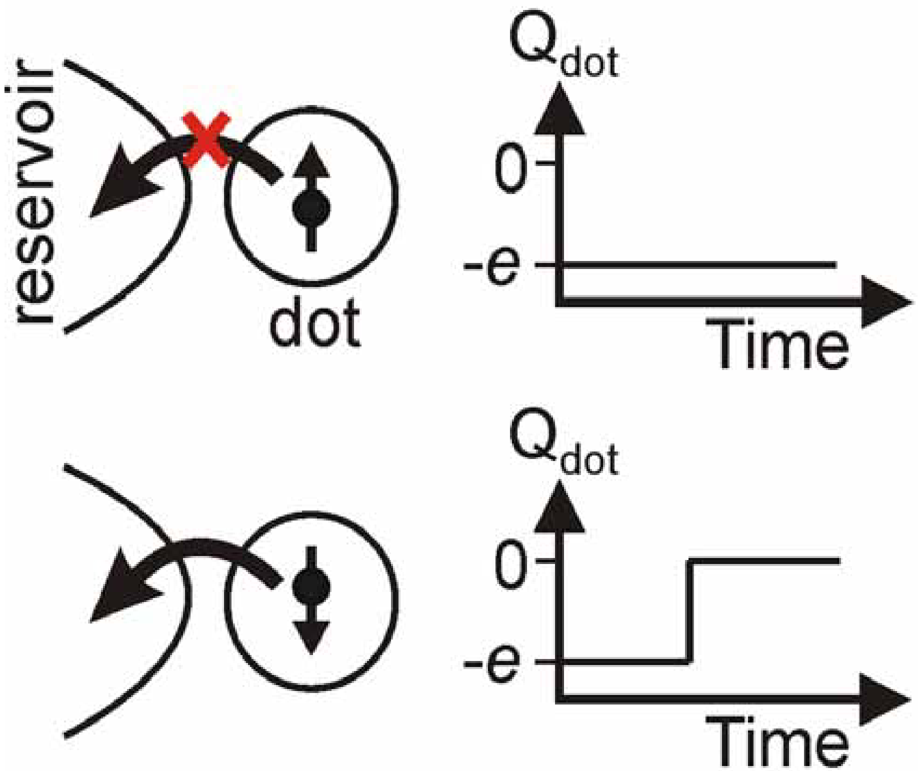
Single-shot measurement of a single electron-spin



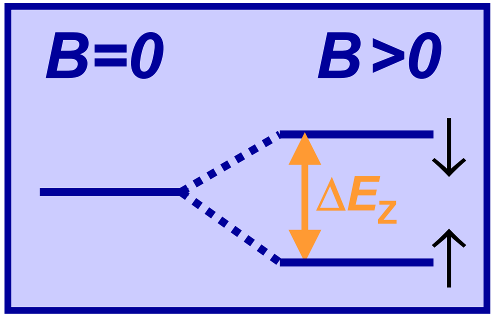


Single-spin measurement concept

- Spin magnetic moment: $\mu_B = 9.27\times10^{-23}$ A m^2 very small!
- But: spin attached to electron (which has charge)
- So: correlate spin orientation to electron's position
- Then measure charge

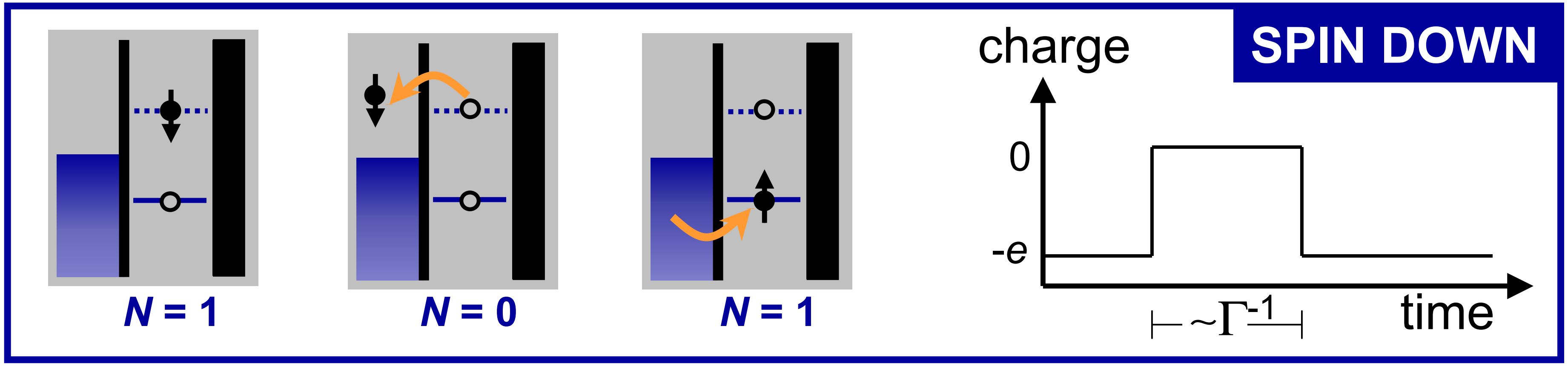


Spin-to-charge conversion

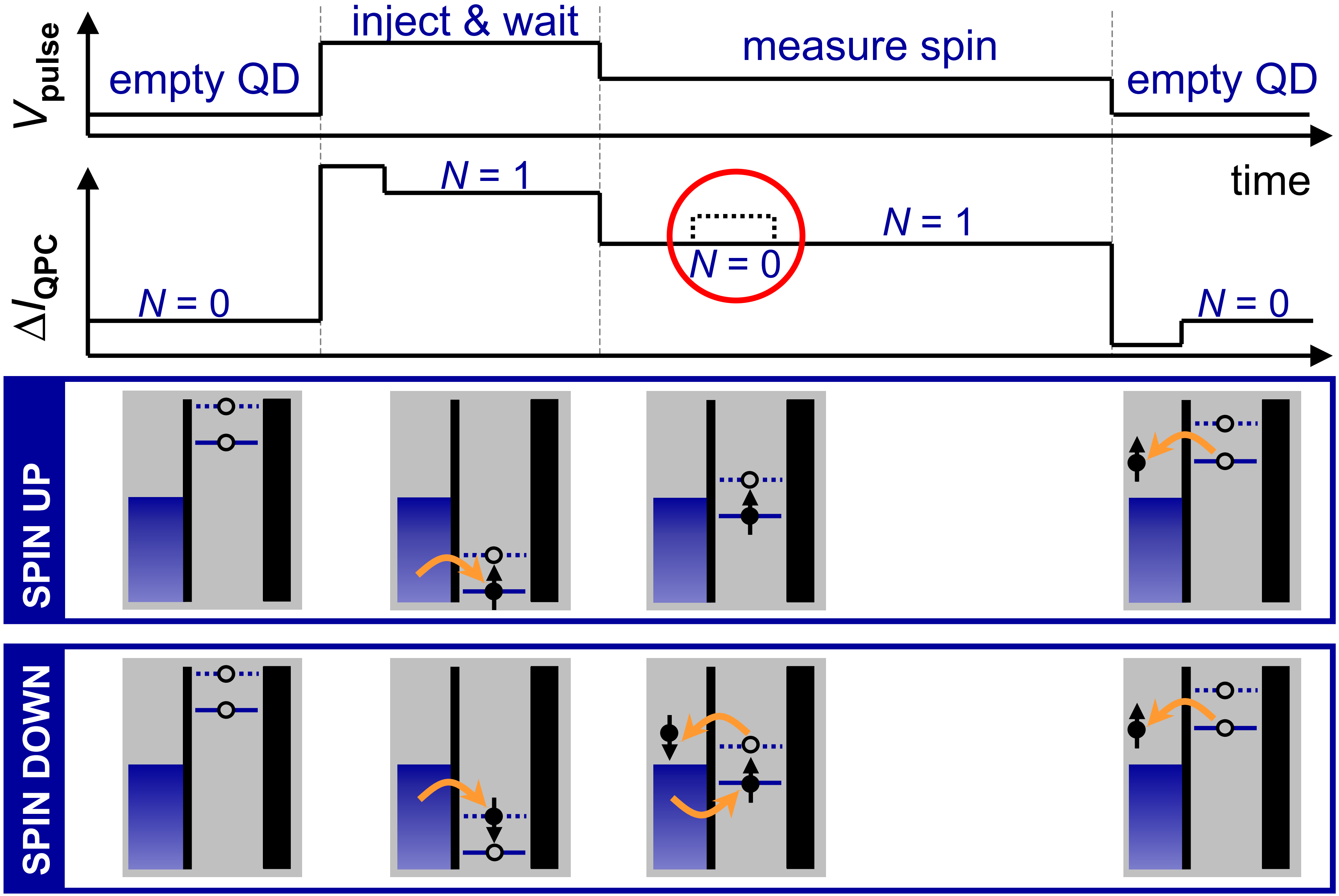


Use Zeeman splitting $\Delta E_Z = g\mu_B B$

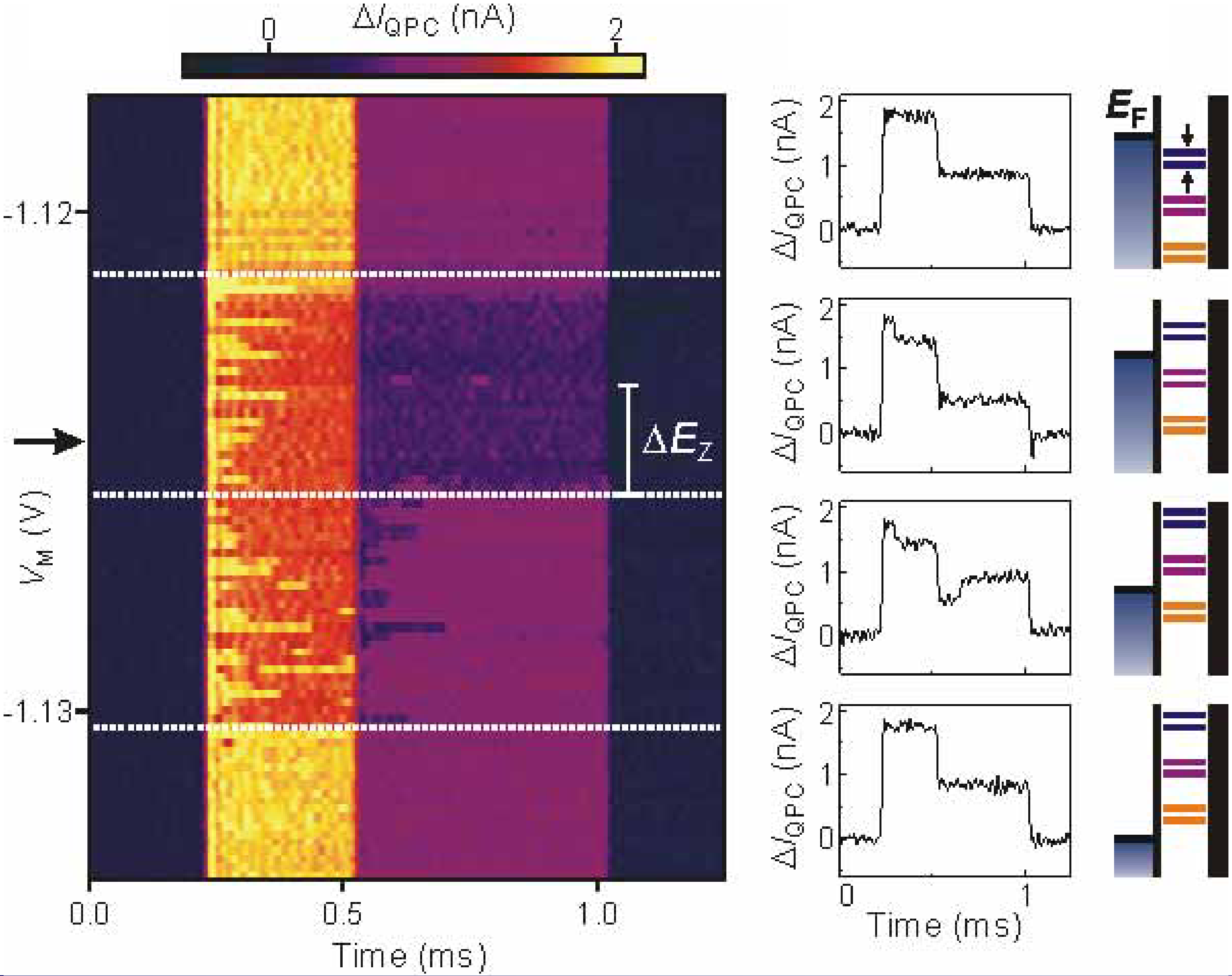
- *Spin-to-charge conversion* (within T_1 >50 μs)
- Fast charge read-out



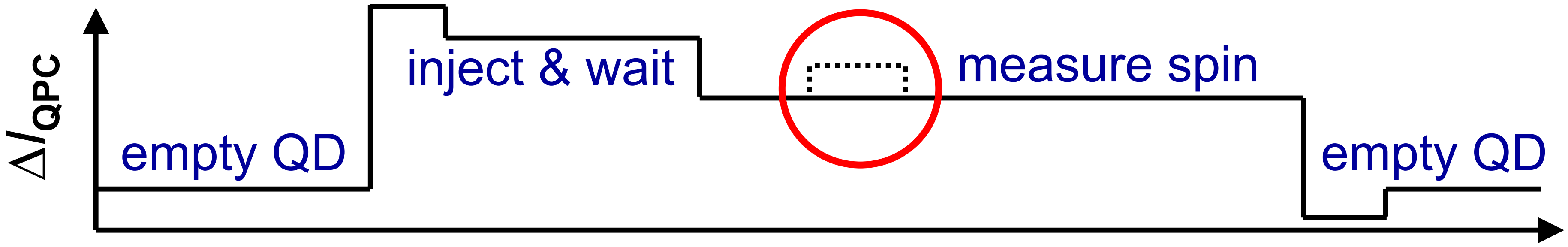
Spin read-out procedure

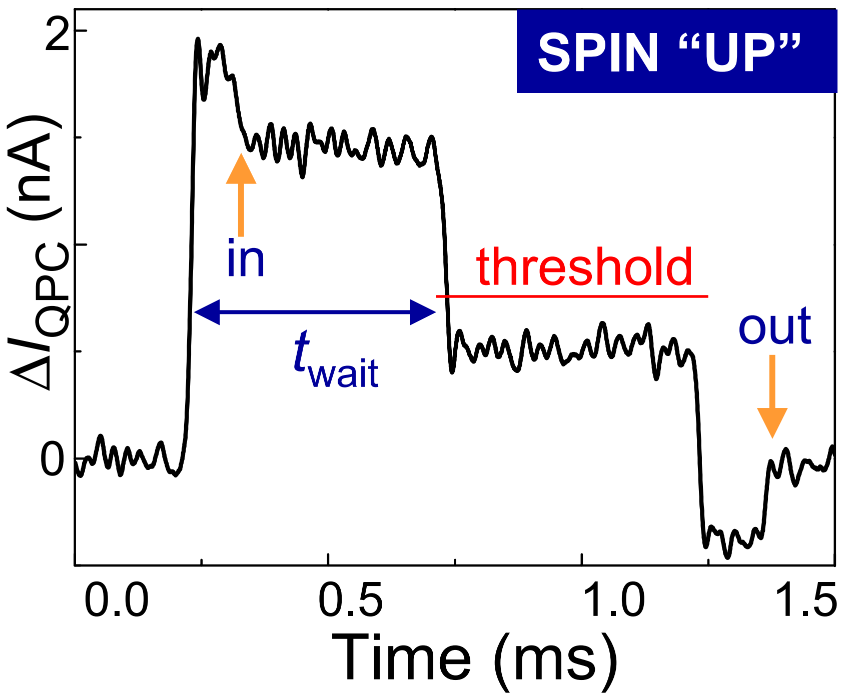


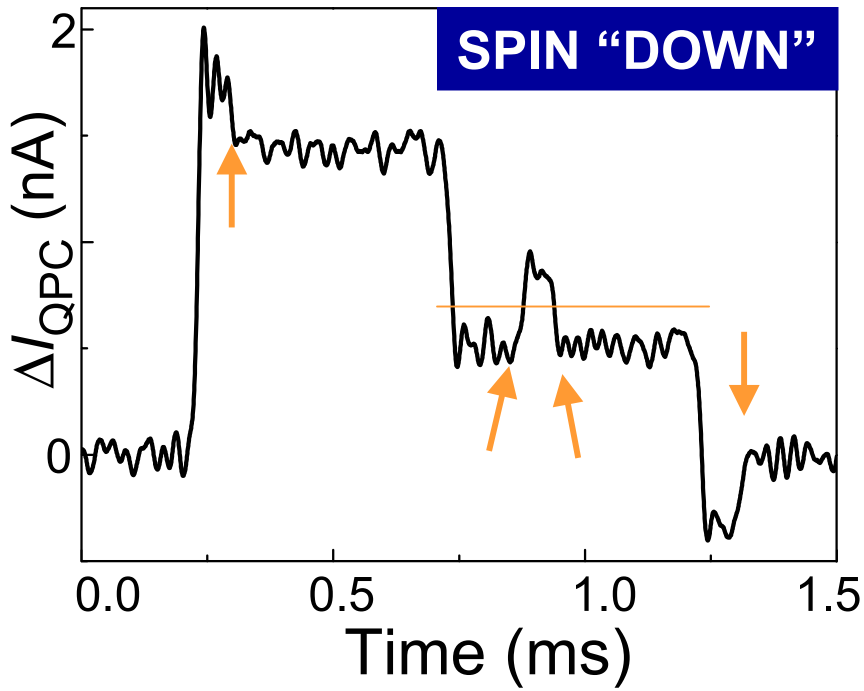
Finding the spin read-out regime



Single-shot spin read-out results



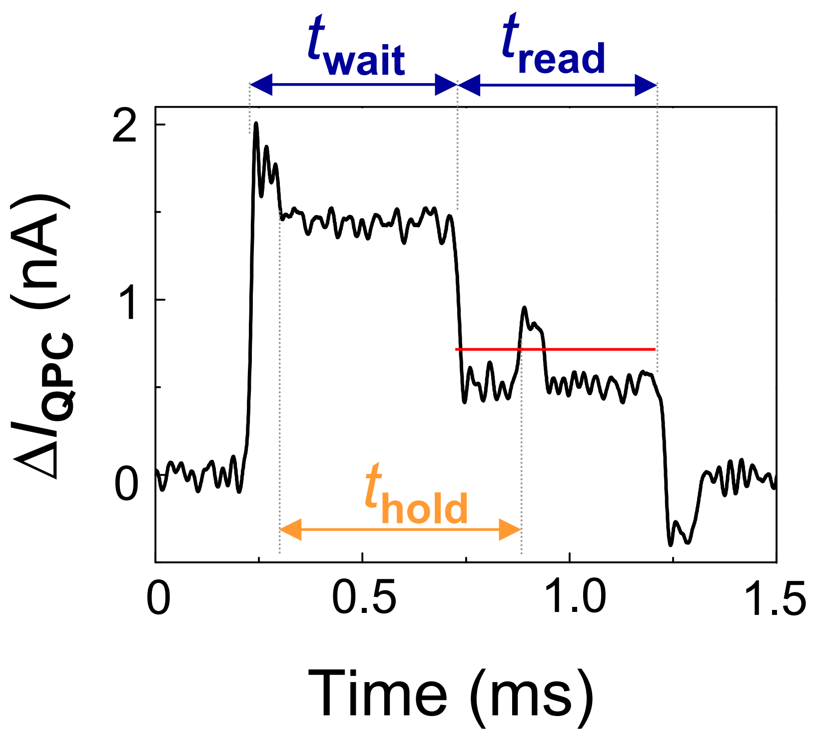


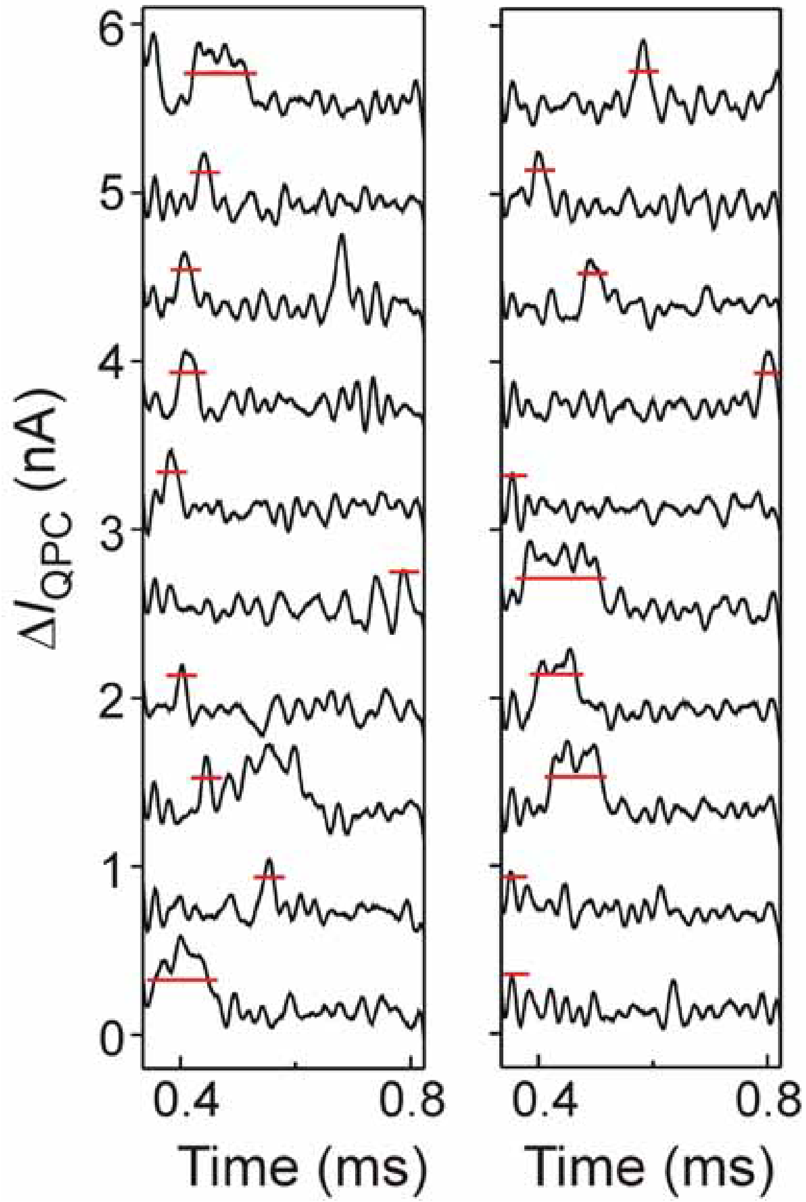


Flat signal in read-out region
♥ spin is "up"

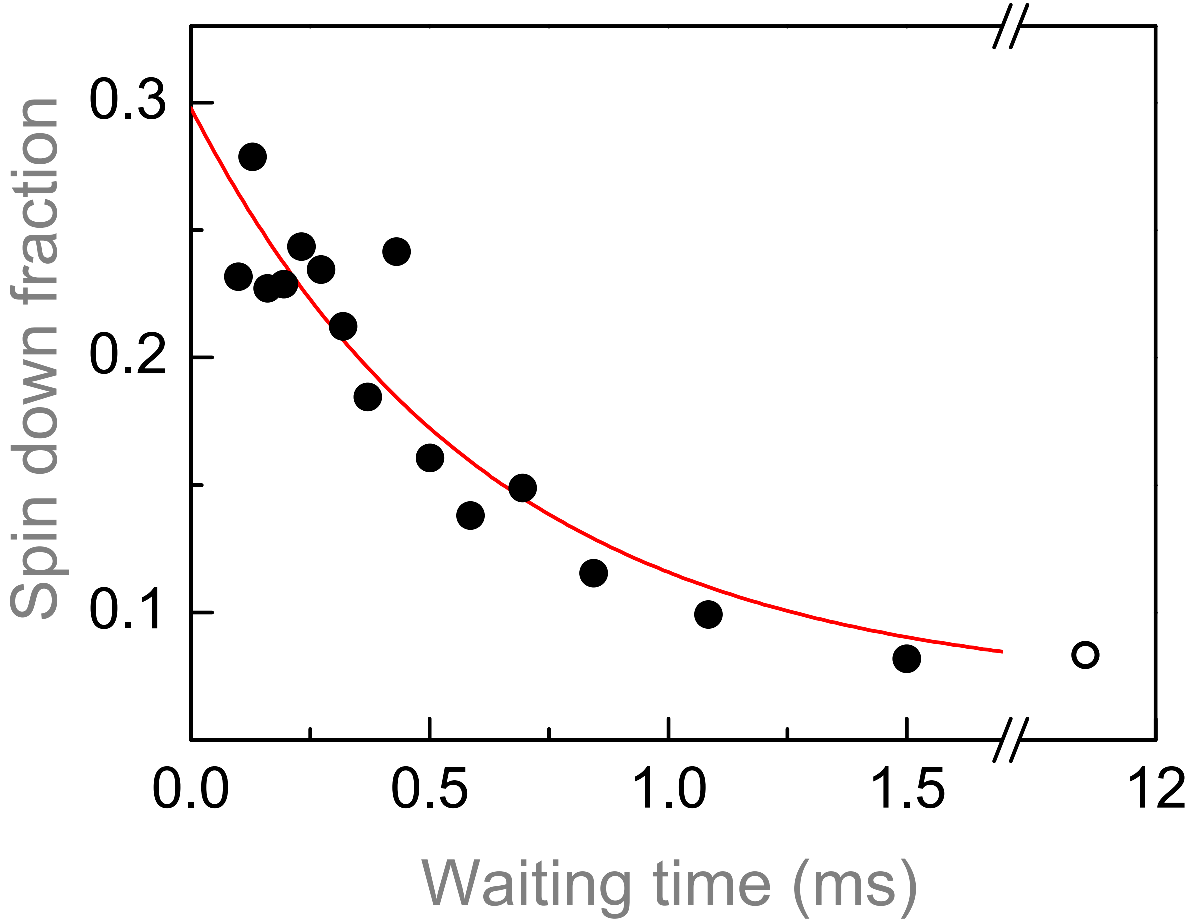
Step during read-out region
♥ spin is "down"

More spin-down traces



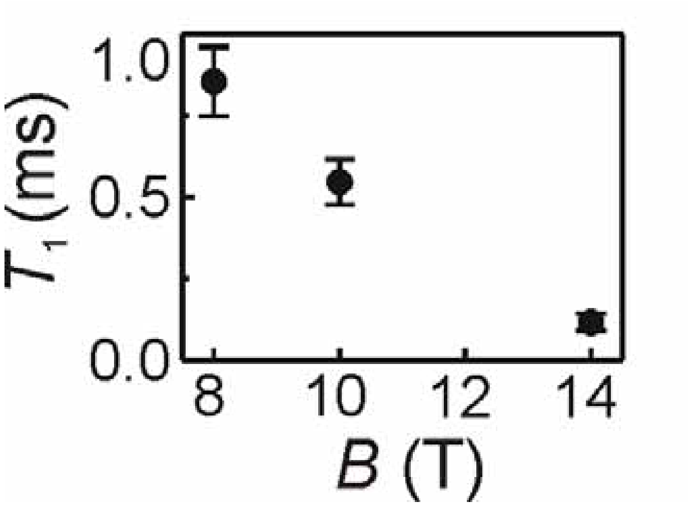


Verification spin read-out

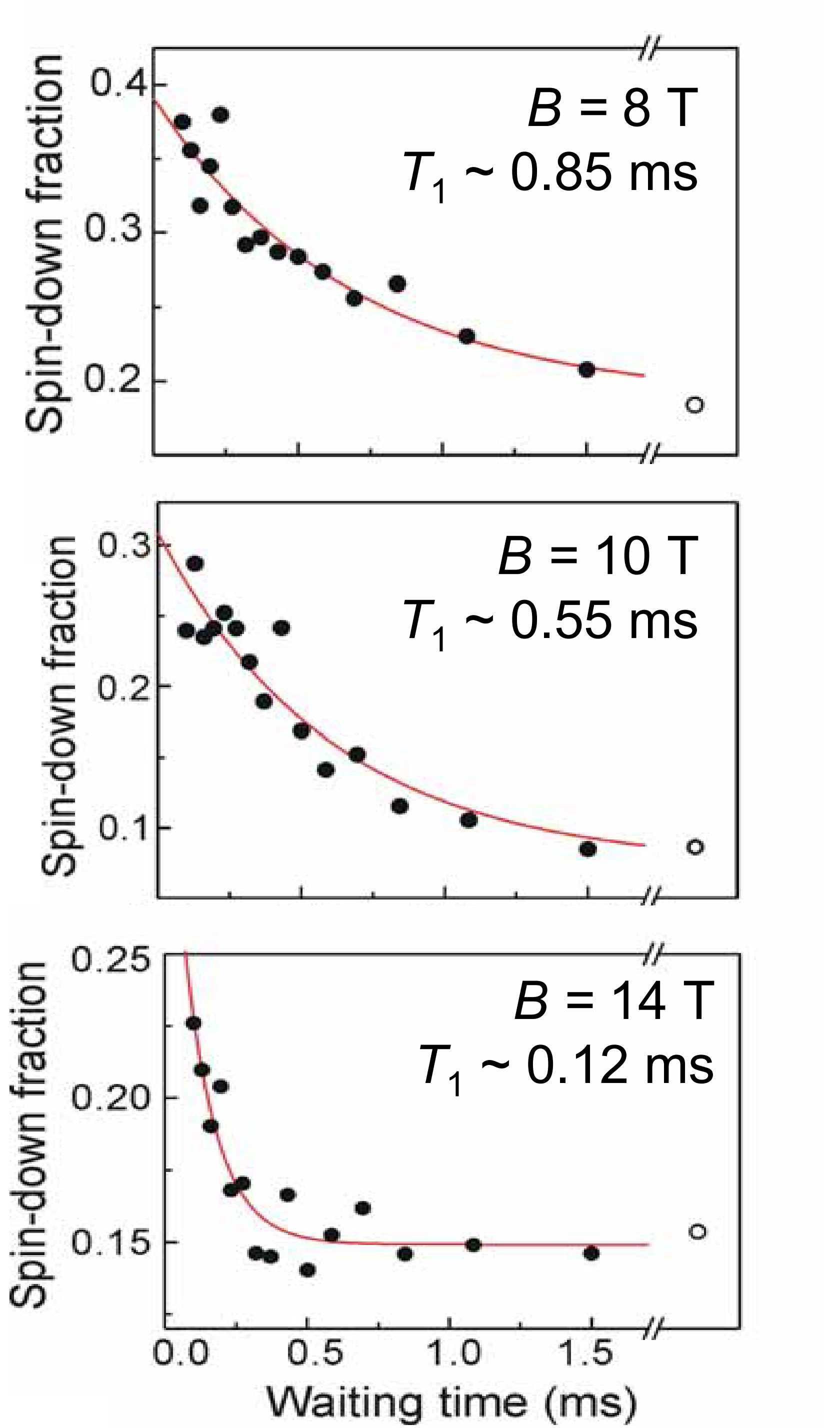


Measurement of T1

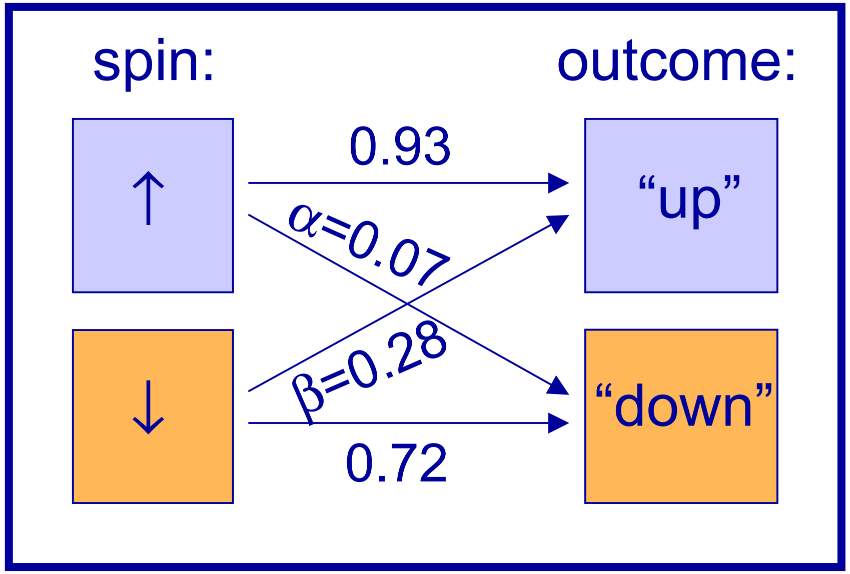
Elzerman *et al.*, to appear in Nature



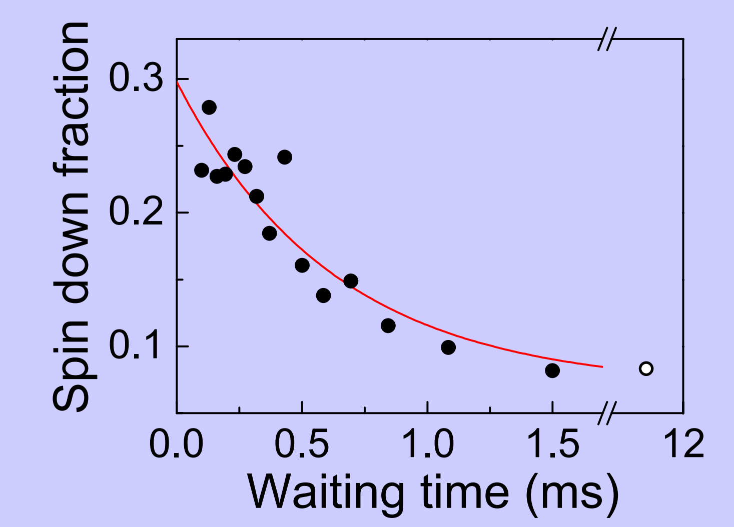
- Surprisingly long T_1
- T_1 goes up at low B

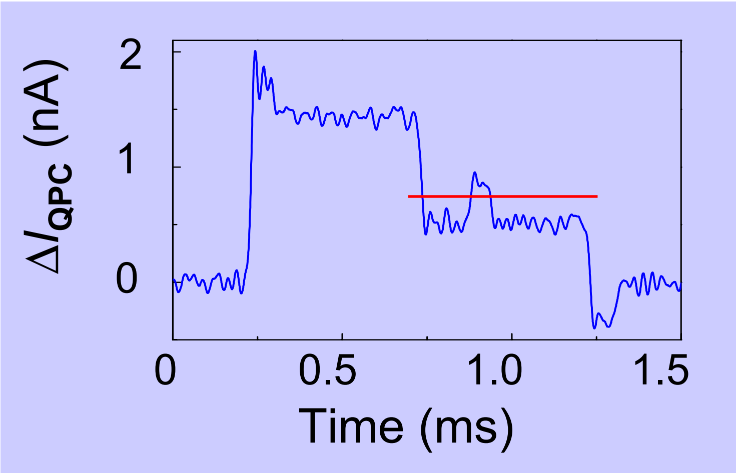


Read-out characterization

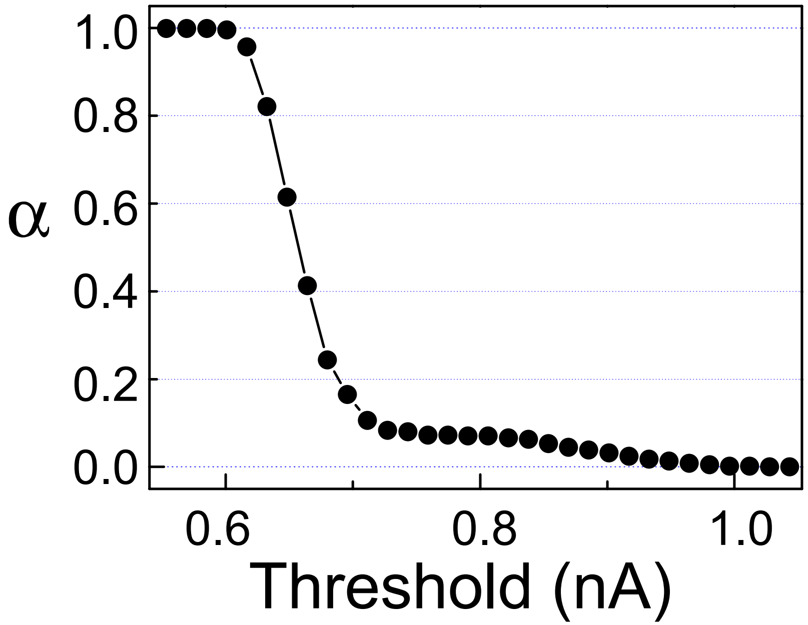


Characterization $\alpha = P$ ("down" if ↑)





$$p\,(1-\beta-\alpha)\,\exp(-\,t\,/\,T_1)+\alpha$$

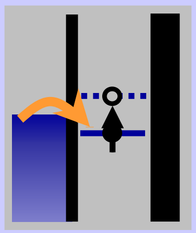


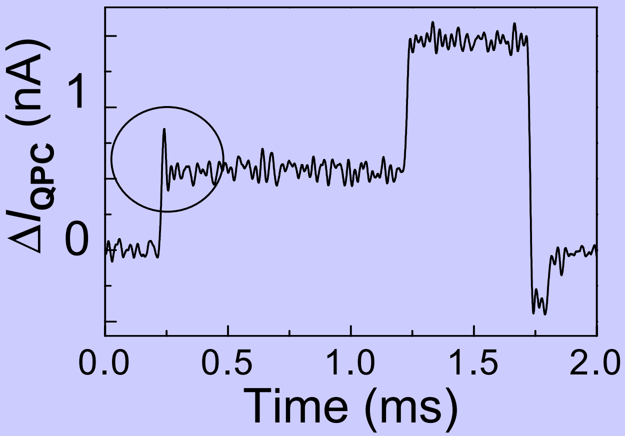
Characterization $\beta = P$ ("up" if $\downarrow$)

β_1 = P (flips before tunnelling)

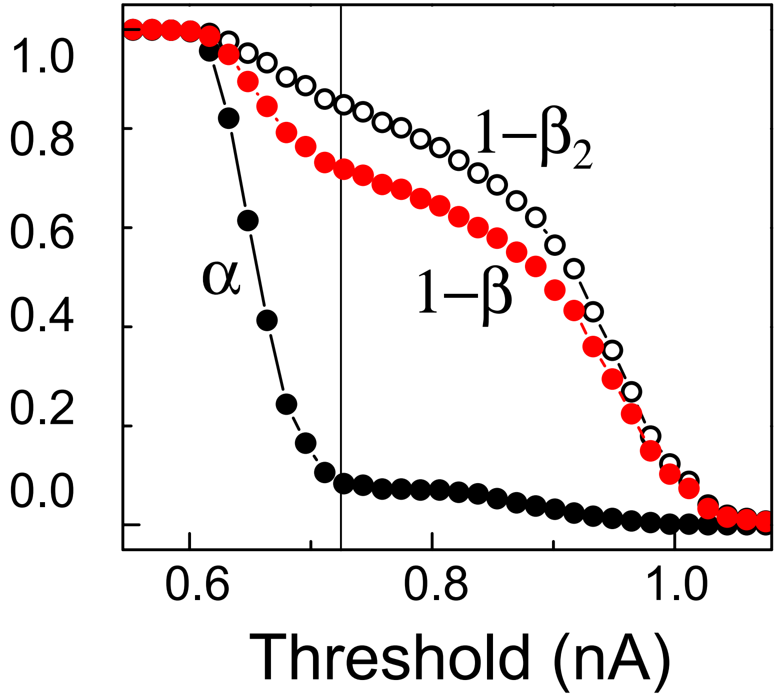
$$\frac{1/T_1}{1/T_1 + \Gamma_\downarrow} = \frac{1}{1 + \Gamma_\downarrow T_1}$$

β_2 = P (miss step)

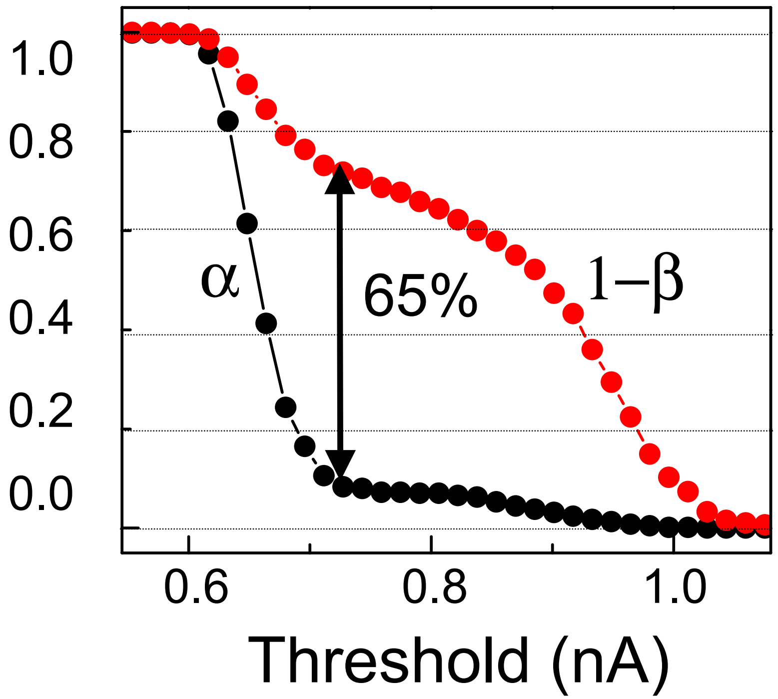


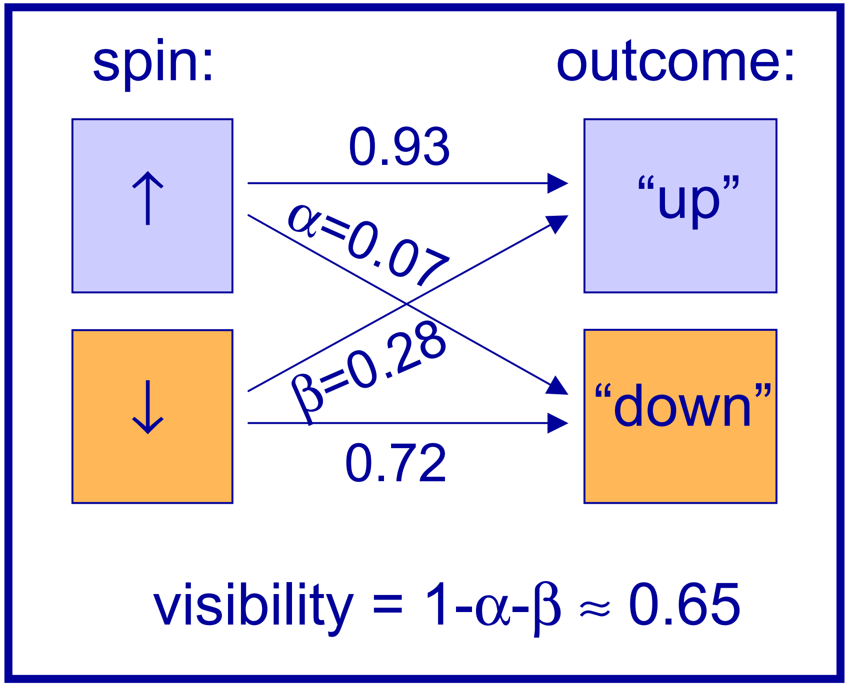


$$1-\beta = (1-\beta_1)(1-\beta_2) + \alpha\beta_1$$



Summary single-shot read-out fidelity





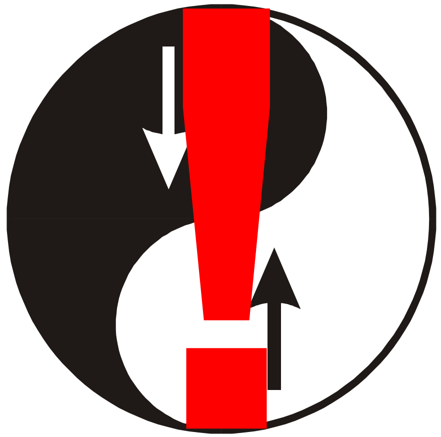
Future improvements:

- α: lower T_{el}
- β: faster charge detection

Summary…

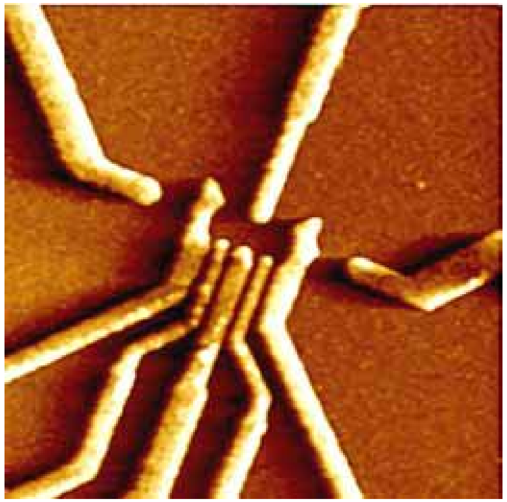
We can:

perform single-shot measurement of one electron-spin

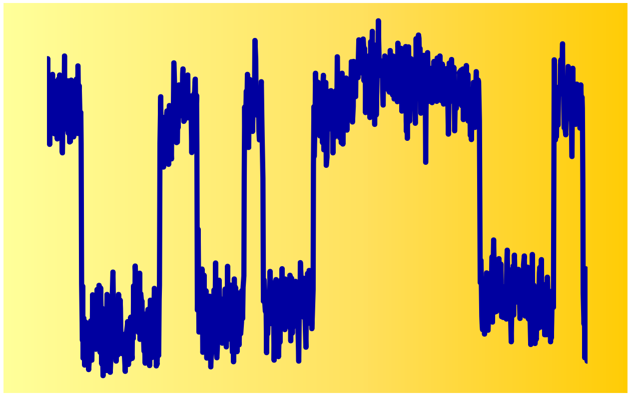


We have...

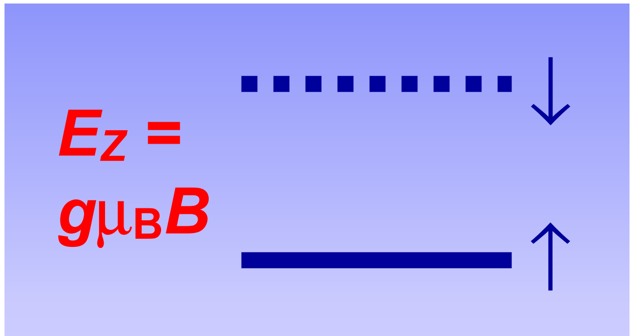
one-electron
double dots…



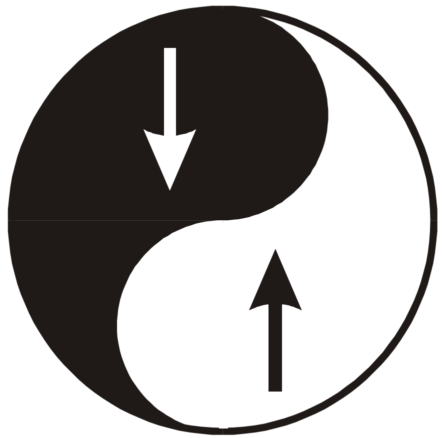
…fast charge
detection…



…two-level
system…



….single spin
measurement!



Part IV: Outlook

Coherent spin manipulation (ESR)

Two-qubit operations ($SWAP^{½}$)

Bell's inequalities for massive particles

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Quantum simulation?

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Quantum computation??