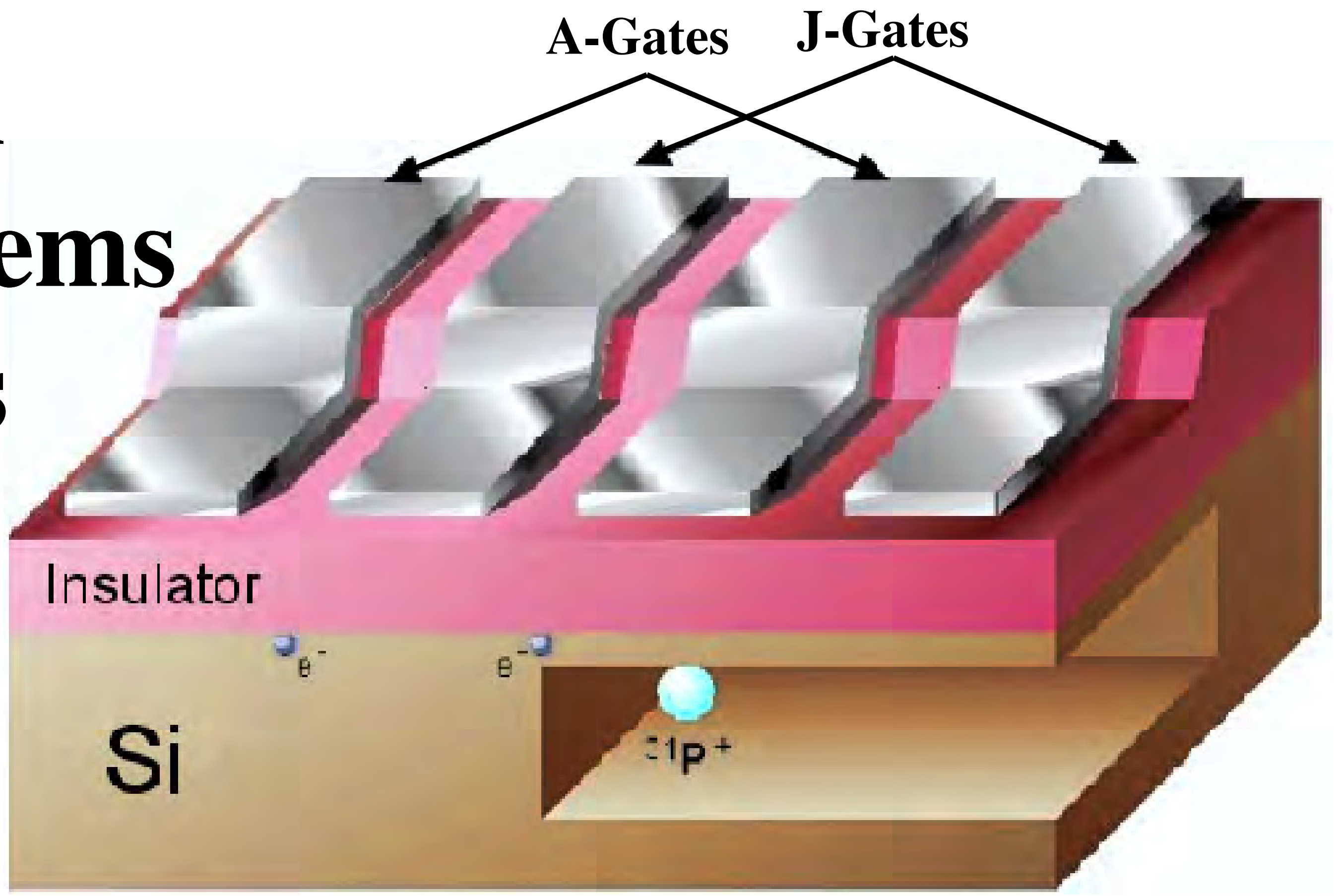
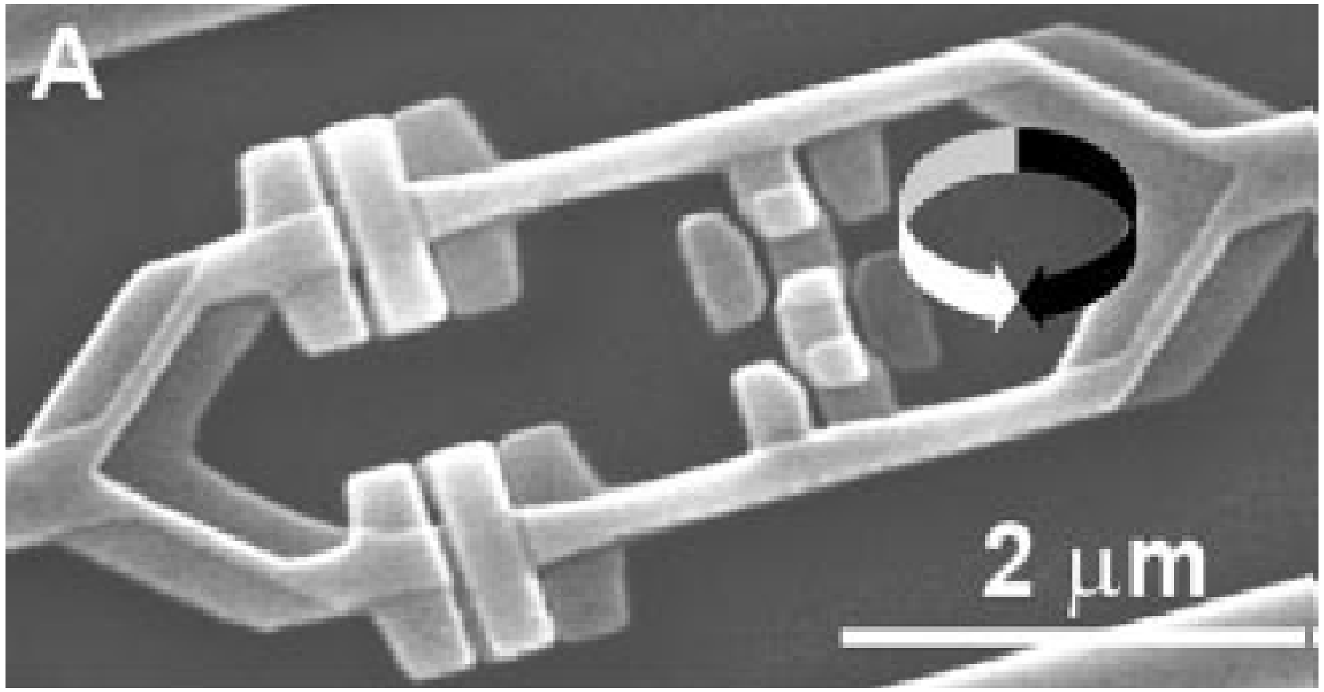
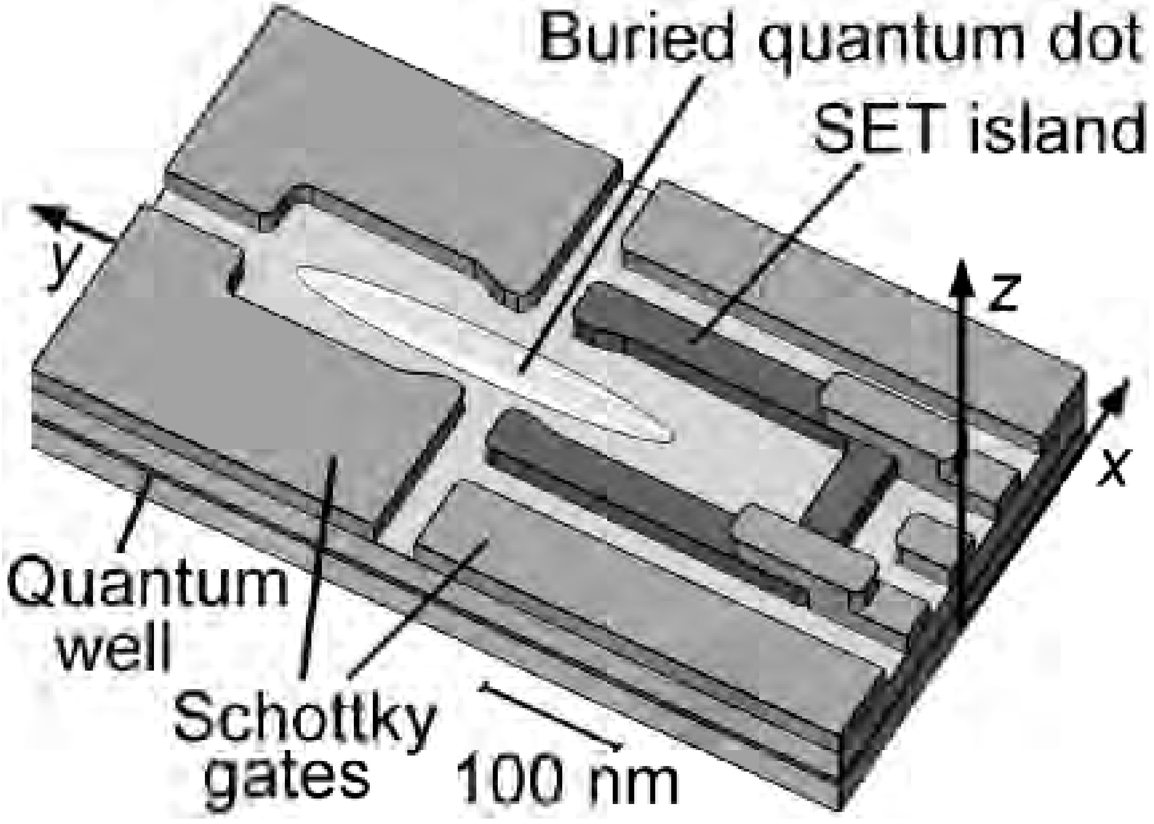
12) Solid-State Systems

12.1 Solid state NMR/EPR
12.2 Superconducting systems
12.3 Semiconductor qubits







12.1

Solid-State NMR / EPR

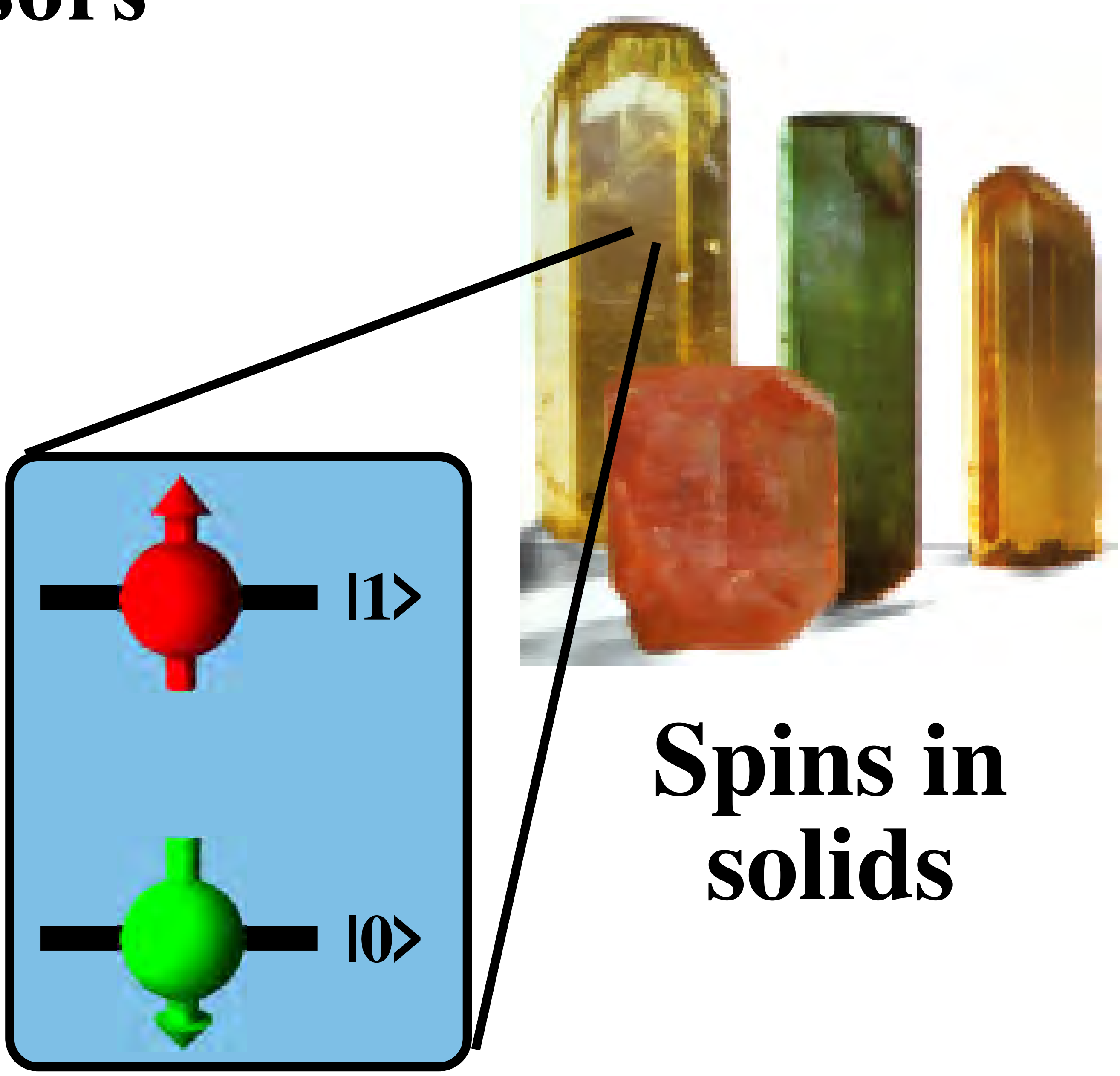
12.1.1 Scaling behavior of NMR quantum information processors

12.1.2 ^{31}P in silicon

12.1.3 N@C60

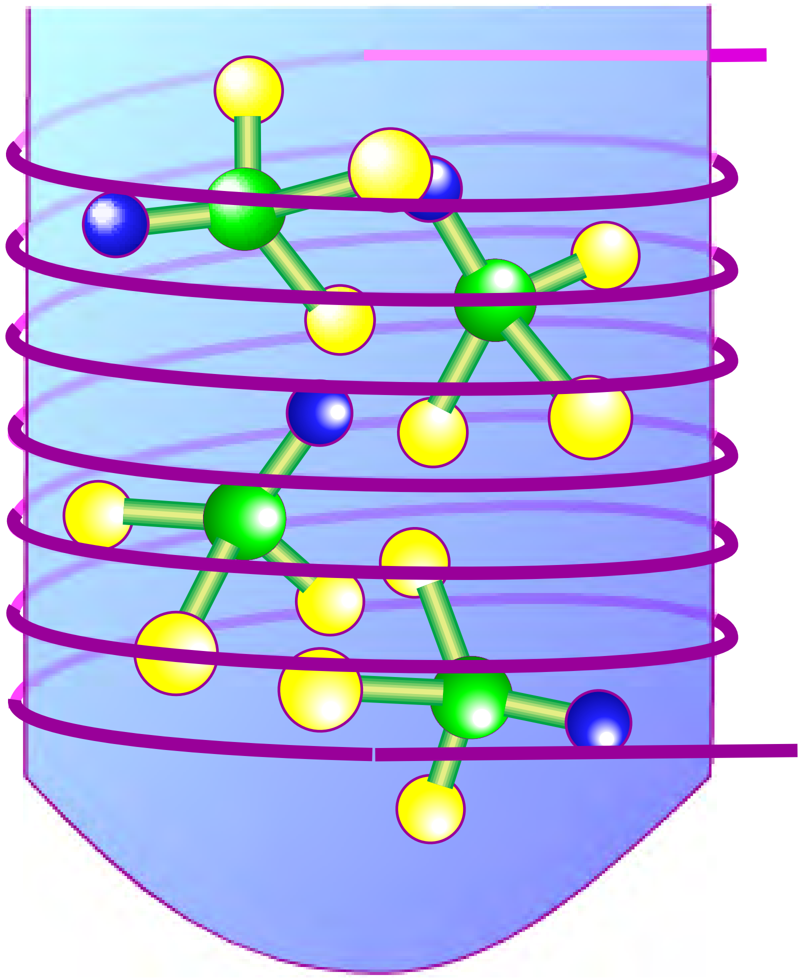
12.1.4 Other proposals

12.1.5 Single-spin readout



Spins in solids

Why Solids ?

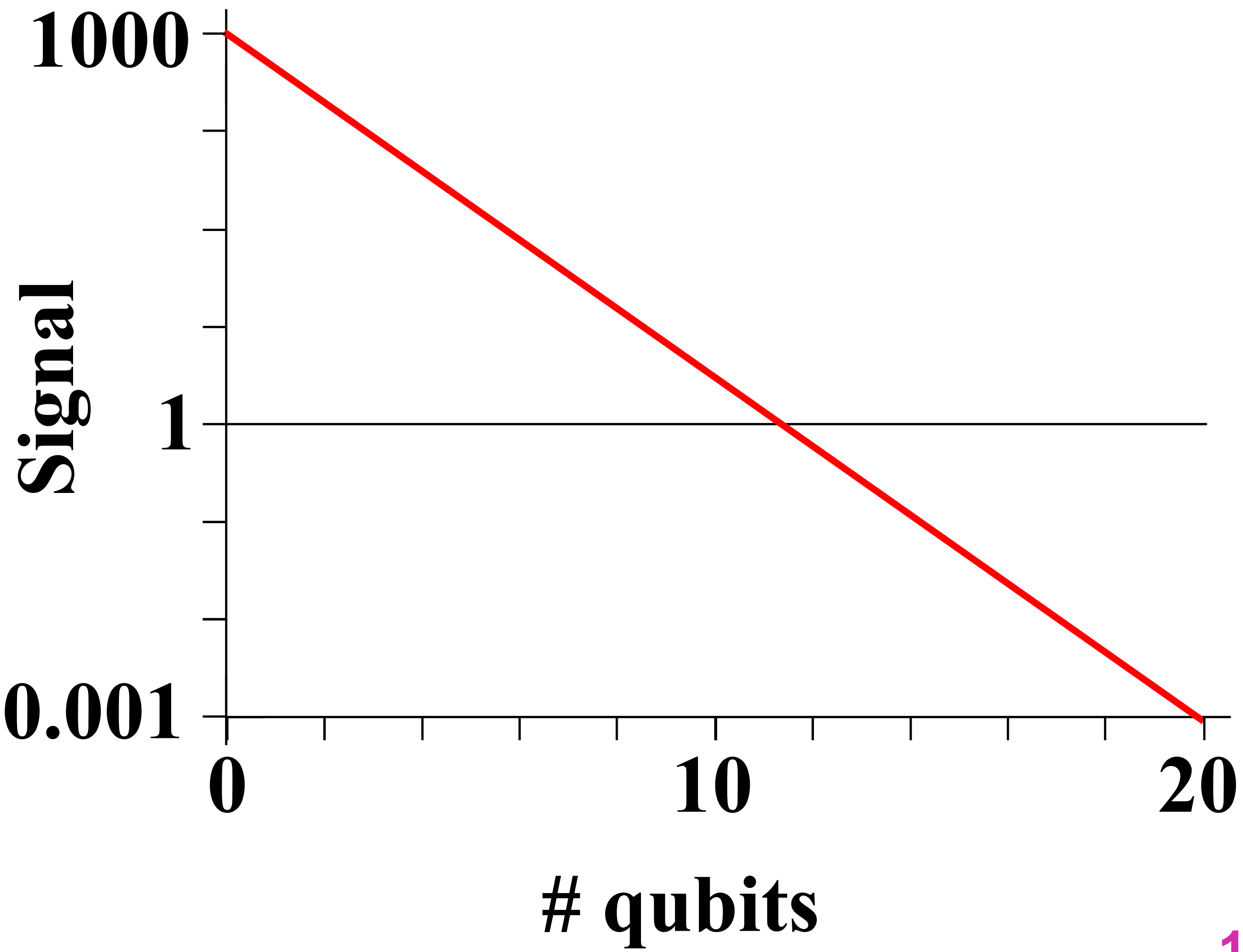


- Liquid state NMR is an excel-lent system for small quantum registers.
- For > 10 qubits, problems arise:
  - addressability
  - decoherence

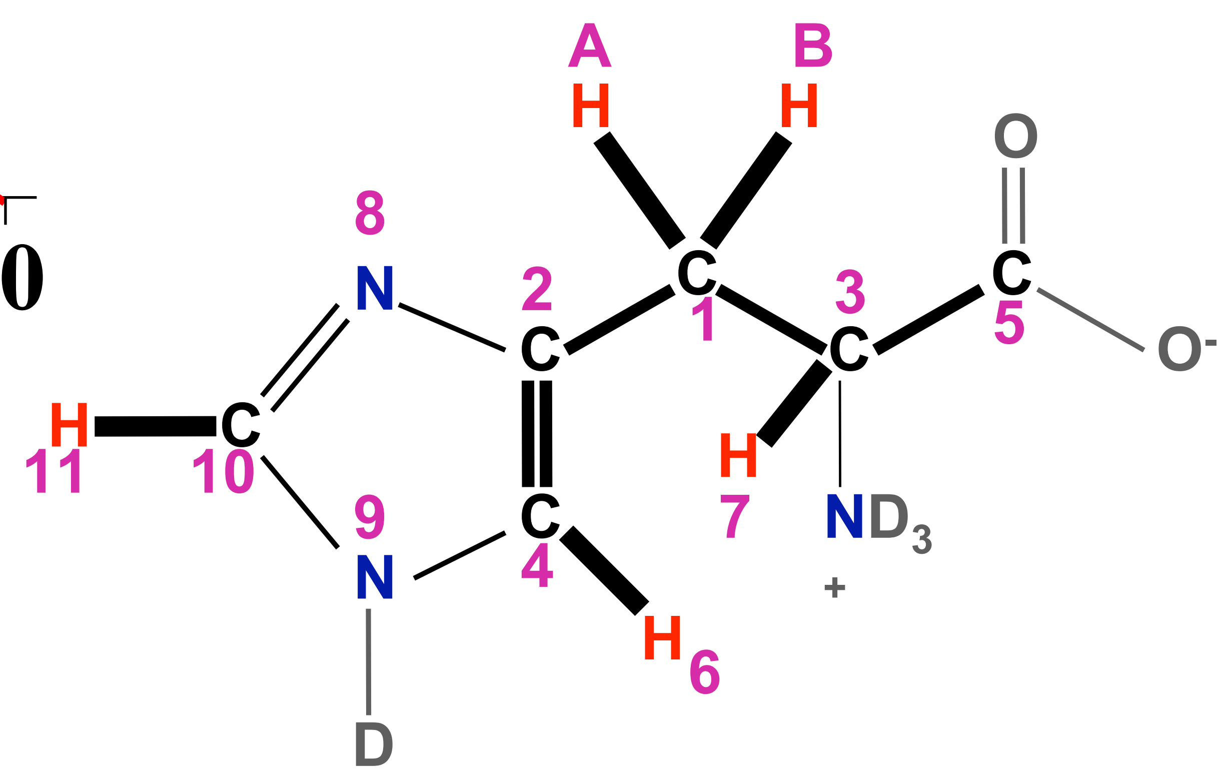
- Solids provide possible solutions:
  - many qubits
  - local addressing
  - low temperature

Scaling Behavior

Signal loss for pps preparation

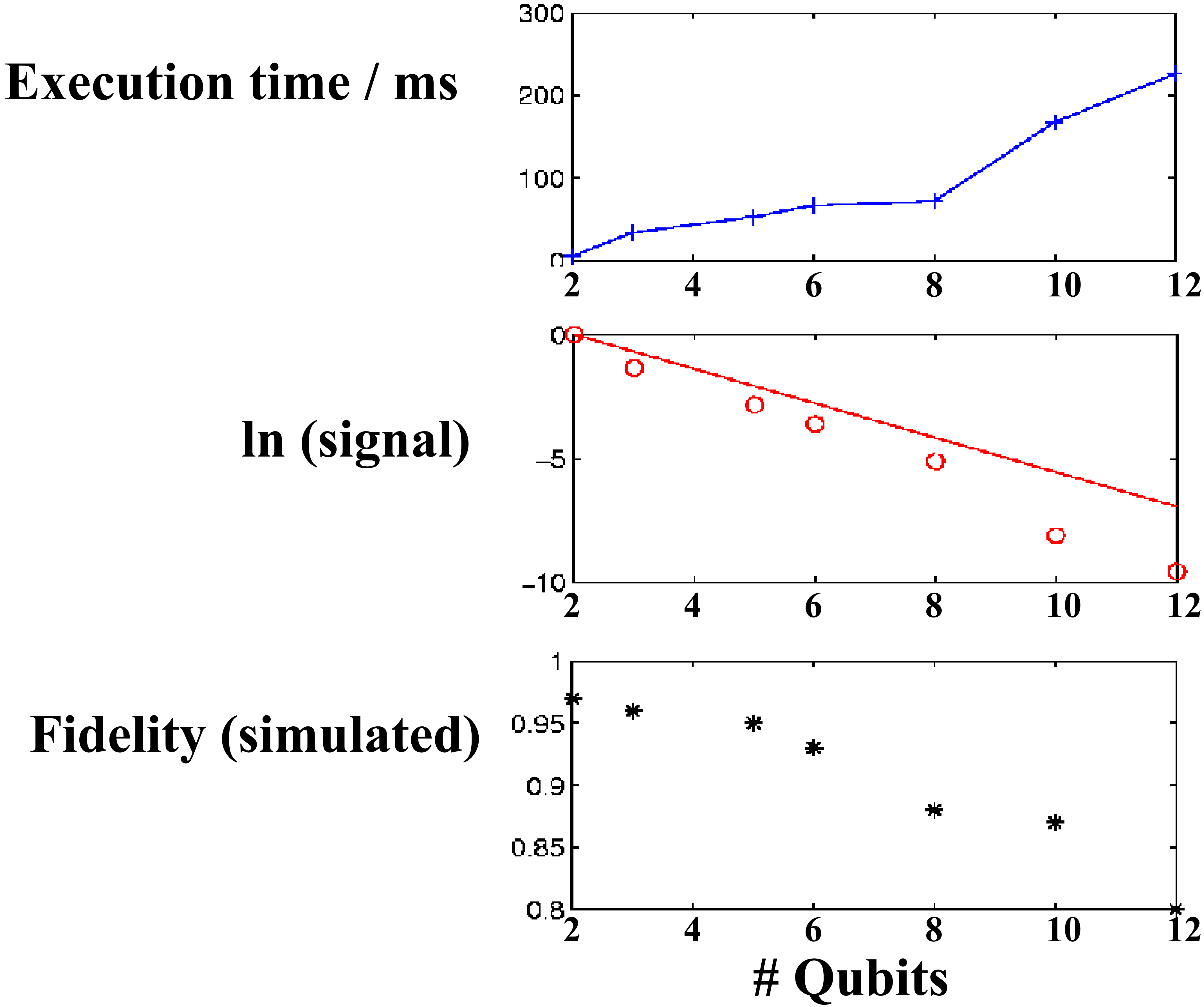


12-qubit system: (Mahesh)



L-Histidine

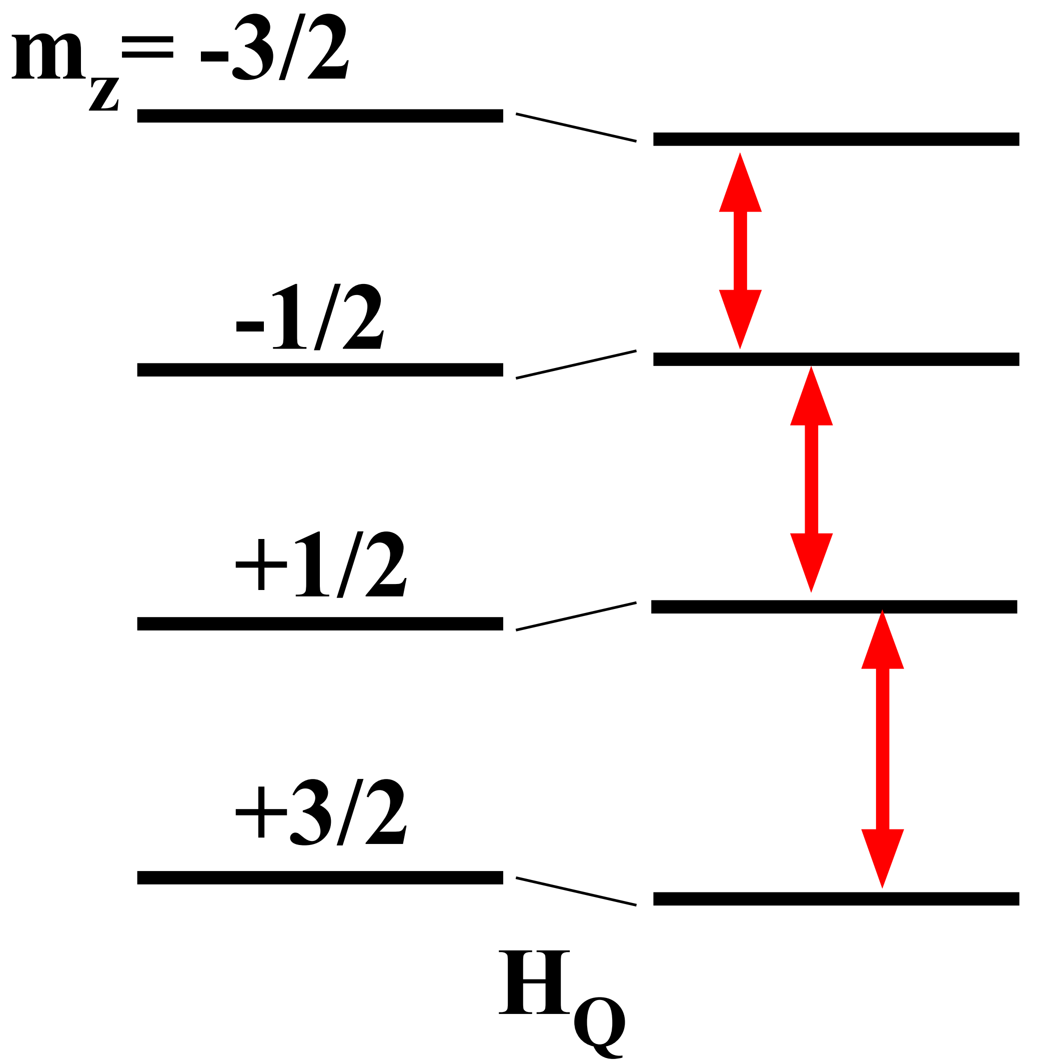
Scaling Behavior

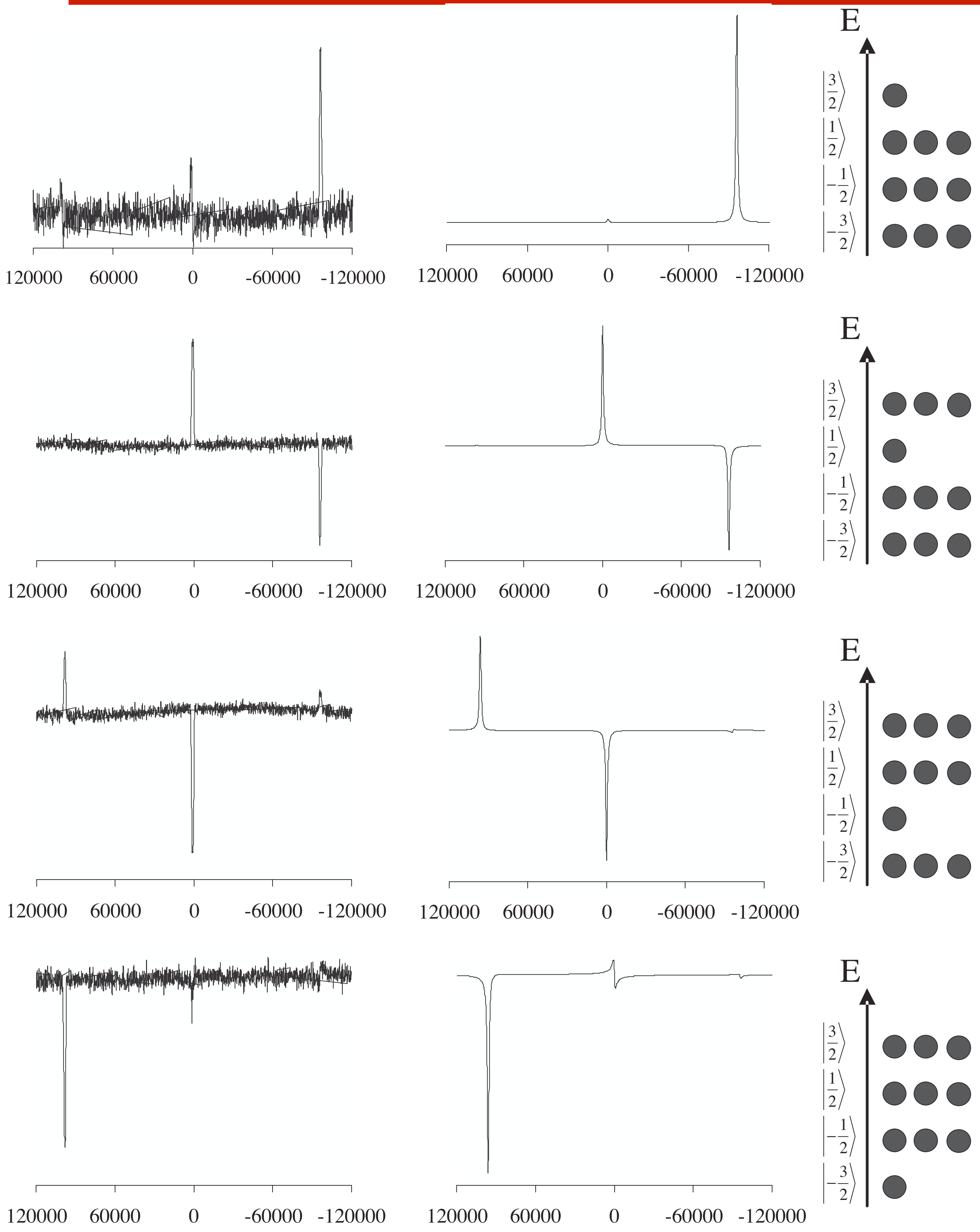


Solid-State NMR

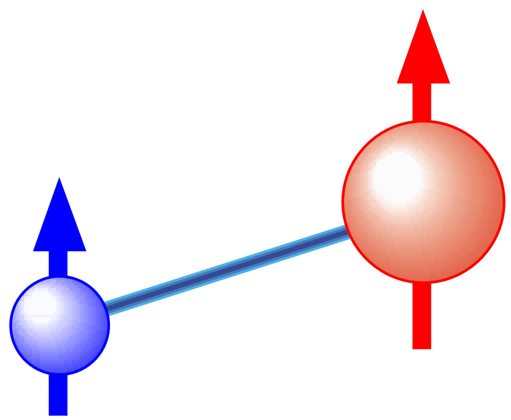
H. Kampermann, and W.S. Veeman, 'Quantum Computing Using Quadrupolar Spins in Solid State NMR', Quantum Information Processing 1, 327 (2002).

^{23}Na : I = 3/2 = 2 qubit





Electron-Nucleus Systems

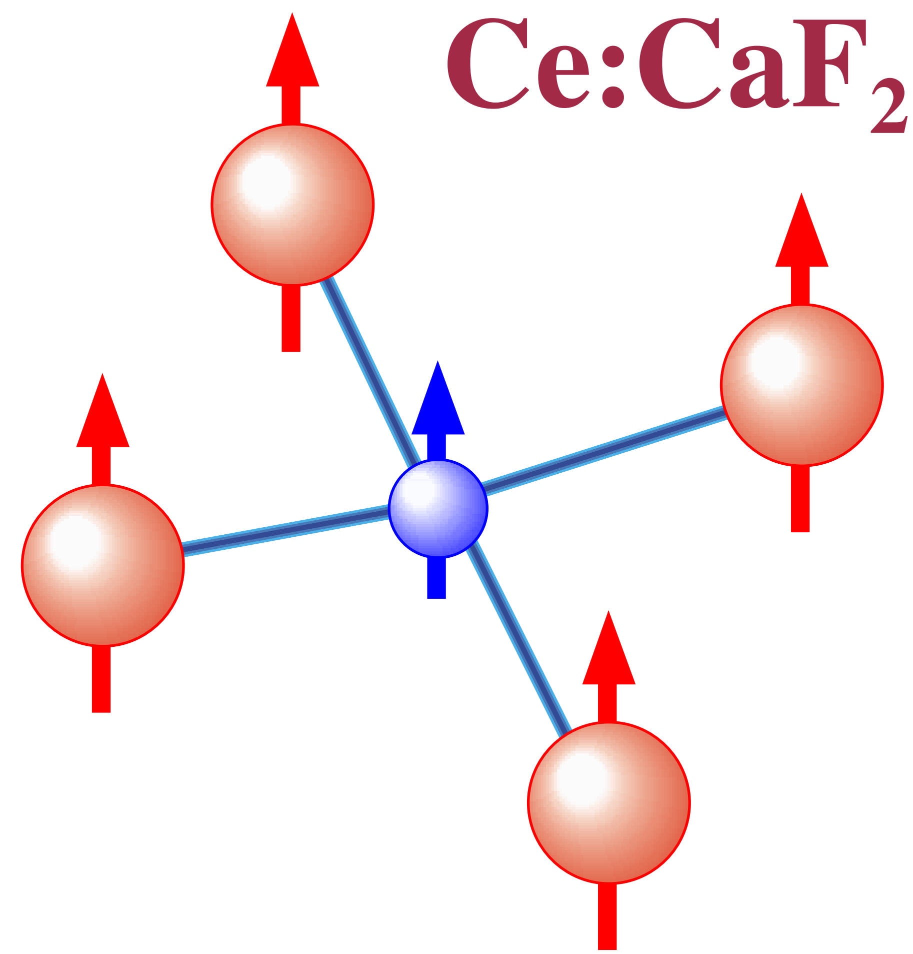


Electron-nucleus entangling in solid malonic acid radical

M. Mehring, J. Mende, and W. Scherer, Phys. Rev. Lett. **90**, 153001 (2003).

Pseudopure state preparation

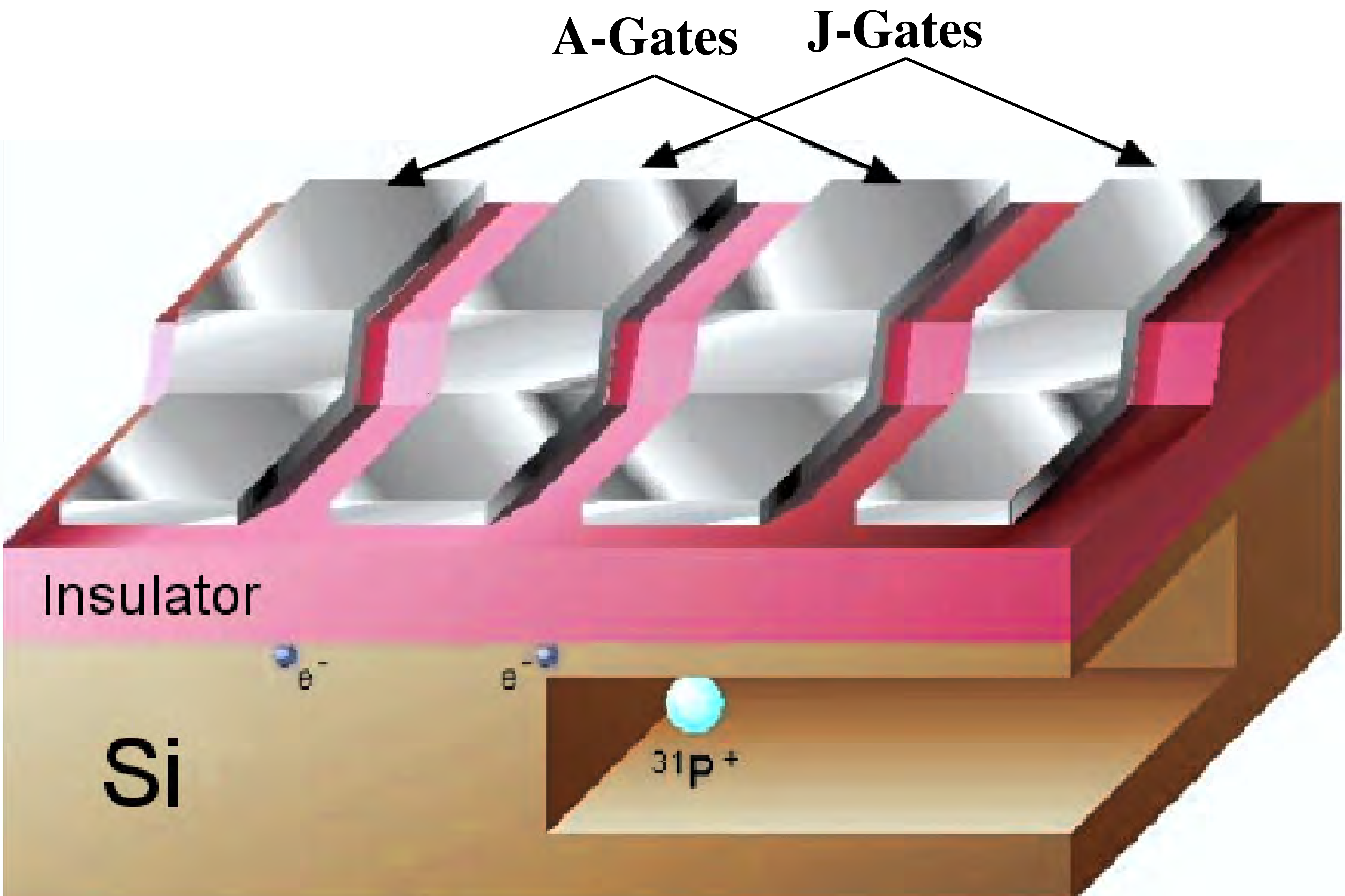
$$\rho_{10} = \begin{pmatrix} 0.01 & 0 & 0 & 0 \\ 0 & -0.06 & 0 & 0 \\ 0 & 0 & 1.02 & 0 \\ 0 & 0 & 0 & 0.03 \end{pmatrix}$$



"S-Bus"

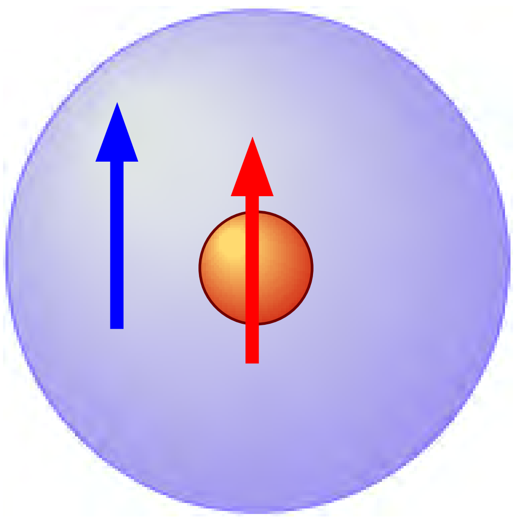
Electron spin mediates nucleus-nucleus couplings

^{31}P in Solicon



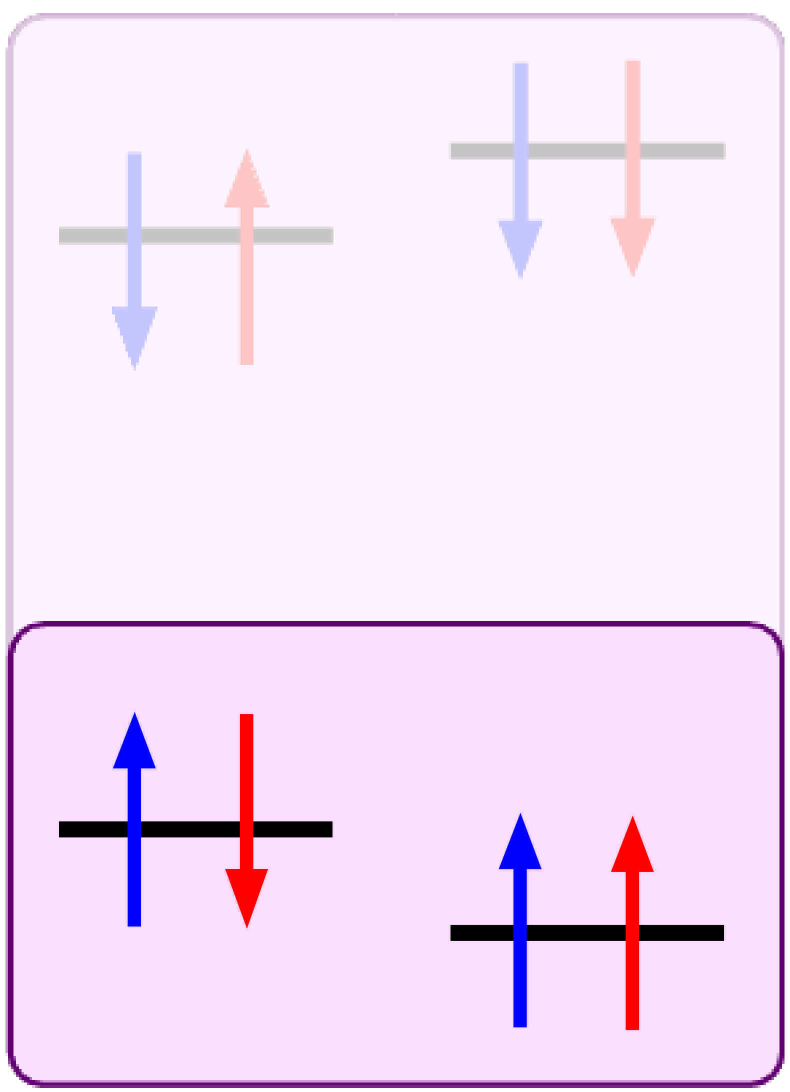
The Qubits

^{31}P = shallow donor



nuclear spin = qubit
electron spin = control

Relevant Interactions



$$\mathcal{H} = -\omega_I I_z - \omega_S S_z - a\,\vec{I}\cdot\vec{S}$$

nuclear Zeeman — electron Zeeman — hyperfine

$|1\rangle$
$|0\rangle$

Qubit

Control

Transition frequency $\omega_0 = \omega_I + a/2$

(high field approximation)

Why ^{31}P in Si ?

- Long decoherence times:

  Electron spin $T_2 \sim 60$ ms in ^{28}Si @ 7K

  Nuclear spin $T_1 > 10$ h

- Excellent technology base

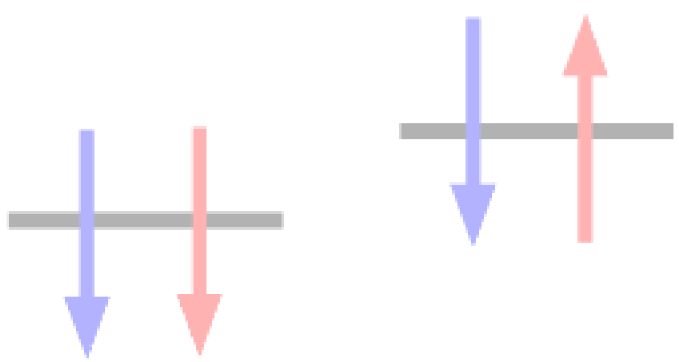
- ^{28}Si has nuclear spin 0

  Natural abundance: 4.6% ^{29}Si

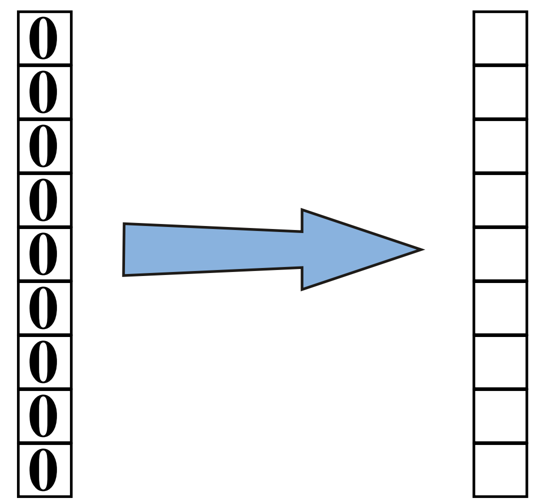
- Spin-orbit coupling small

Initialization

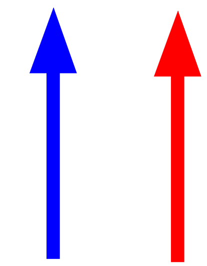
DiVincenzo's rule 2:
Initialization into a well defined state.

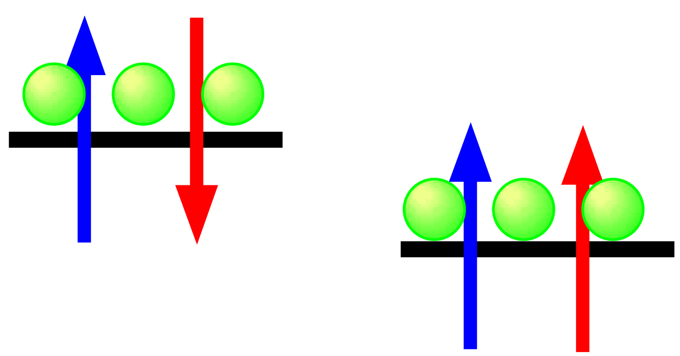


Quantum register



ground state:

$|0\rangle =$ 



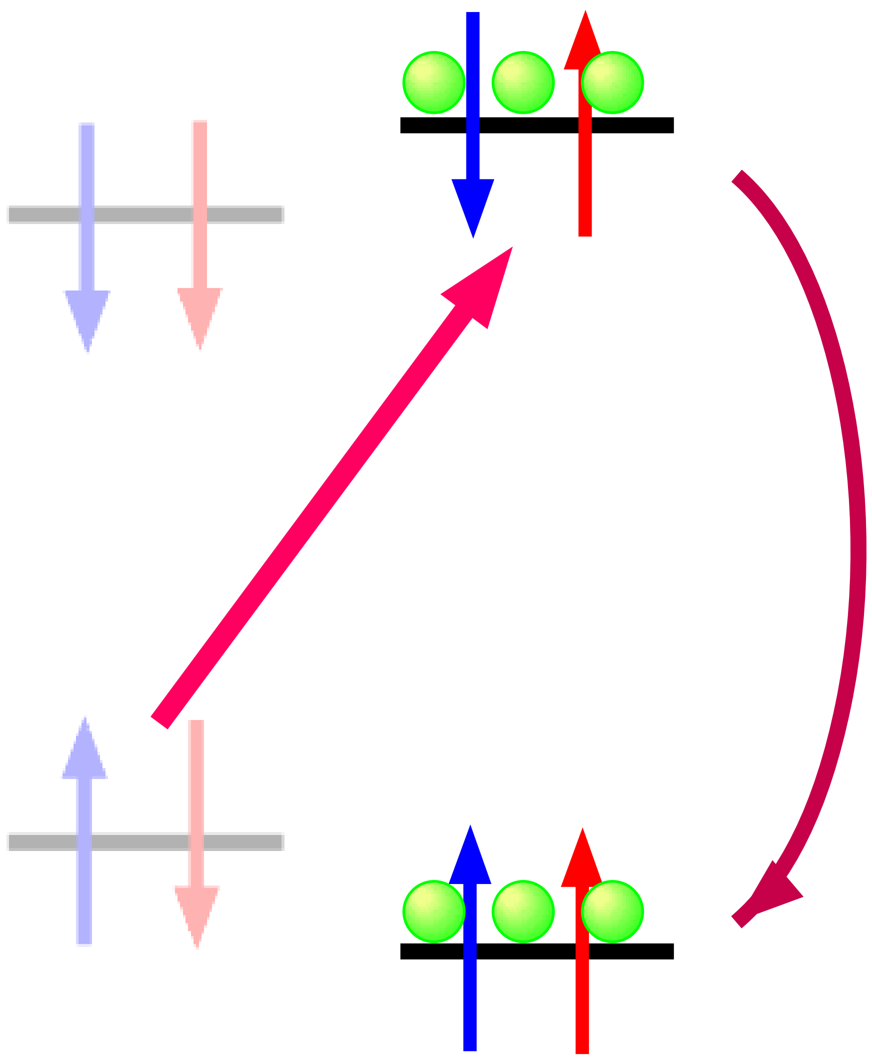
Boltzmann factor @ 100 mK, 2T:

electrons: $\frac{n\uparrow - n\downarrow}{n\uparrow + n\downarrow} \approx 1$

nuclei: $\frac{n\uparrow - n\downarrow}{n\uparrow + n\downarrow} \approx 5 \cdot 10^{-3}$

Initialization

Initialize nuclear spin qubit
by microwave pulse



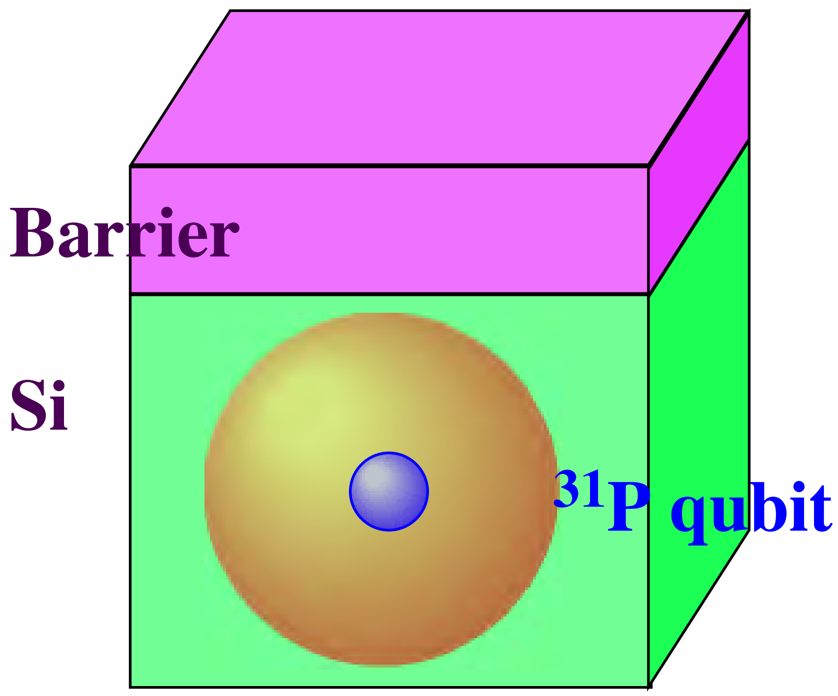
Relaxation
Dissipation required

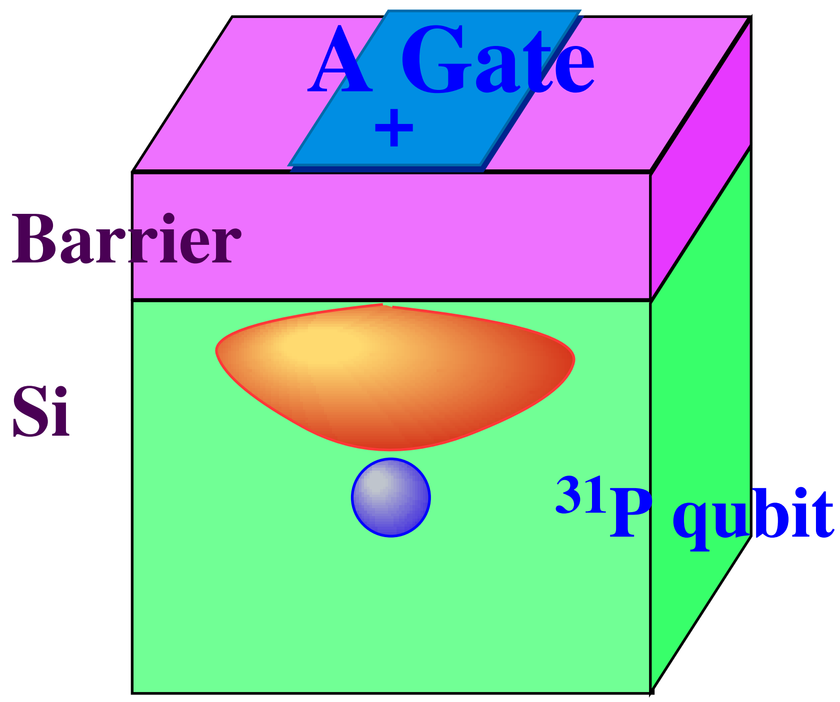
Alternatives:

- Optical spin injection through SiGe superlattices or quantum dots
- Electrical spin injection
- Readout

Modify Frequency : A-Gates

$\mathcal{H} = -\omega_I I_z - \omega_S S_z - a \vec{I} \cdot \vec{S}$ $\qquad a \sim |\Psi_{el}(\vec{r}_n)|^2$

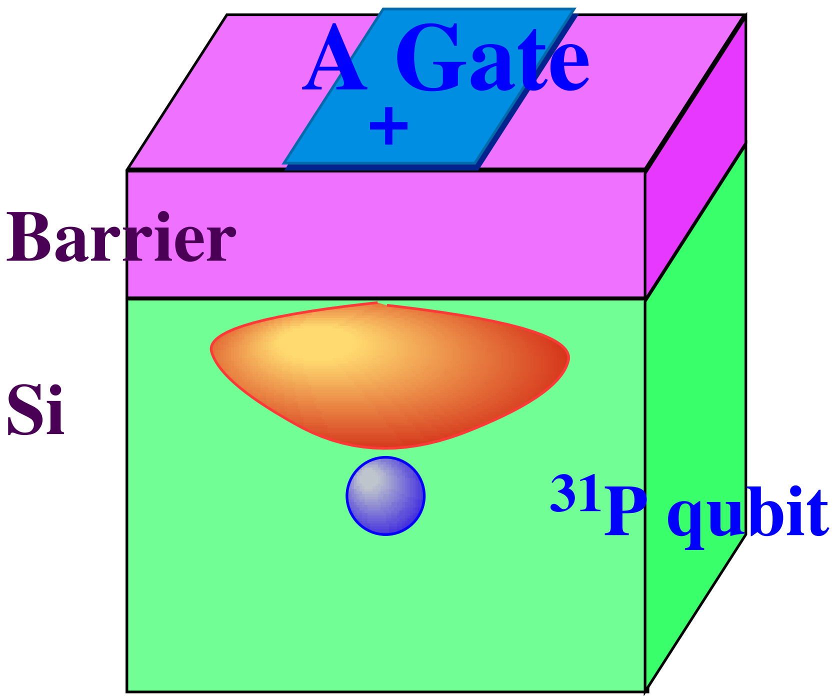


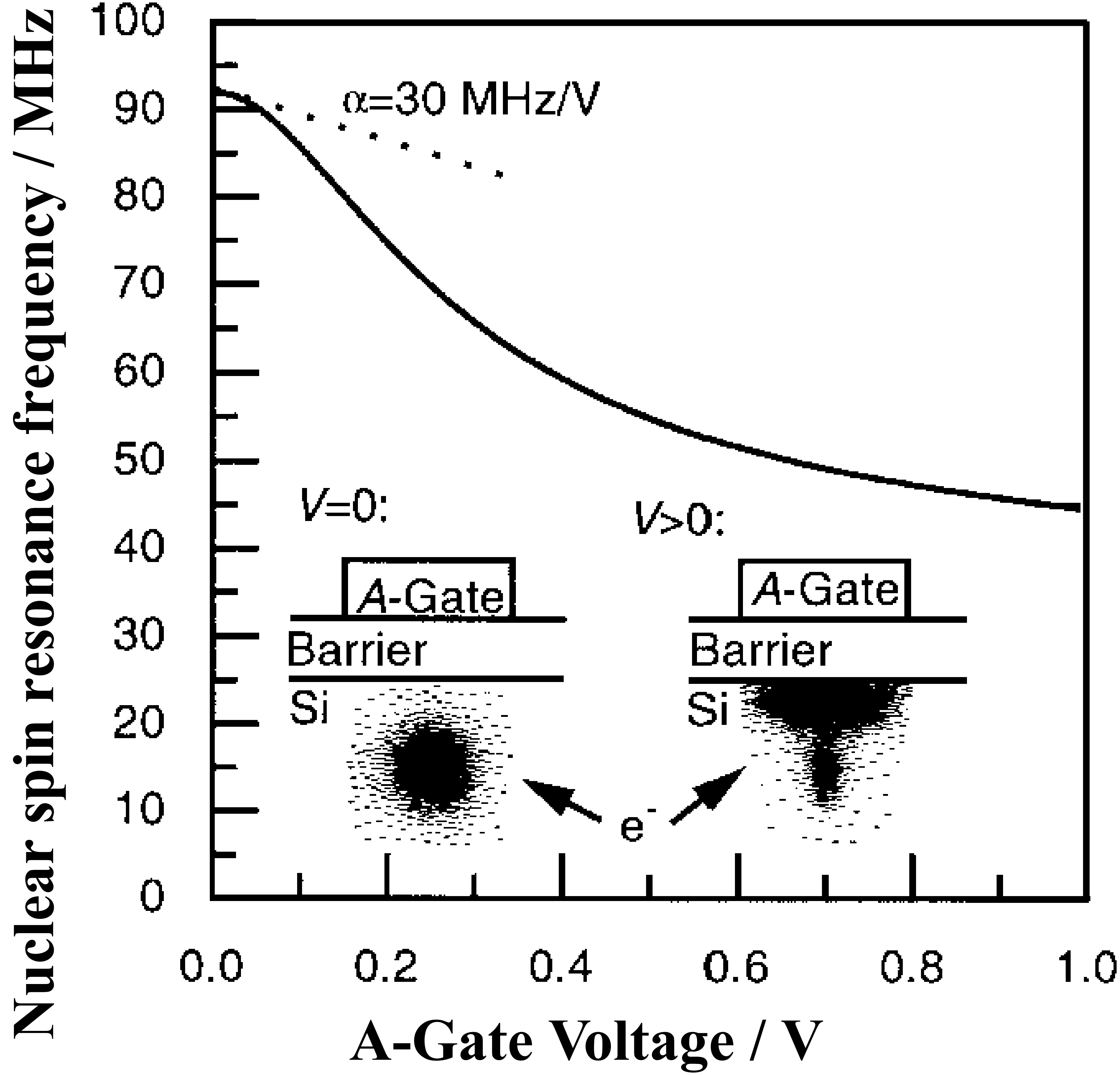


$|\Psi_{el}(\vec{r}_n)|$ large $\qquad |\Psi_{el}(\vec{r}_n)|$ small

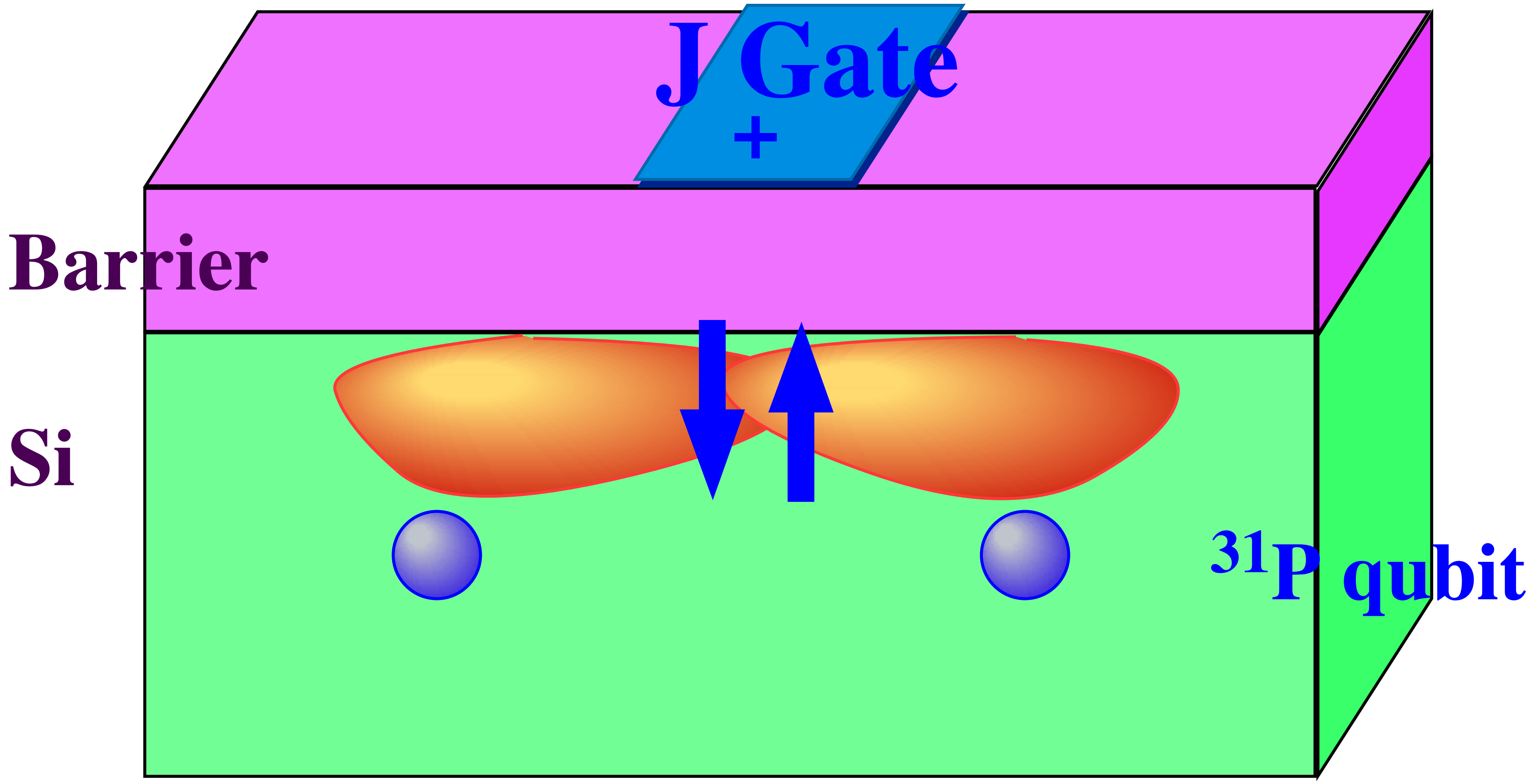
$\nu_0 \sim 90$ MHz $\qquad \nu_0 \sim 50$ MHz (for U ~ 0.7 V)

Electronic Frequency Tuning





Modify Couplings : J-Gates

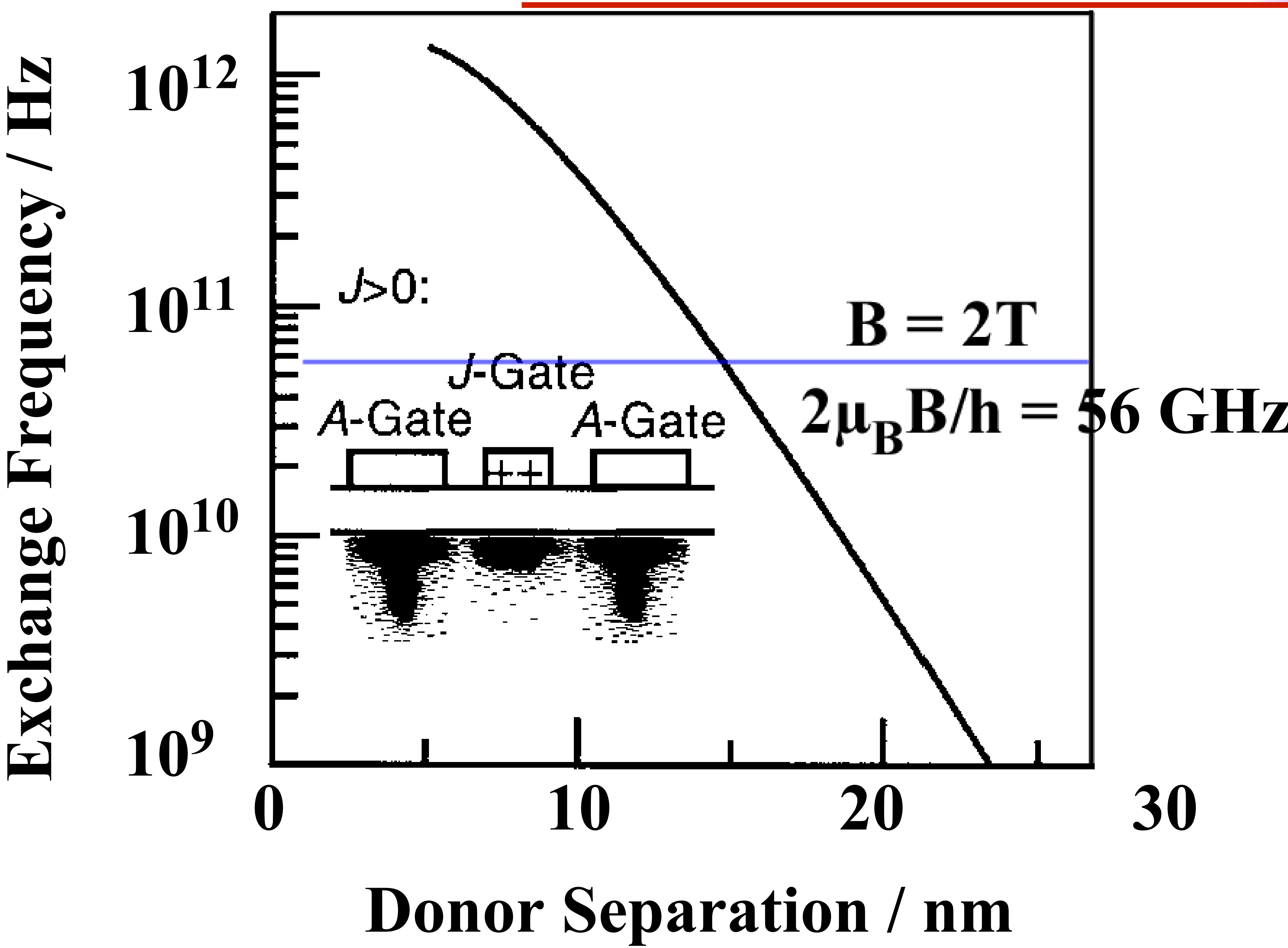


J gate draws electrons into overlap region

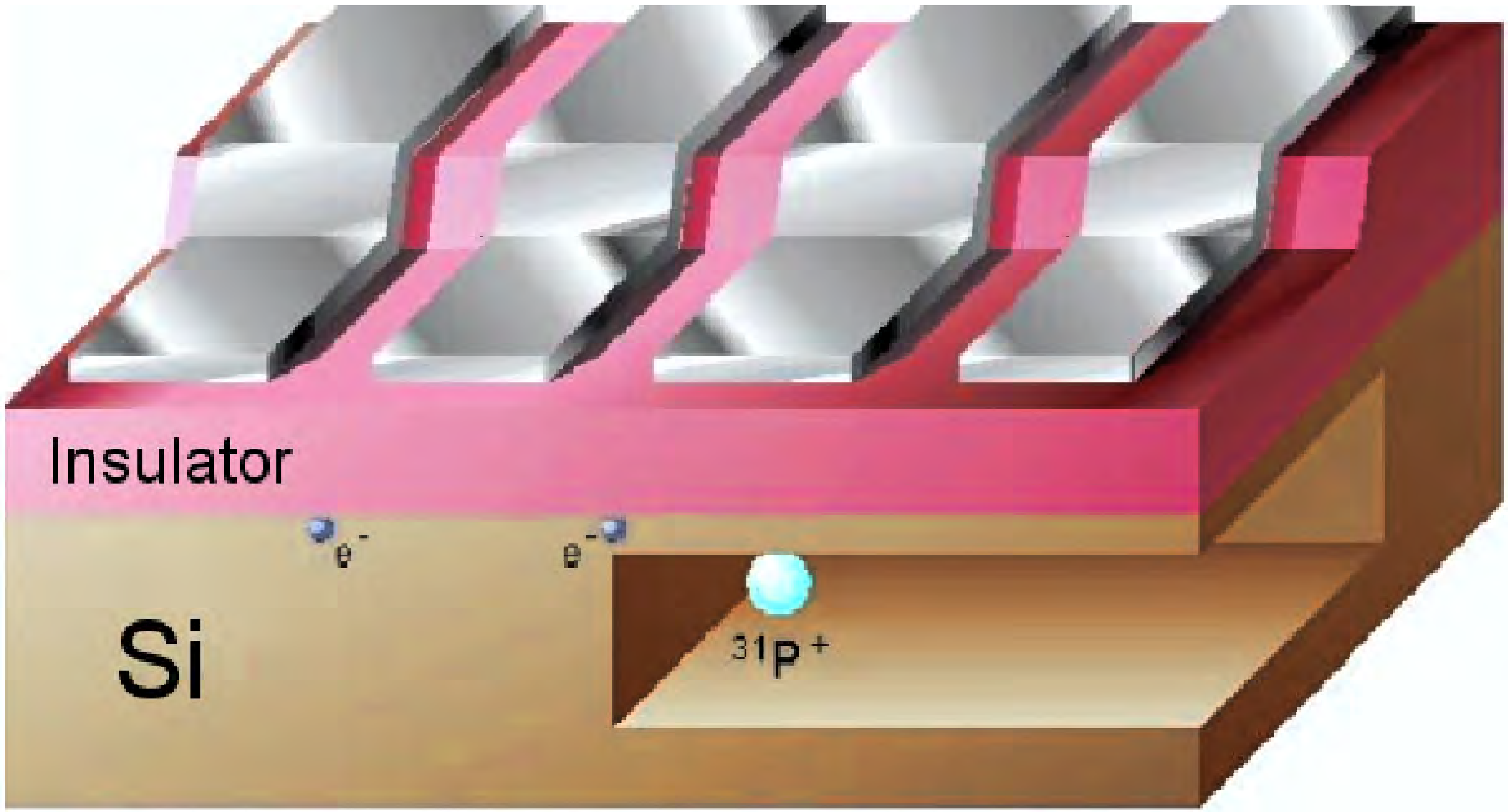
coupling operator: $\mathcal{H}_J = J\, \vec{I}_1 \cdot \vec{I}_2$

effective qubit-coupling: 75 kHz **depends on B-field, gates**

Tuning of Couplings



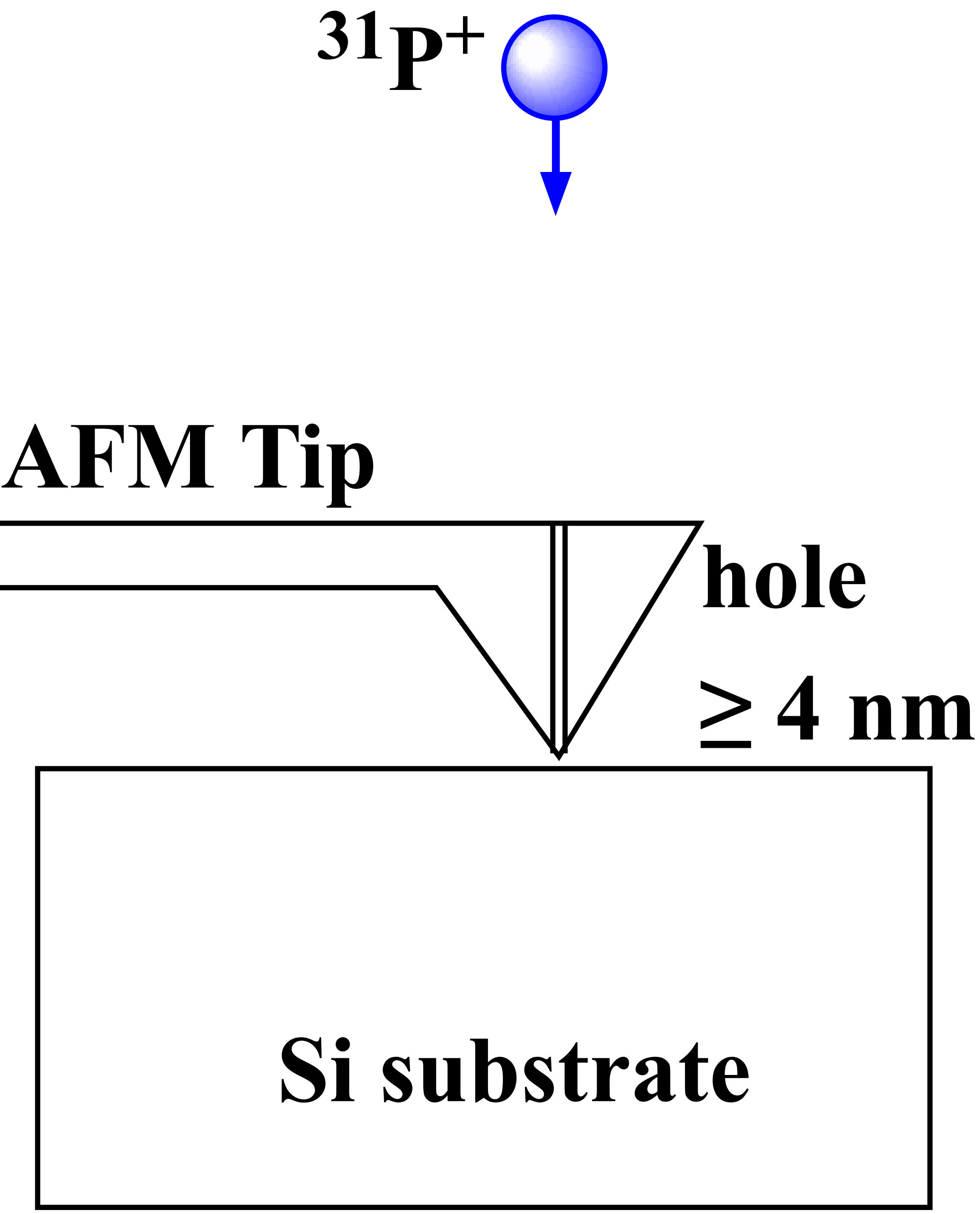
Donor Placement

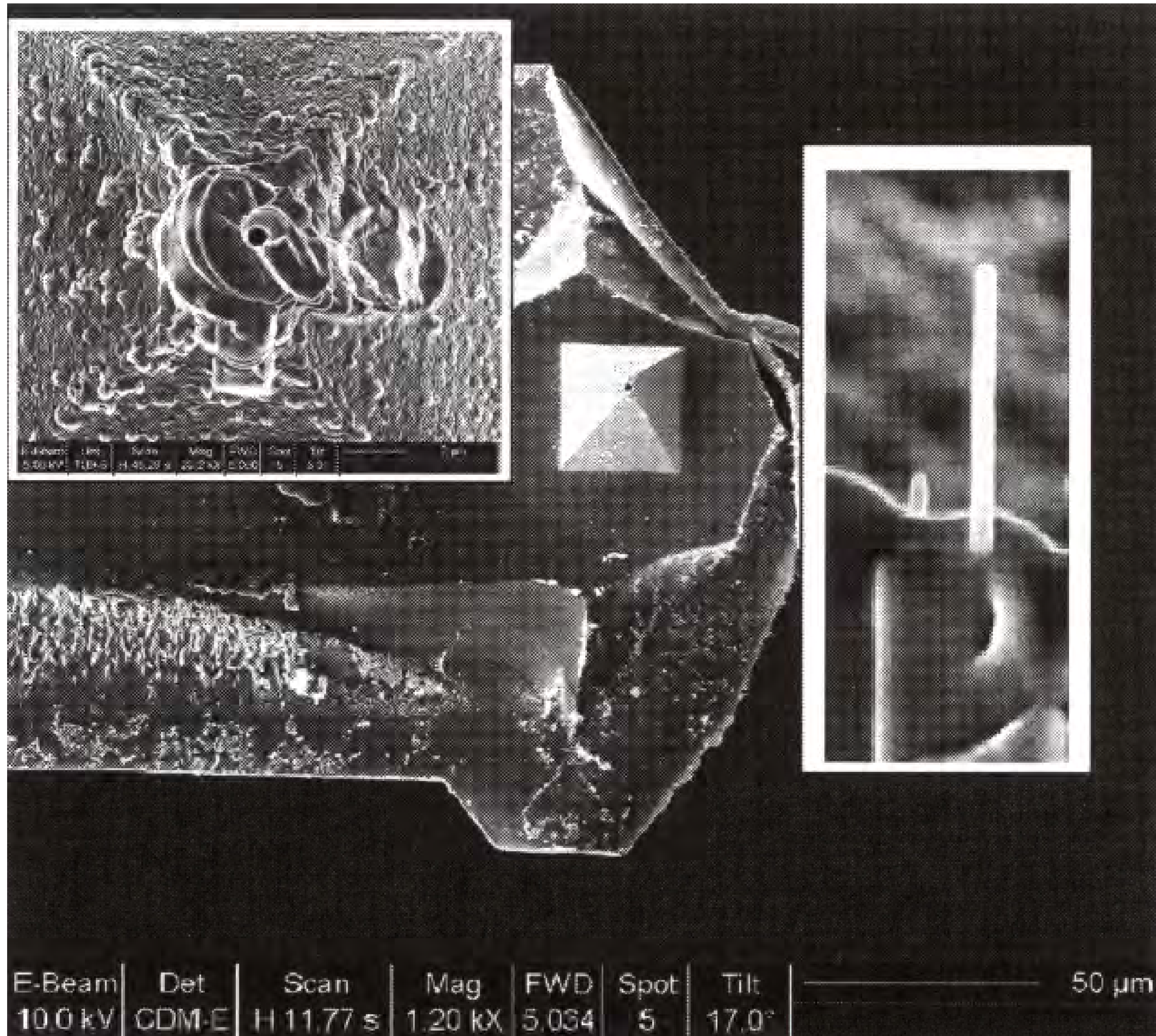


How to put exactly one atom at the right position ?

^{31}P Implantation

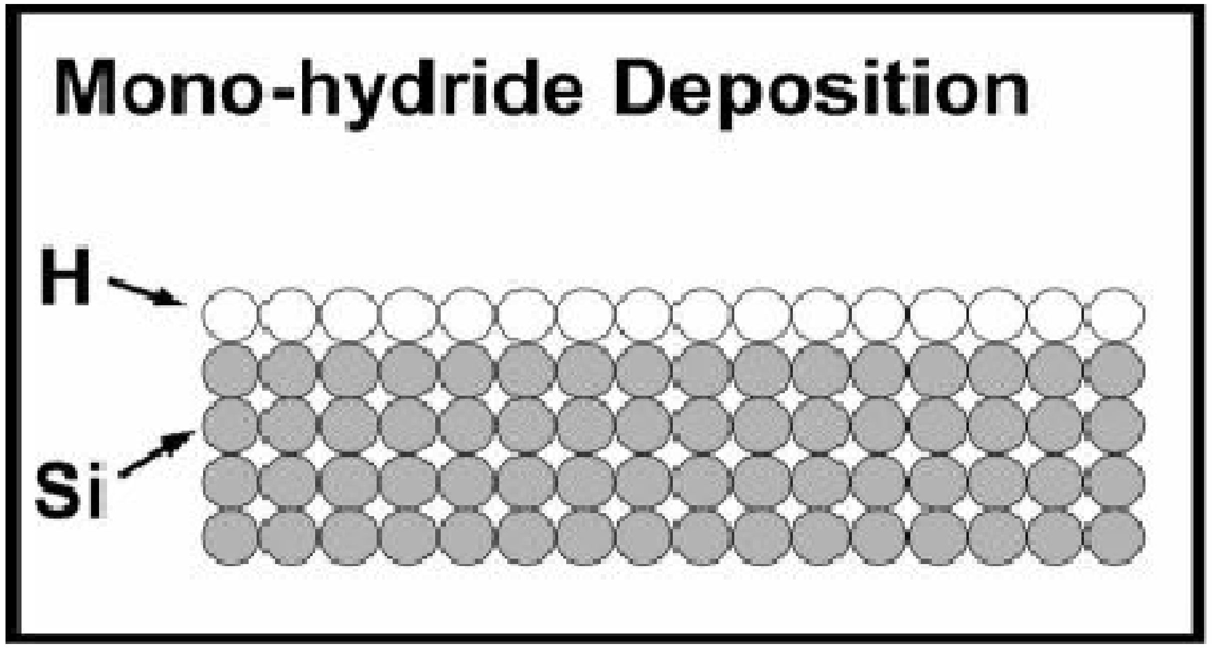
Focused ion beam

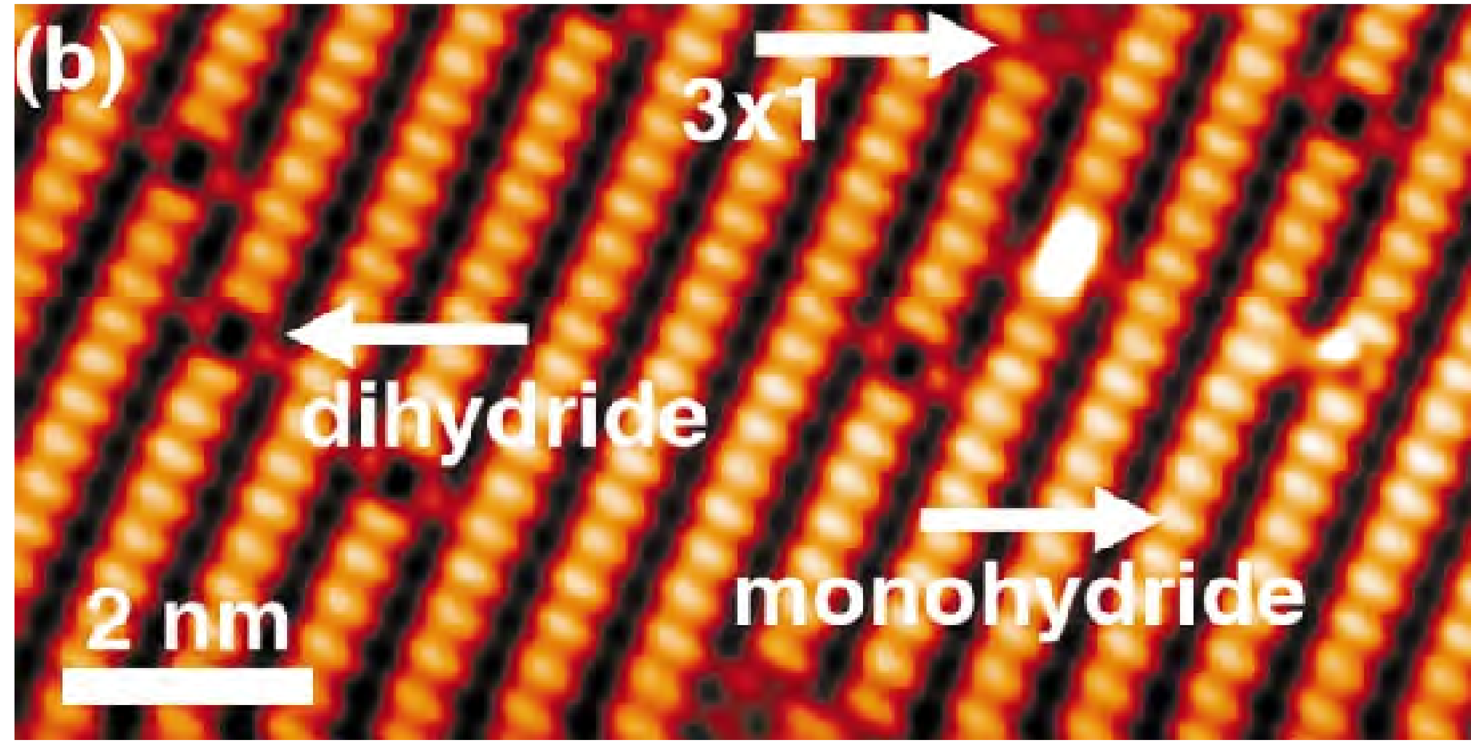




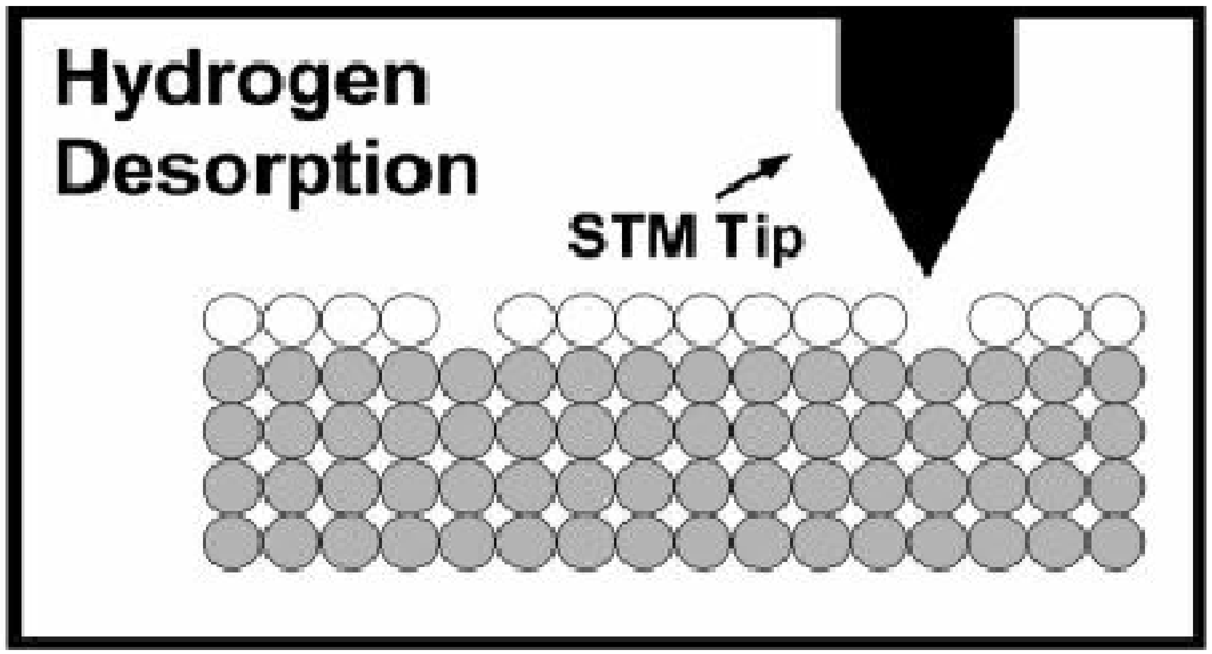
Depositing ^{31}P

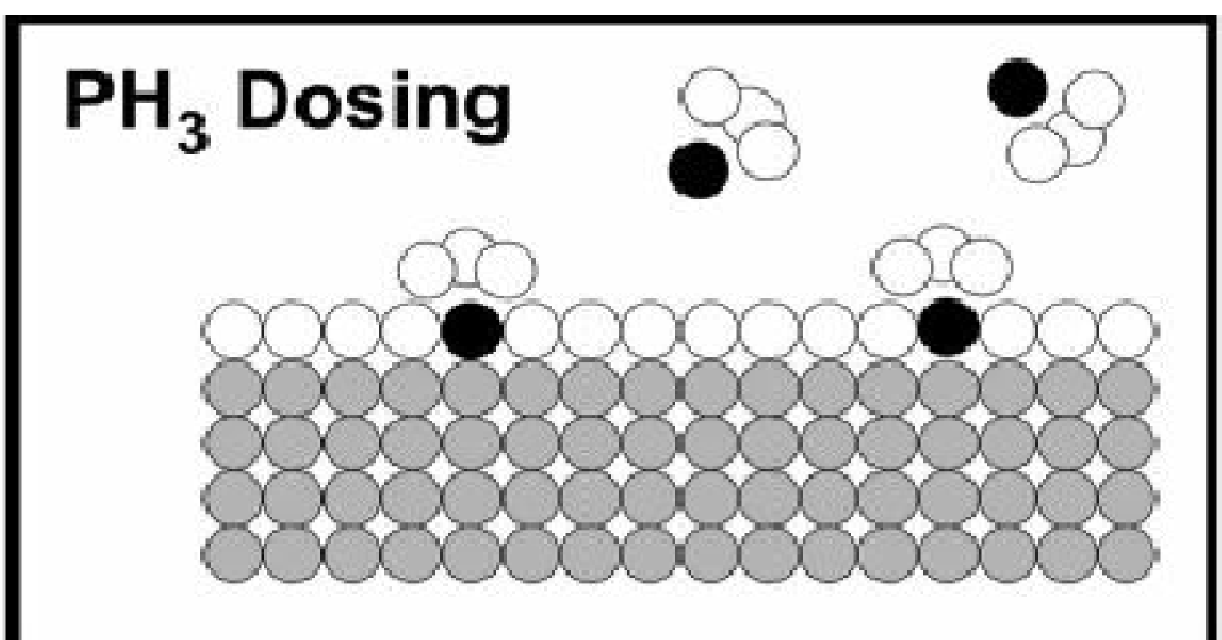
Phys. Rev. B, 64:161401 (2001).

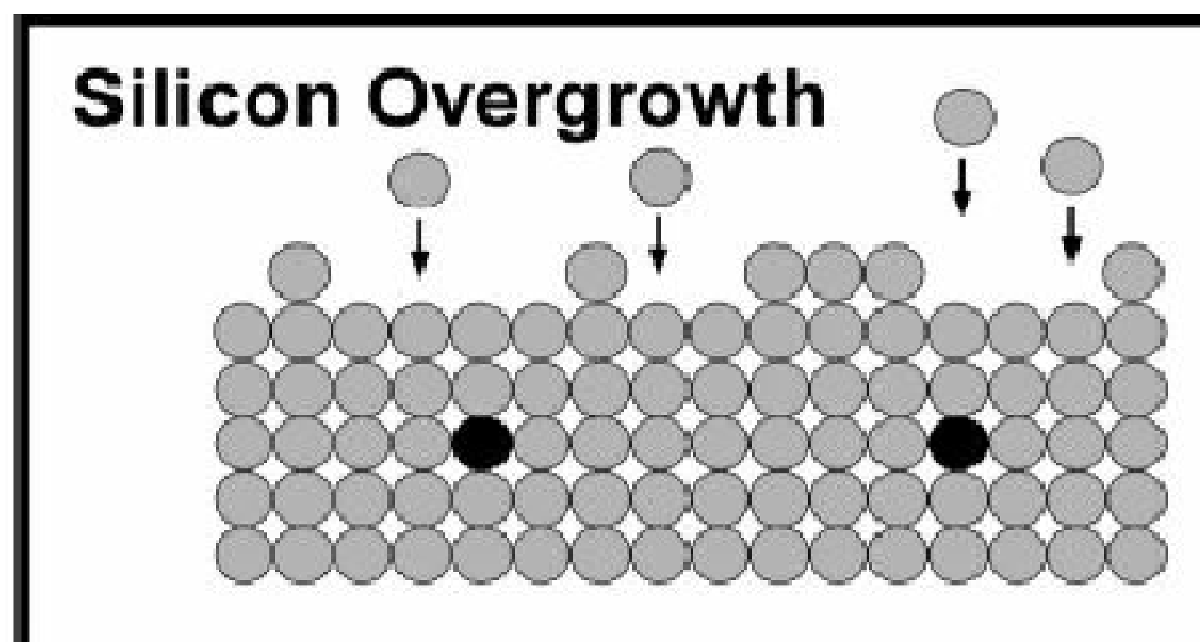




STM of H-terminated Si surface

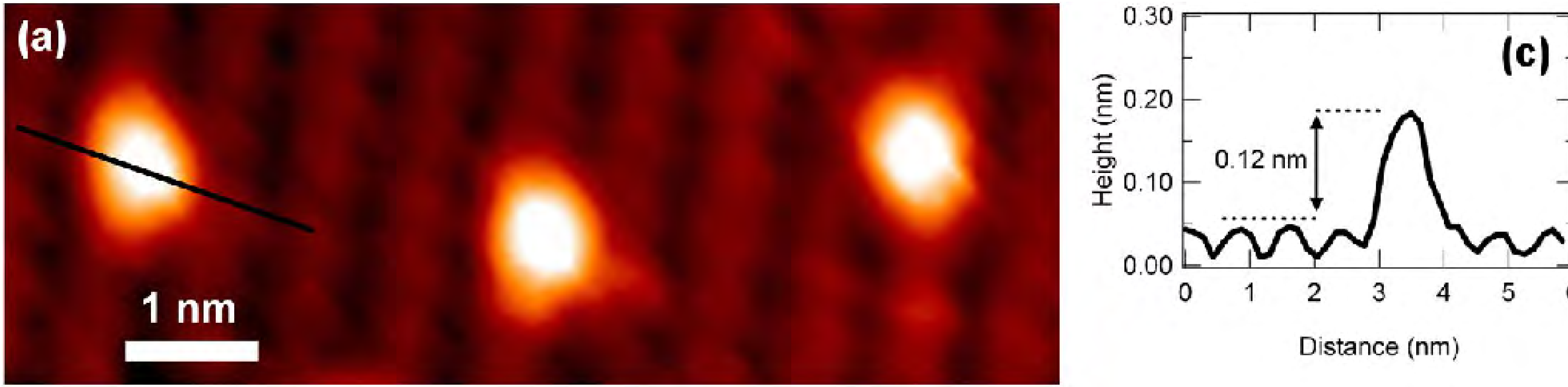




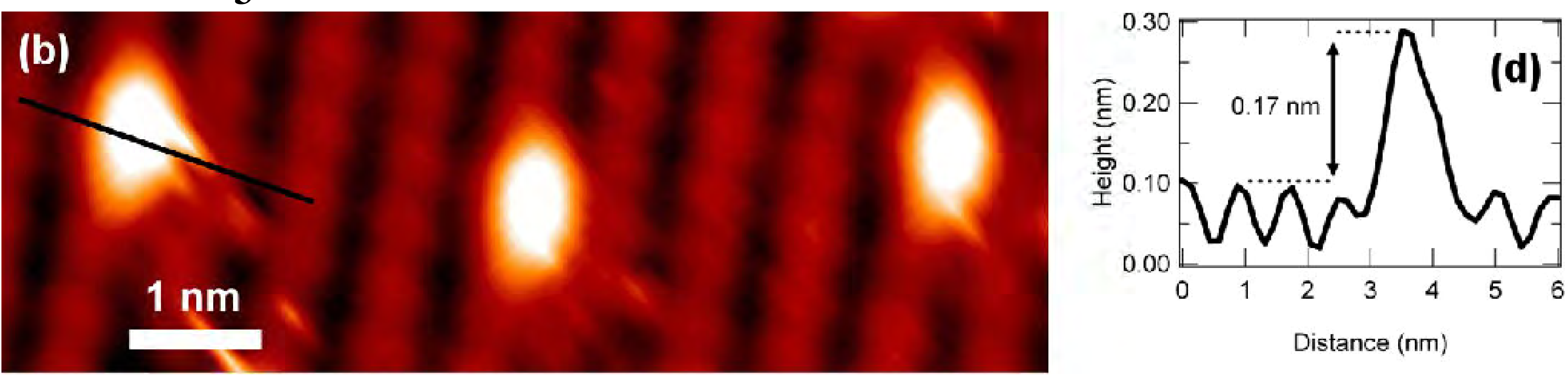


Chemisorbed ^{31}P

Hydrogen desorbed



After PH_3 dosing



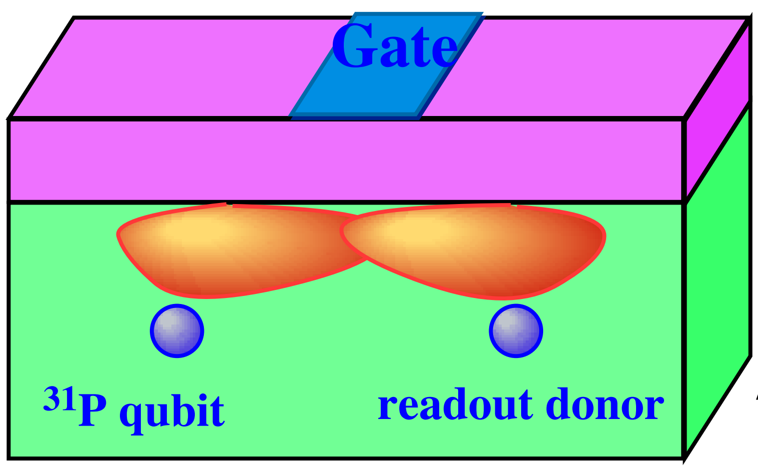
Phys. Rev. B, 64:161401 (2001).

Qubit Readout

DiVincenzo's rule 5: Qubit-selective readout.

1) Transfer qubit to electron spin

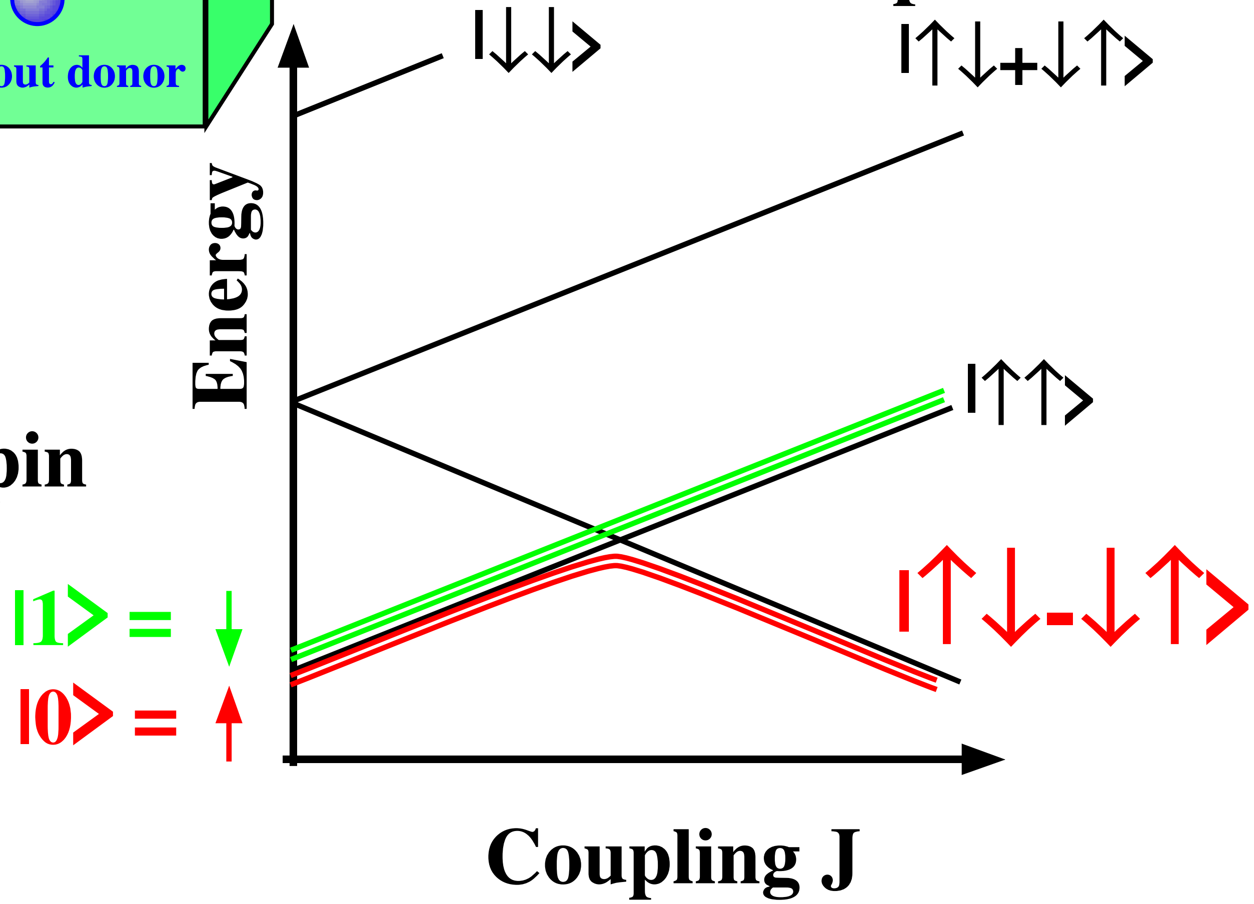
2) Transfer to readout donor



Scan converts |0> to electron singlet state

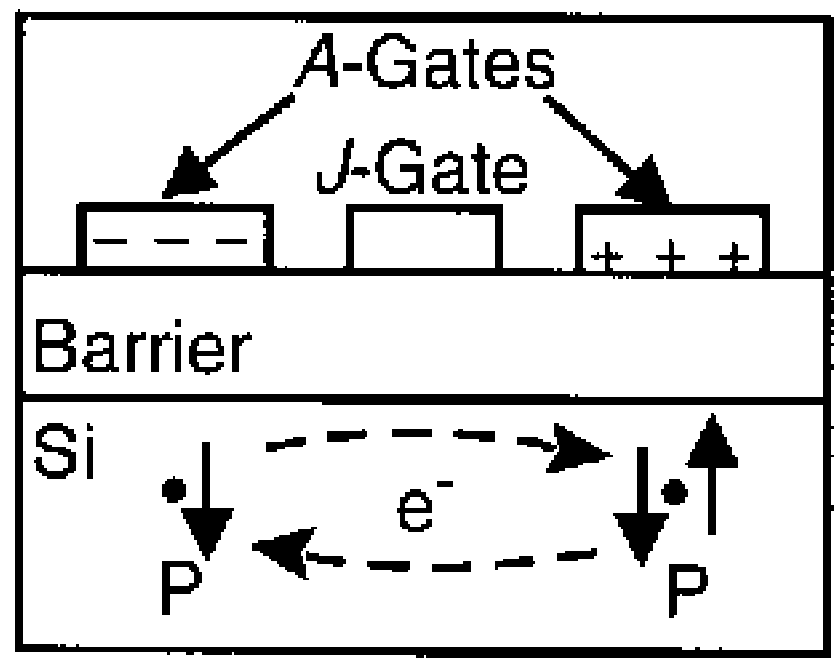
electron spins

nuclear spin



singlet pair can form D-

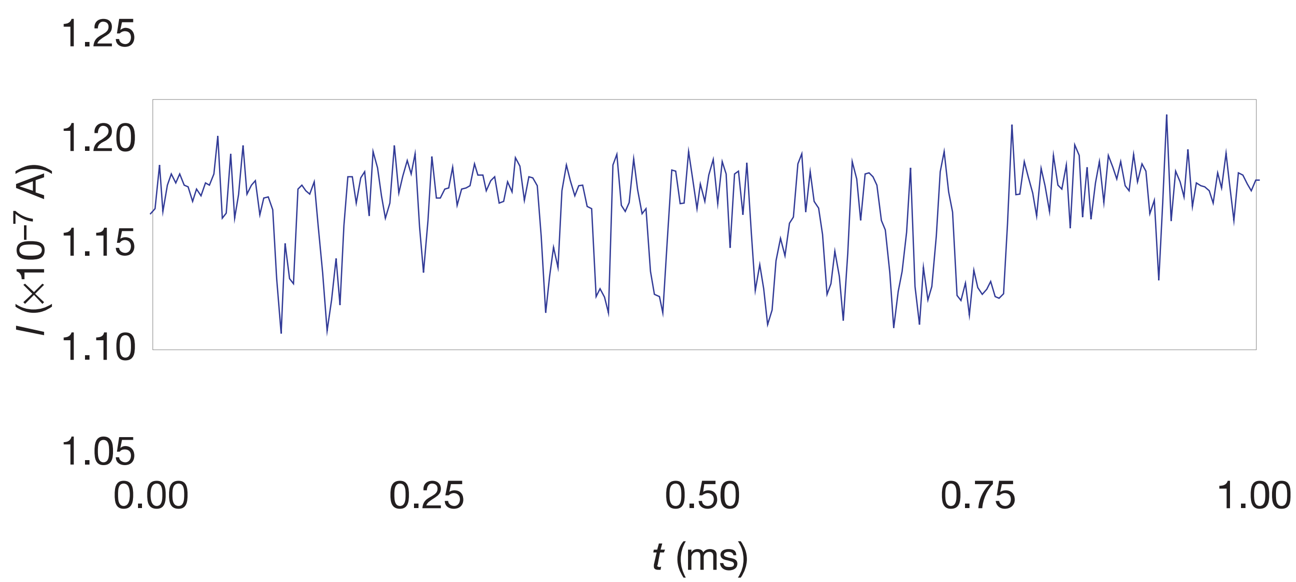
3) Detection of singlet state

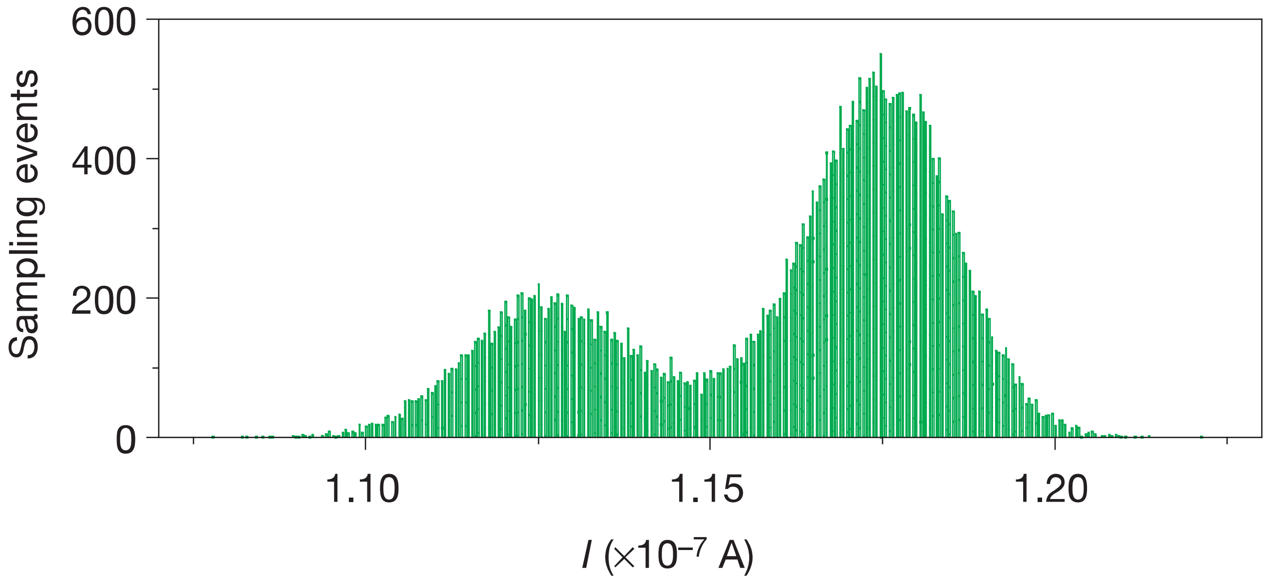


electrostatic detection of D-

Current State

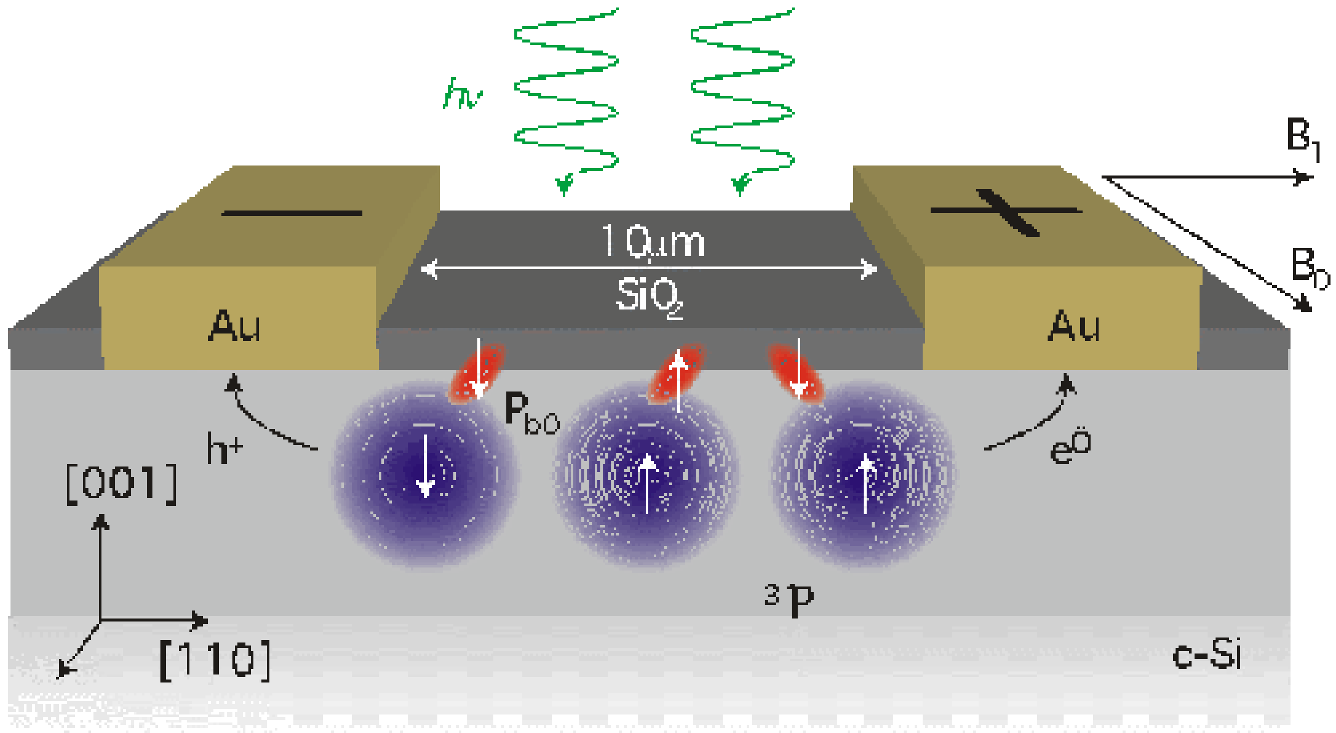
Single spin ESR

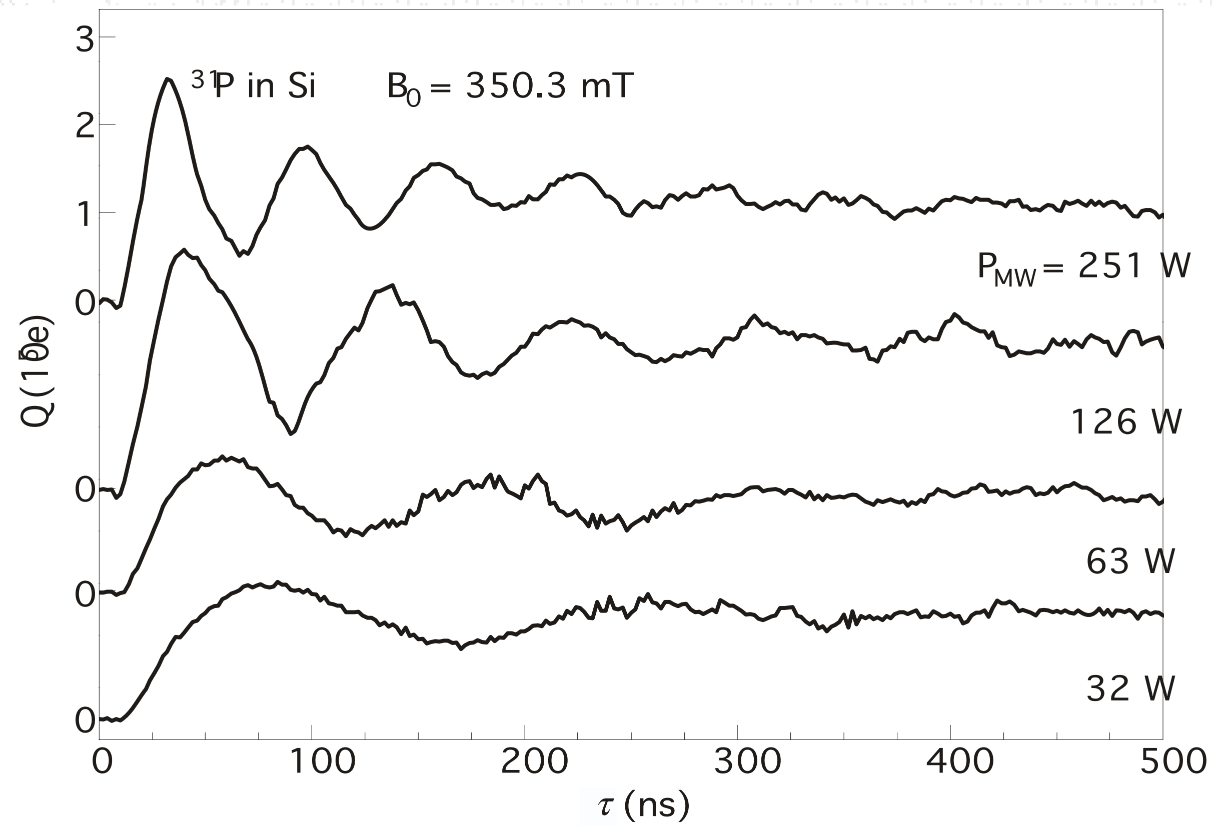




Xiao et al., Nature, 430, 435 (2004).

Coherent excitation

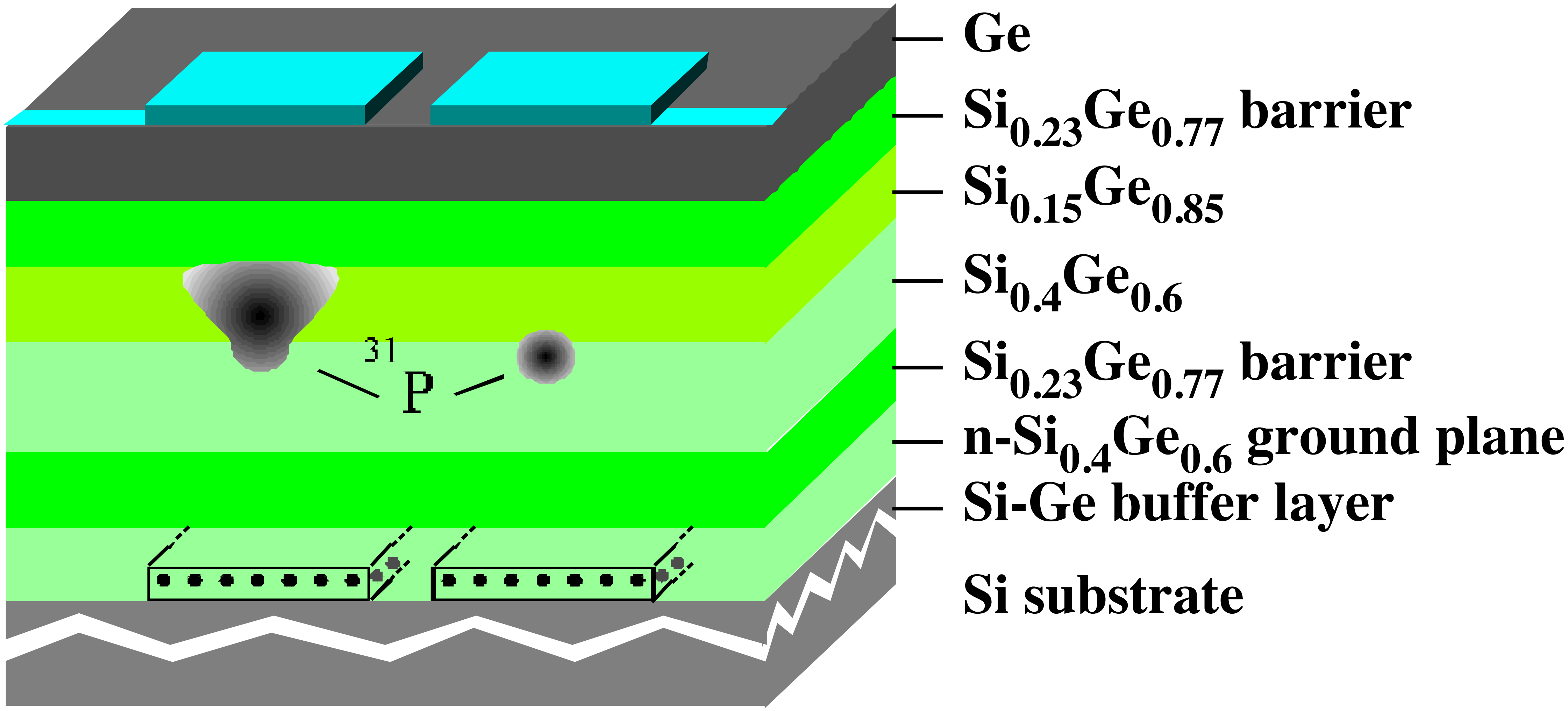




Stegner et al., Nature Physics 2, 835–838 (2006).

SiGe Spin-Transistor

R. Vrijen et al, Phys. Rev. A 62, 012306 (2000)



Modification of Kane proposal:

- Use SiGe heterostructure

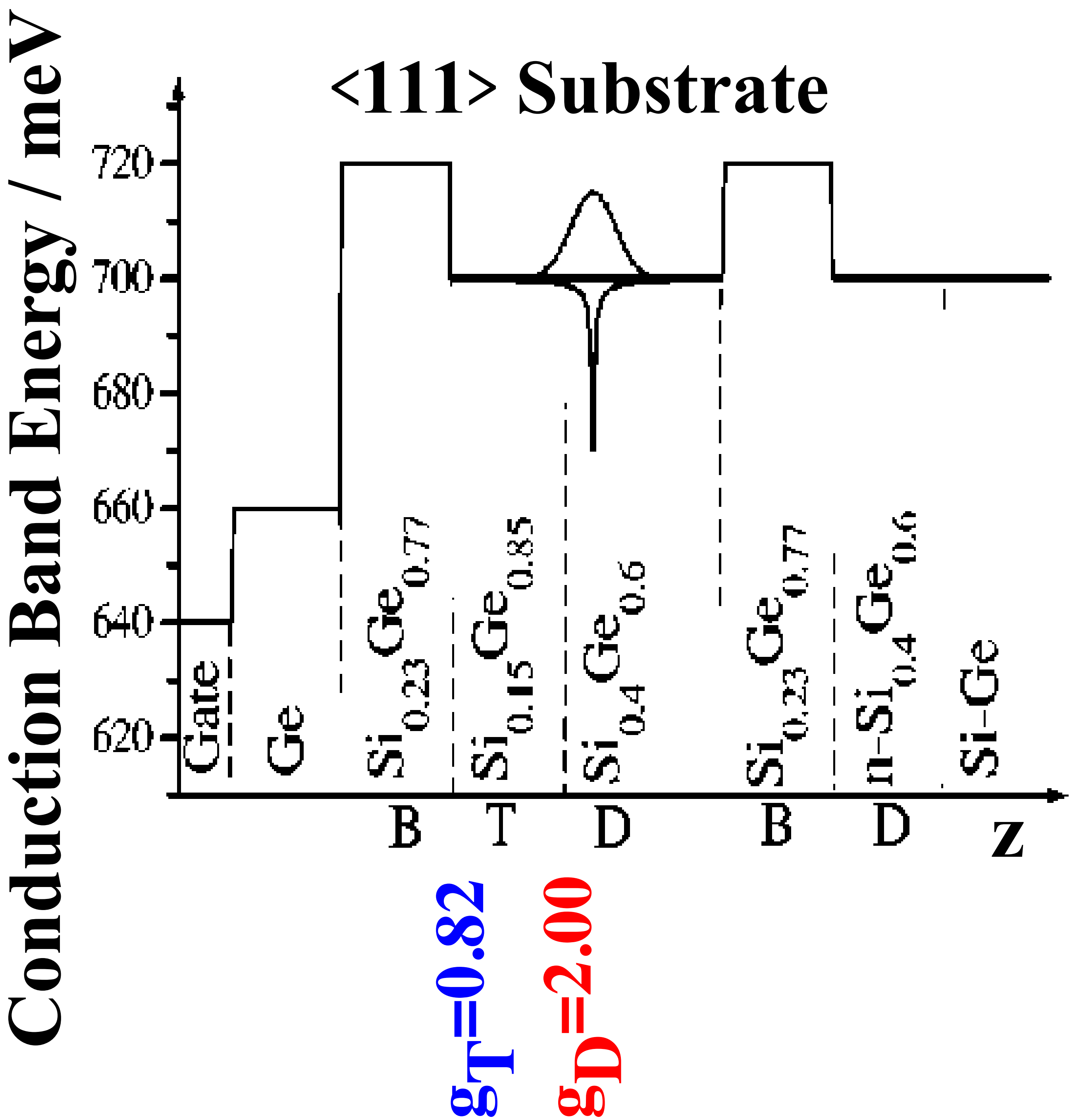
- Use electron spin instead of nuclear

- Only one type of gates needed

g-factor Tuning

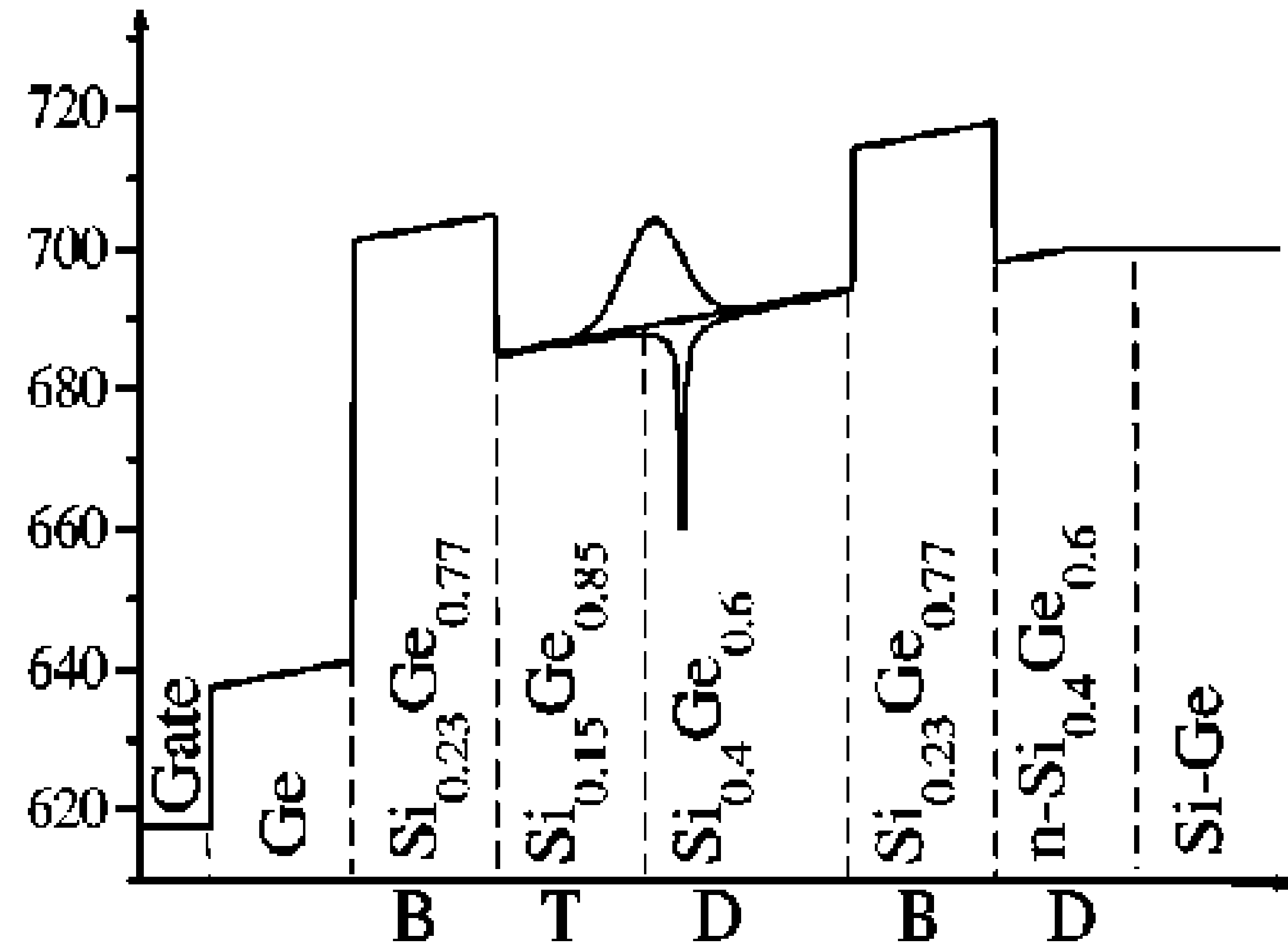
gate off

<111> Substrate



g_{av}=2.00

biased gate



g_{av}~1.5

1-qubit gates

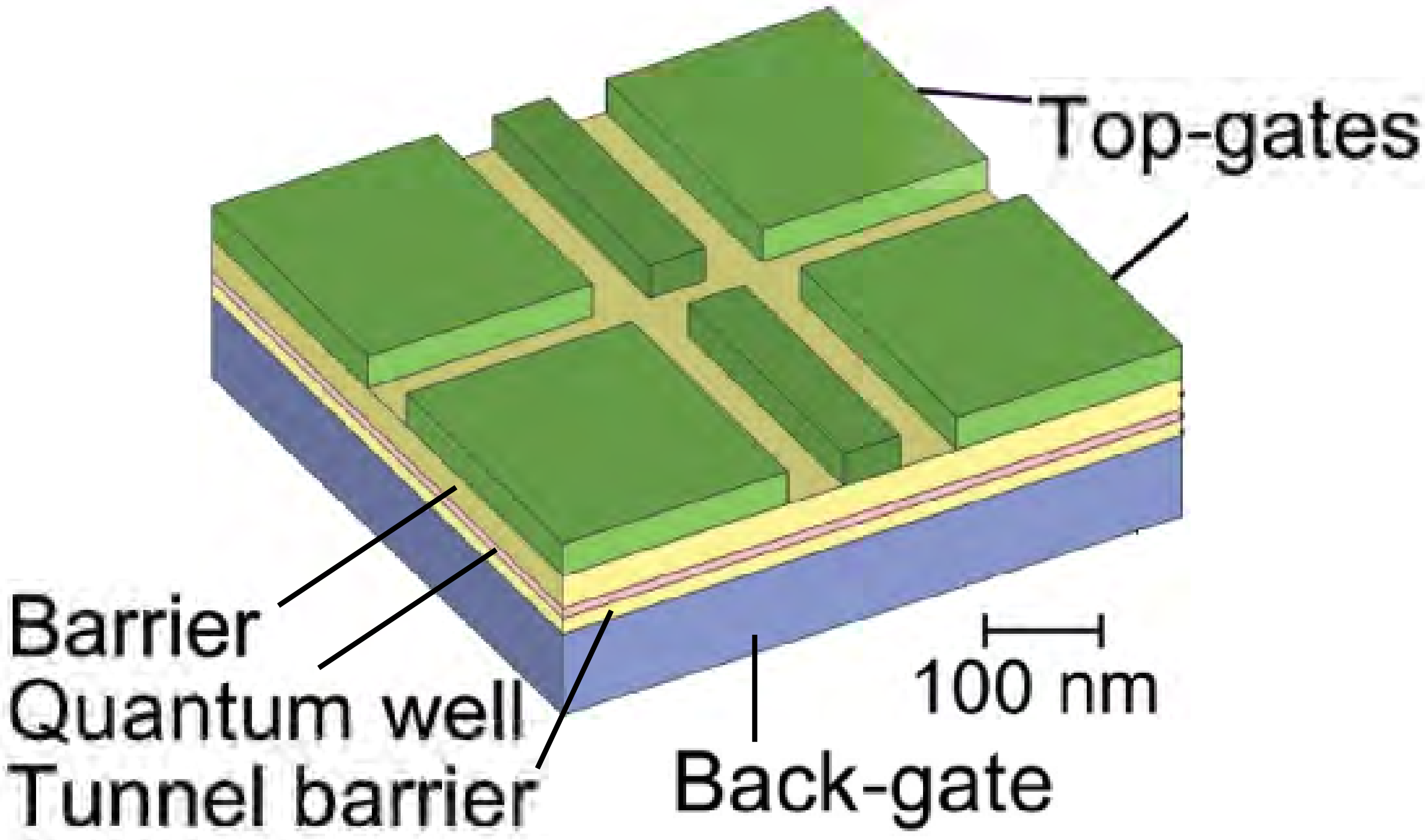
also changes Bohr radius
can be used for 2-qubit gates

Quantum-Dot Qubits

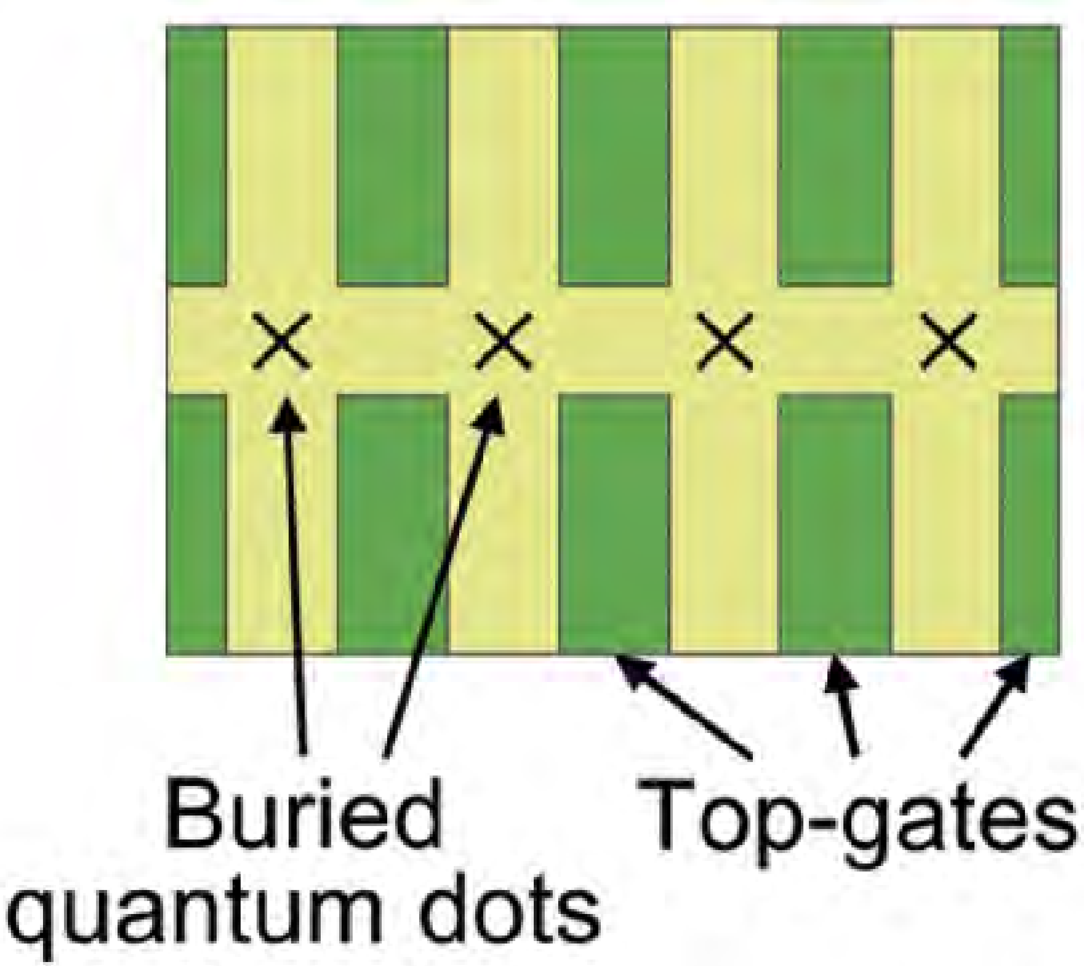
M. Friesen et al., PRB 67, 121301 (2003).

Electrostatically confined quantum dots in Si - SiGe QW

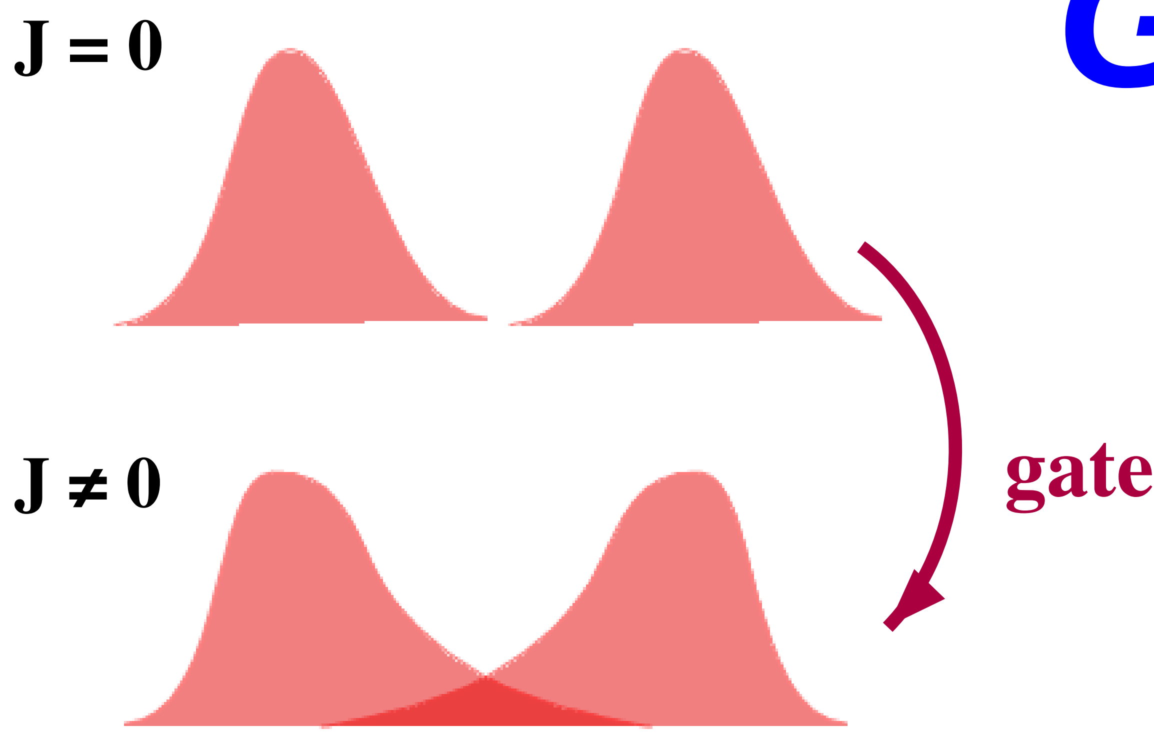
2 qubits



4 qubits

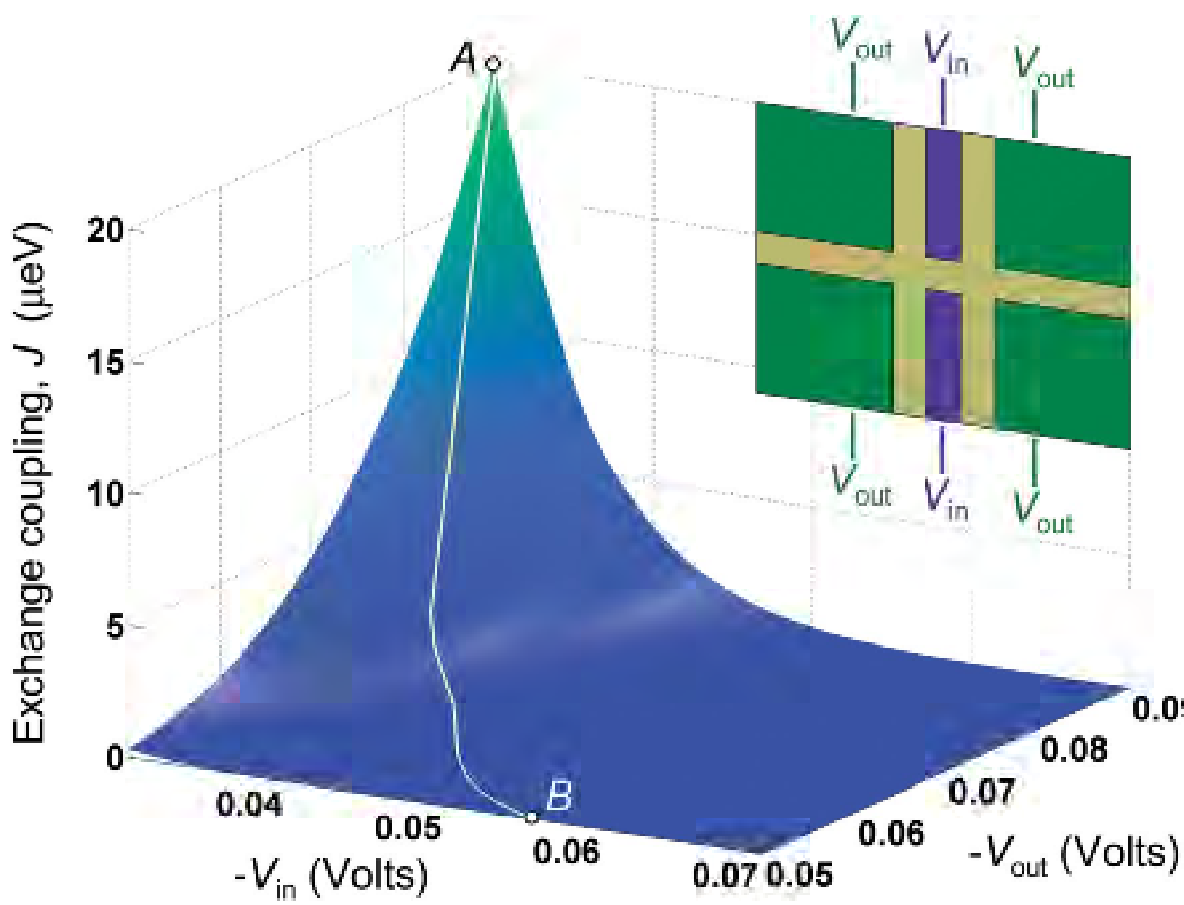


Gated Exchange



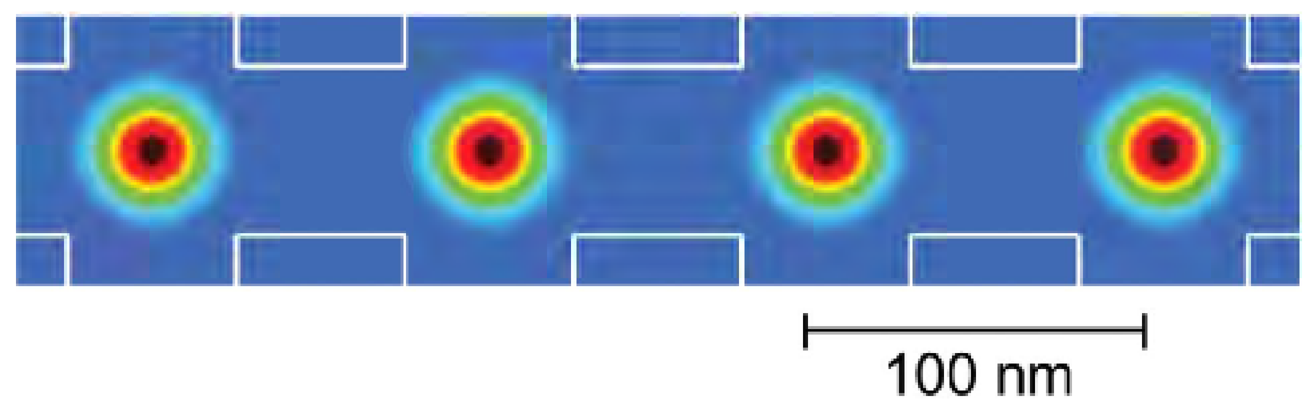
$$\mathcal{H}_J = J\,\vec{S}_1 \cdot \vec{S}_2$$

Tuning of exchange in 2-qubit system

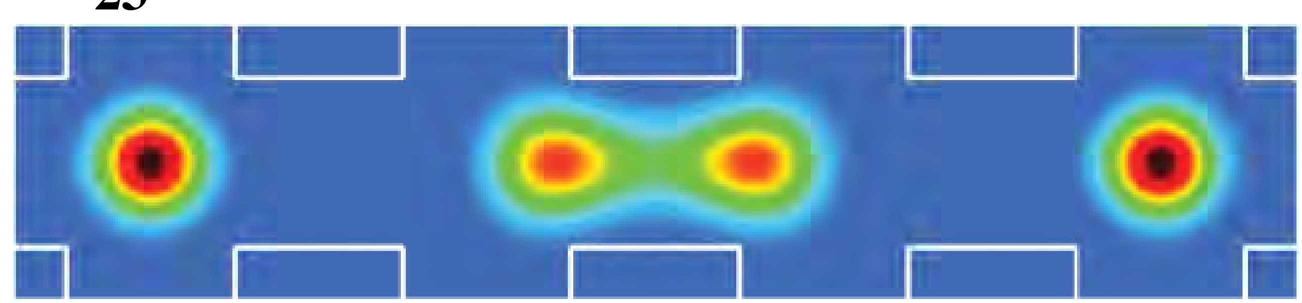


4-qubit system

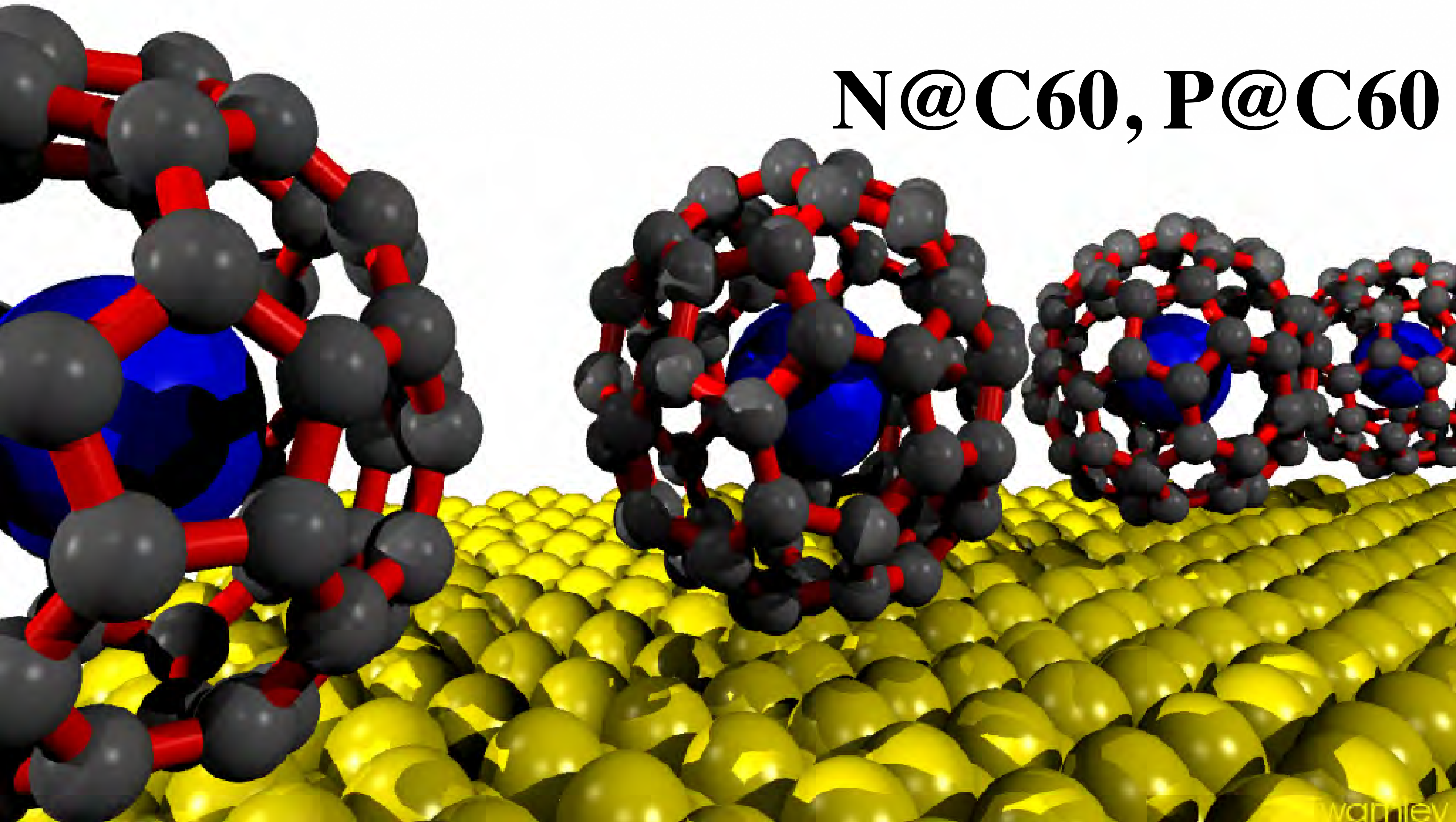
J = 0



J_{23} = 100 MHz

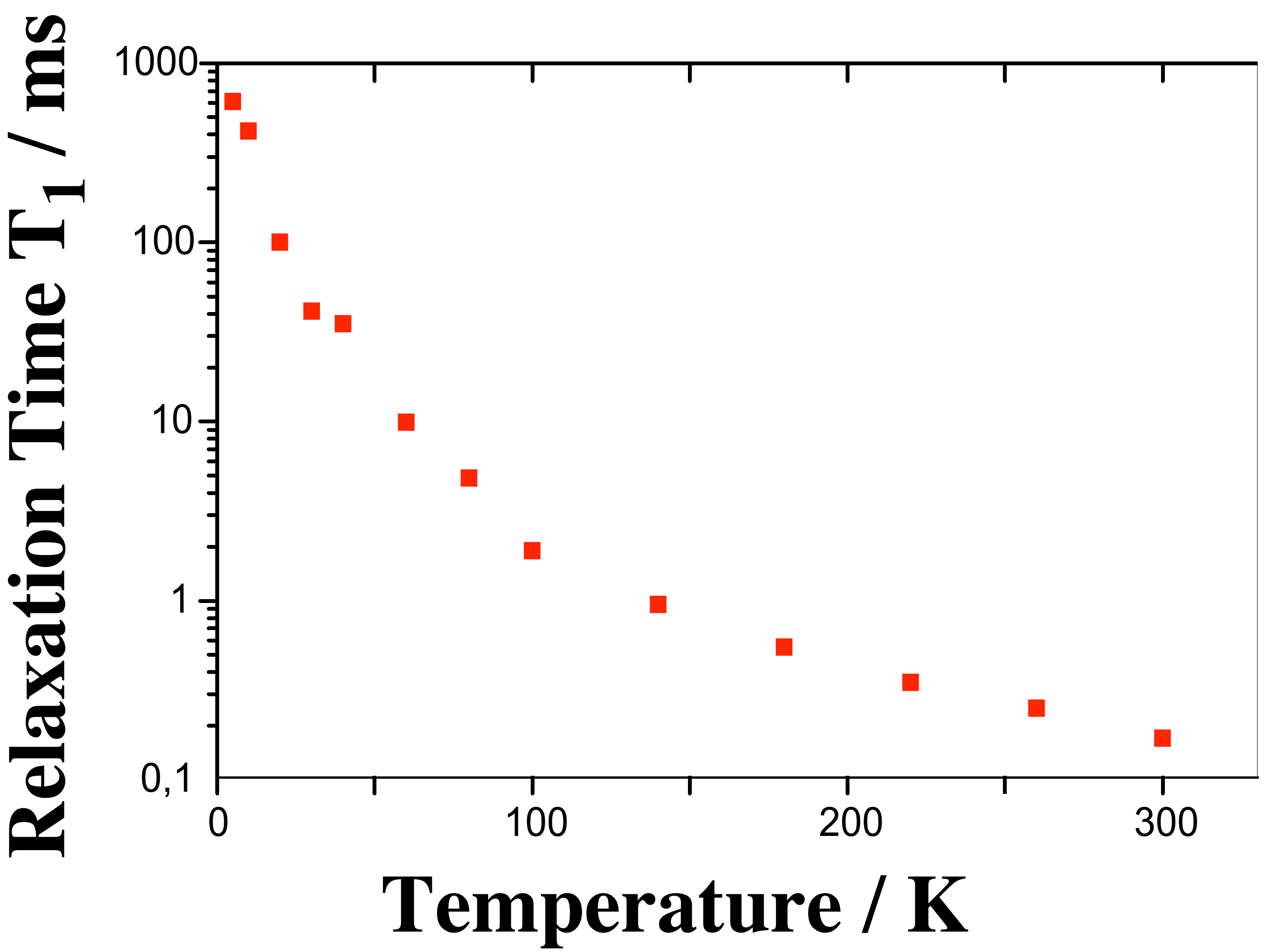


Endohedral Fullerenes



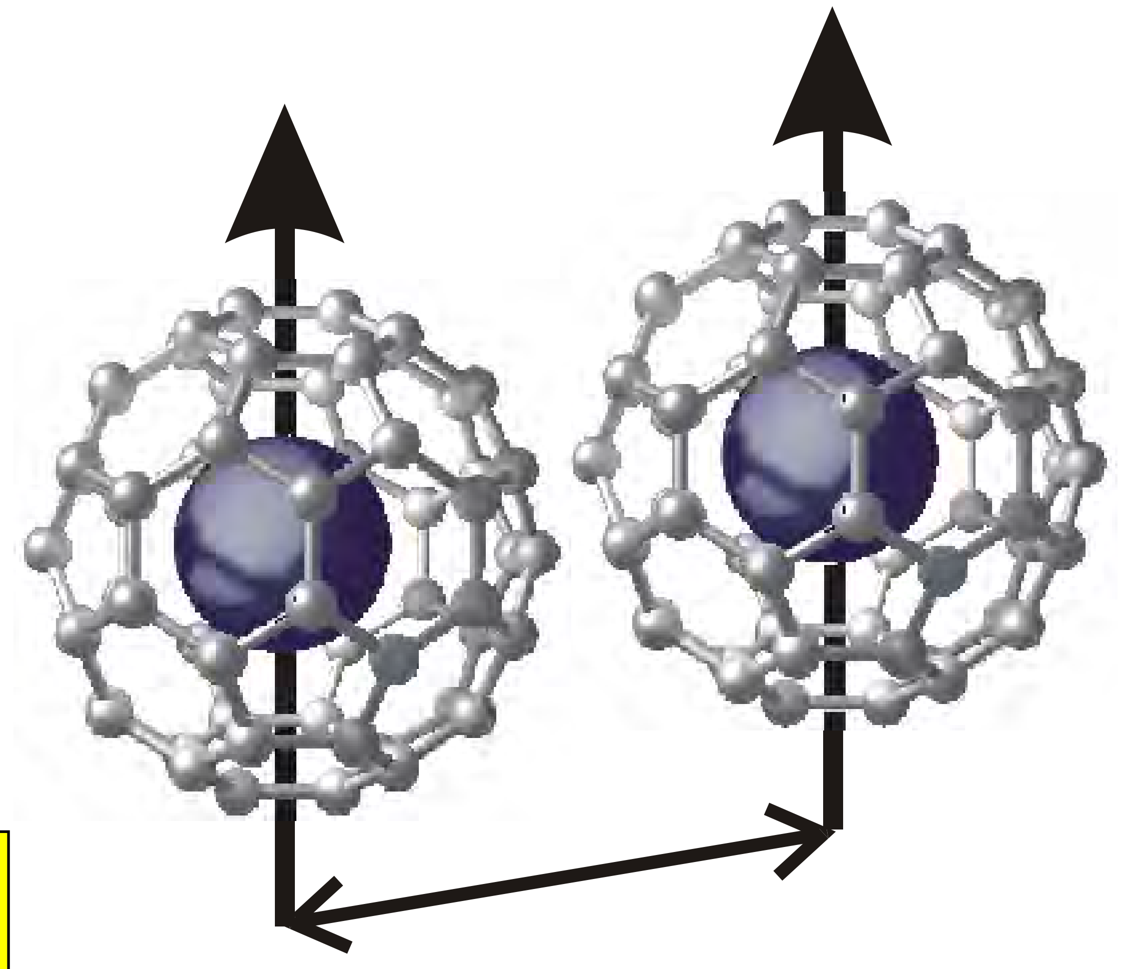
Why N@C_{60} ?

Decoherence Time vs. **Switching Time**



may be ~ 10 ns

based on dipole-dipole coupling @ 1 nm

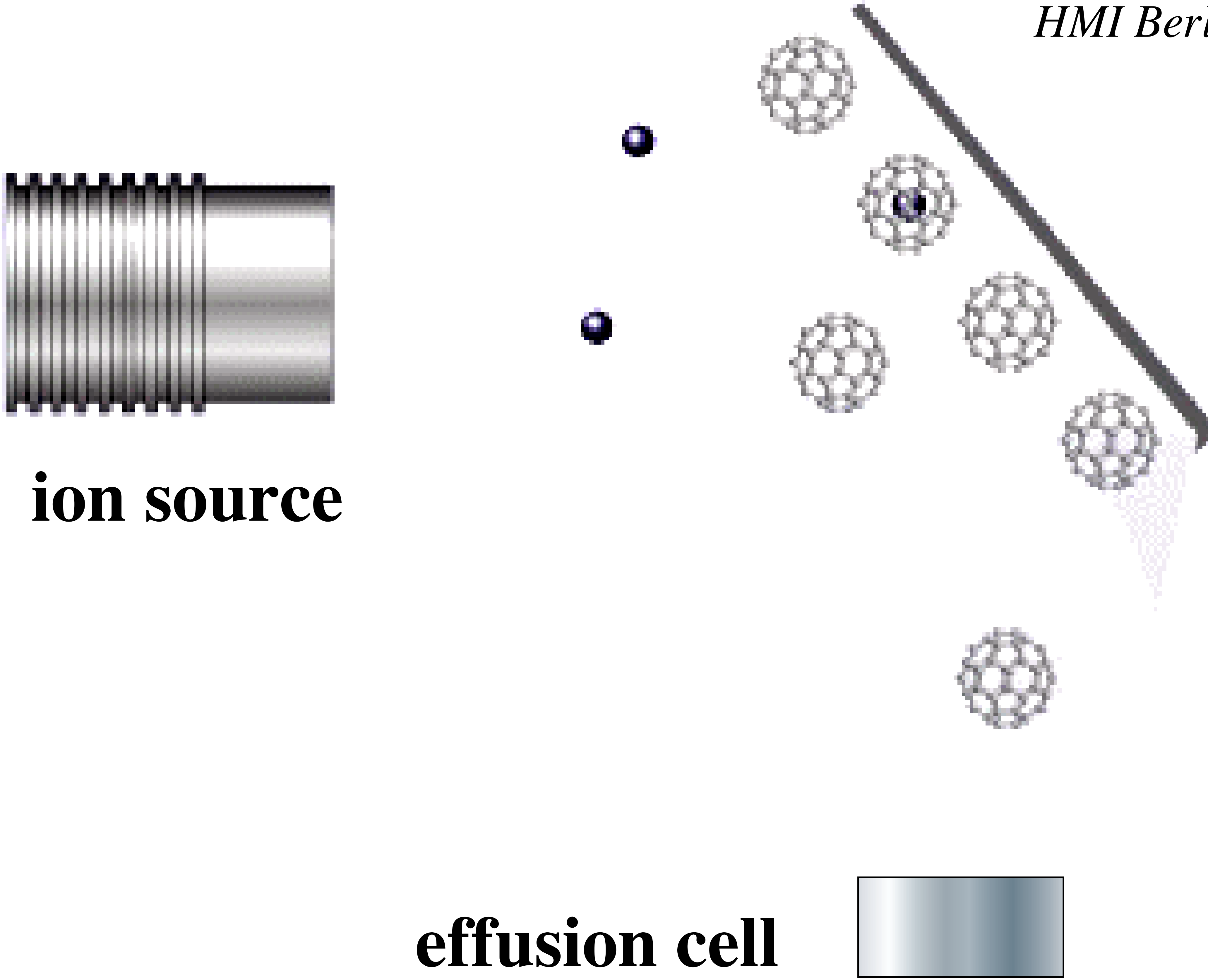


→ # gates ~10^8

Production

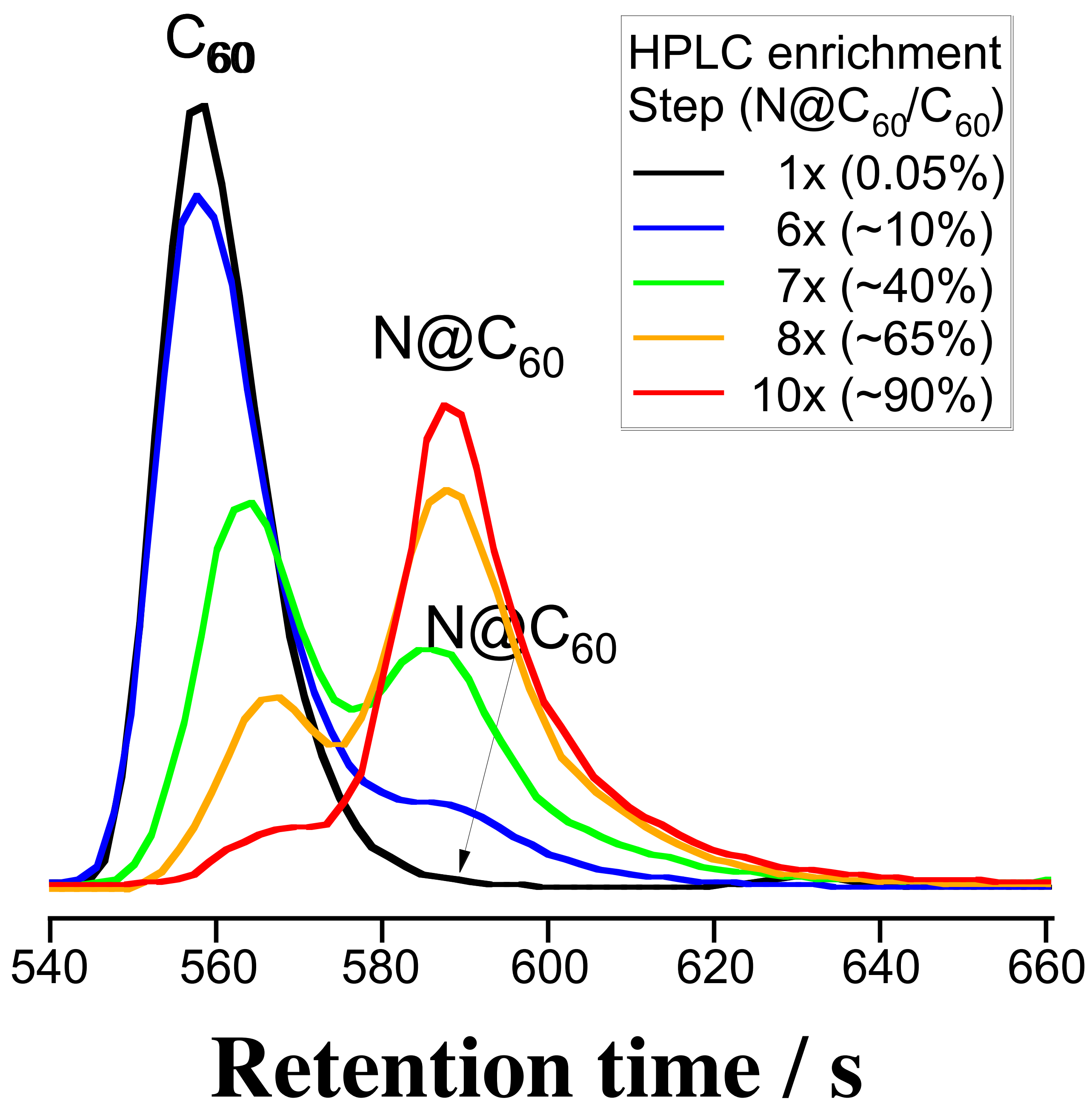
Implantation into empty cages

HMI Berlin

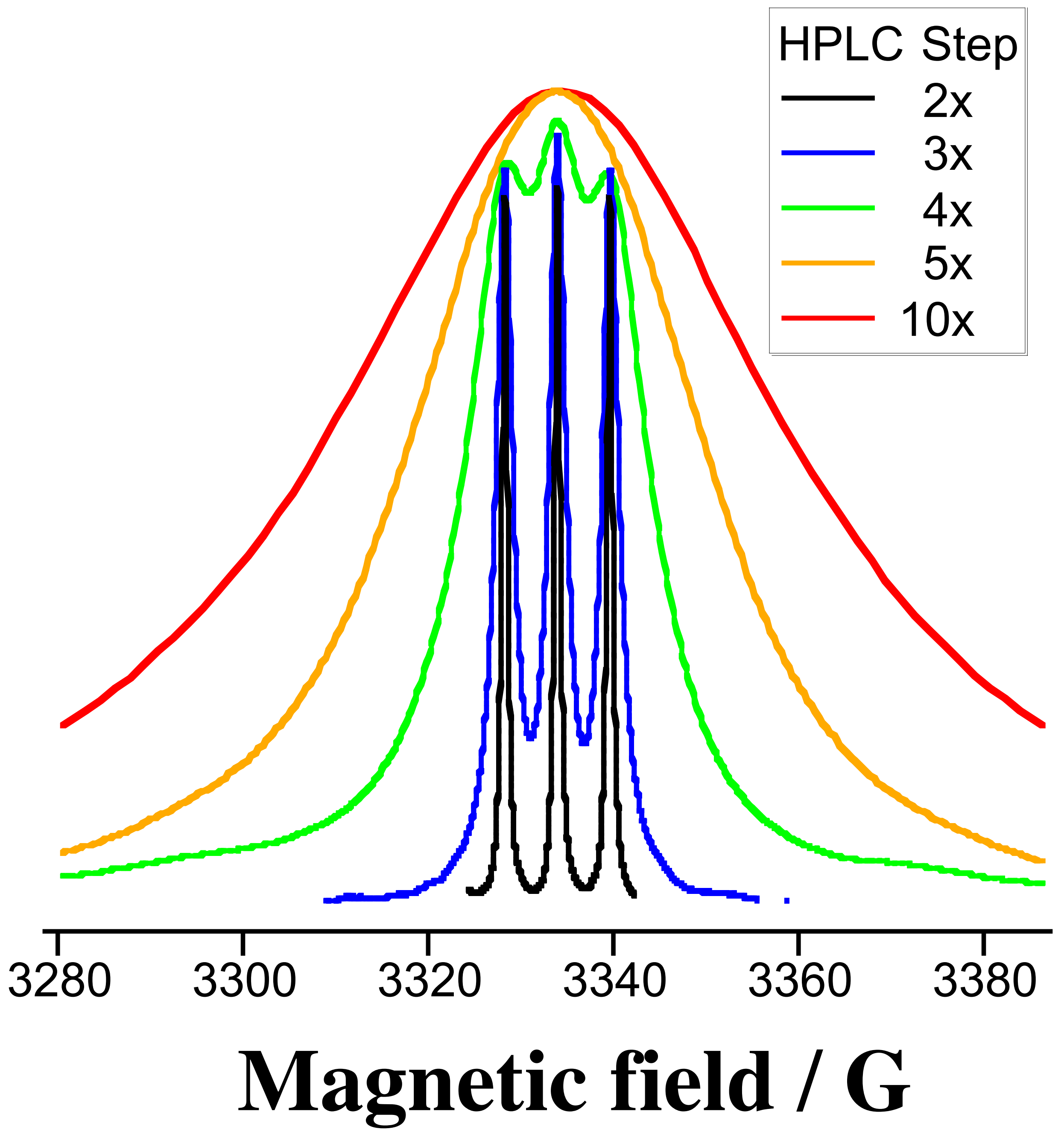


Purification by HPLC

HPLC Chromatograms



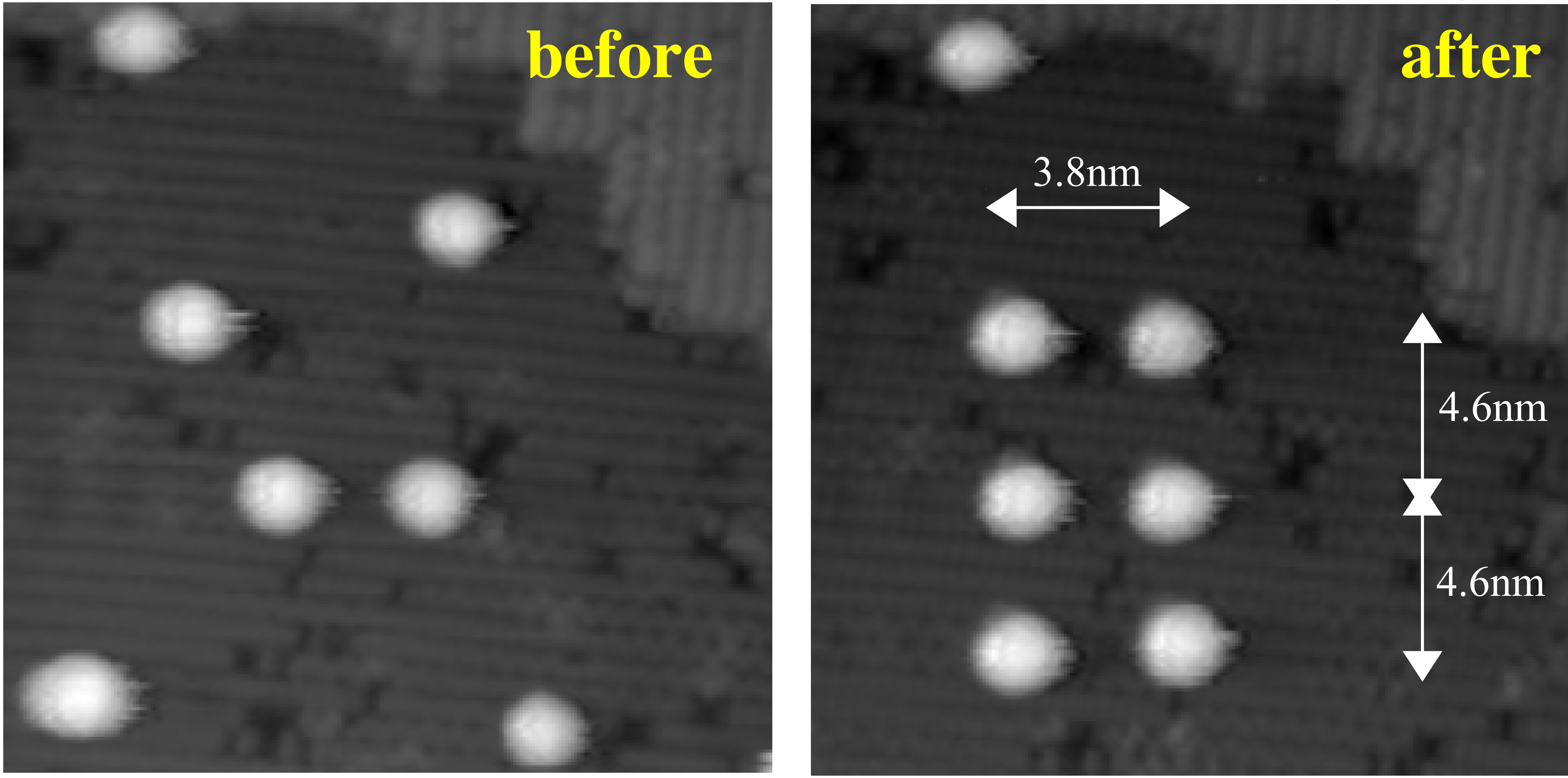
EPR Spectra



$C_{59}N$ on Si

Nano-Positioning

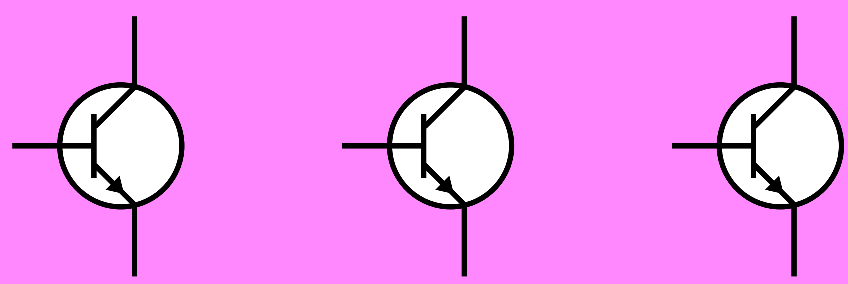
University of Nottingham



- **Accuracy of positioning determined by surface lattice constant.**
- **Manipulation process does not induce additional defects on underlying surface**

Addressing Qubits

Solid-State Computer

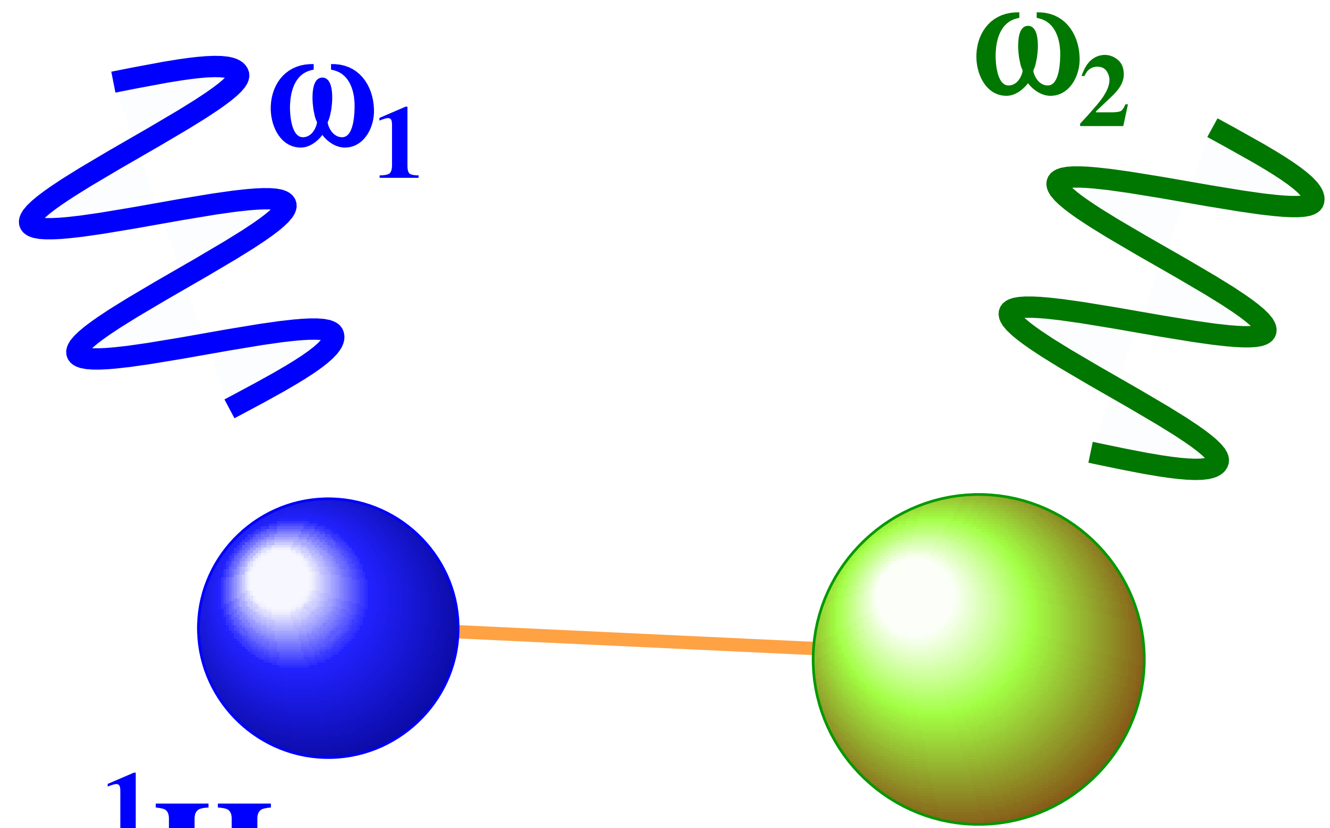


bit 1 bit 2 bit 3

separate leads

space

NMR in Liquids



^{1}H

qbit 1

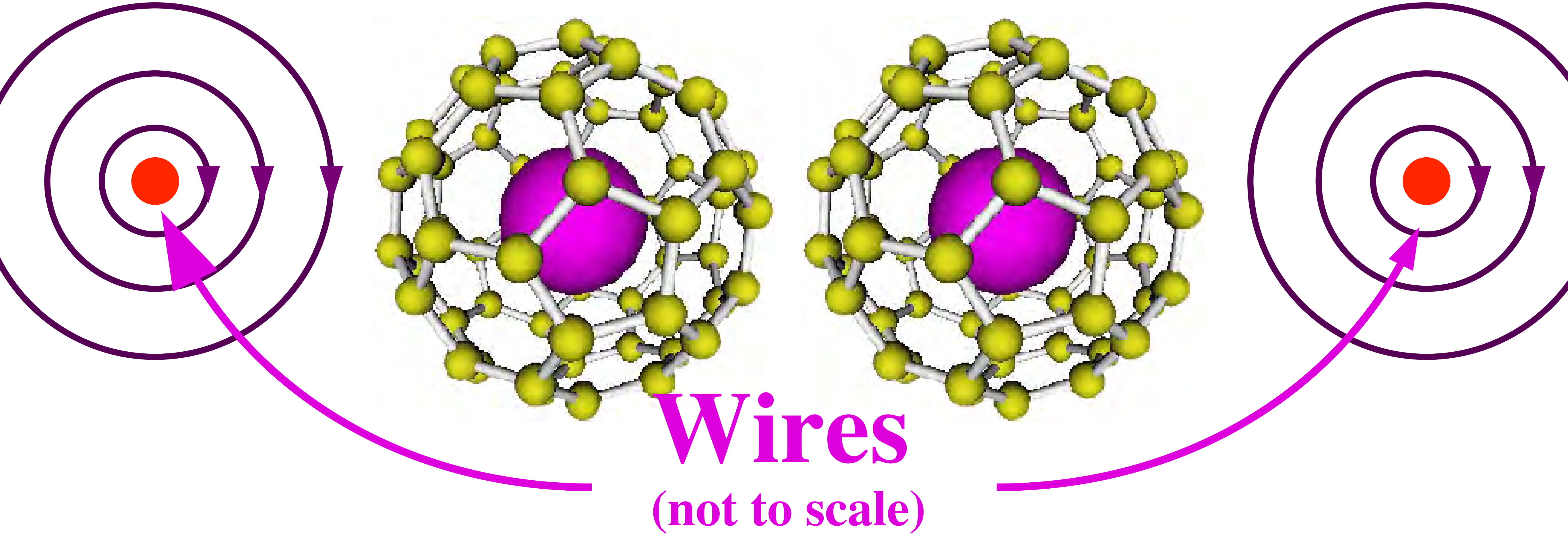
^{13}C

qbit 2

monochromatic radiation
affects only one type of spins

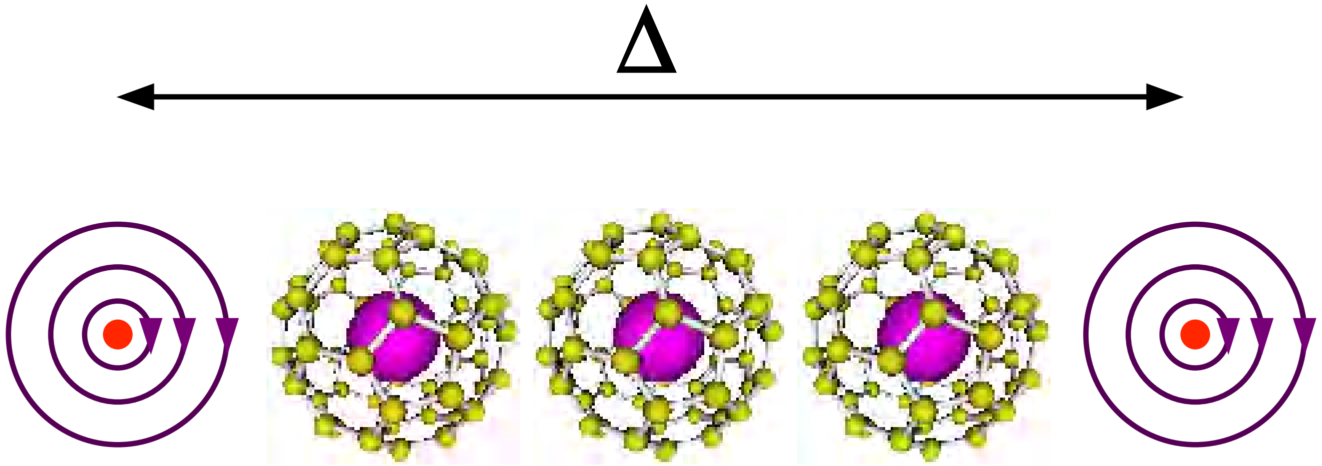
Addressing N@C60

Phys. Rev. A ***65***, *052309 (2002).*

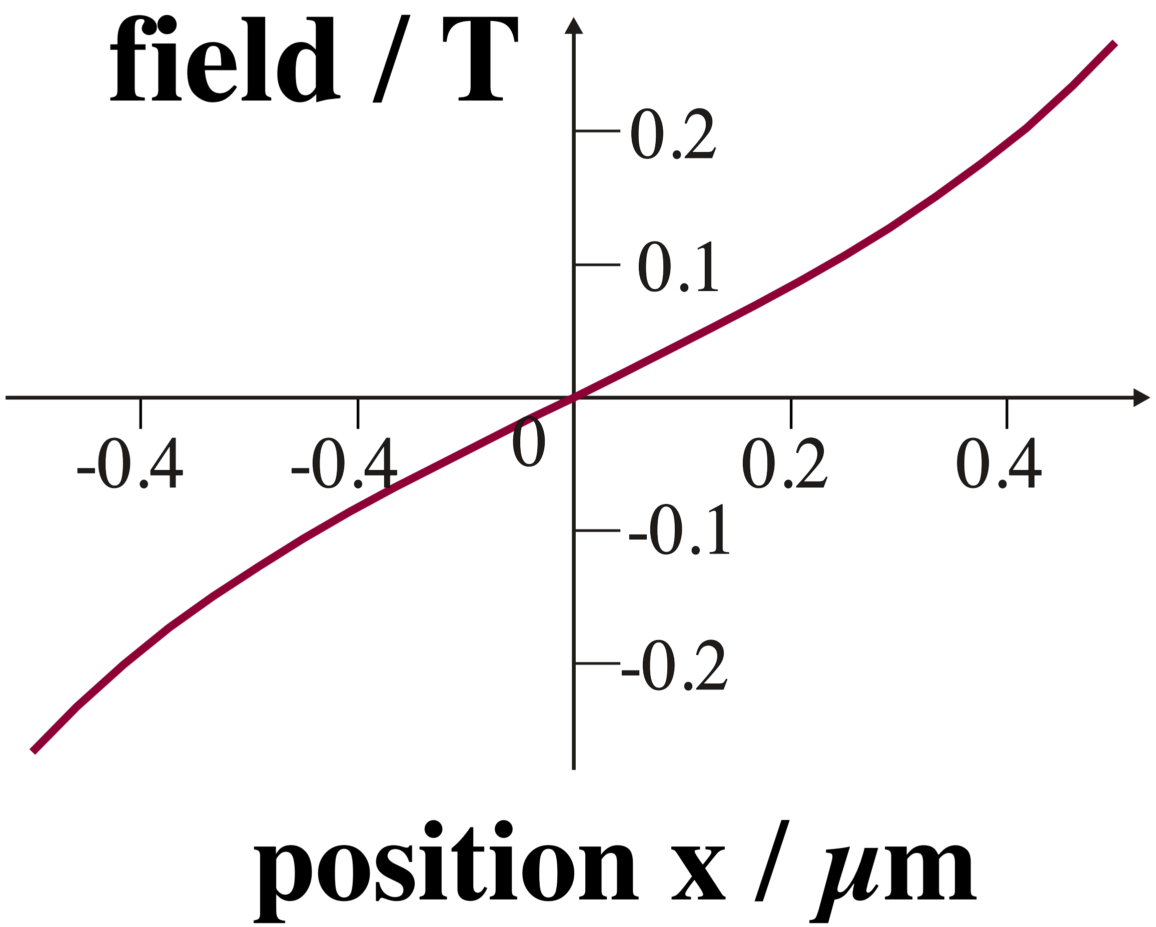


Current pulses through μm-scale wires could shift frequencies by multi-MHz

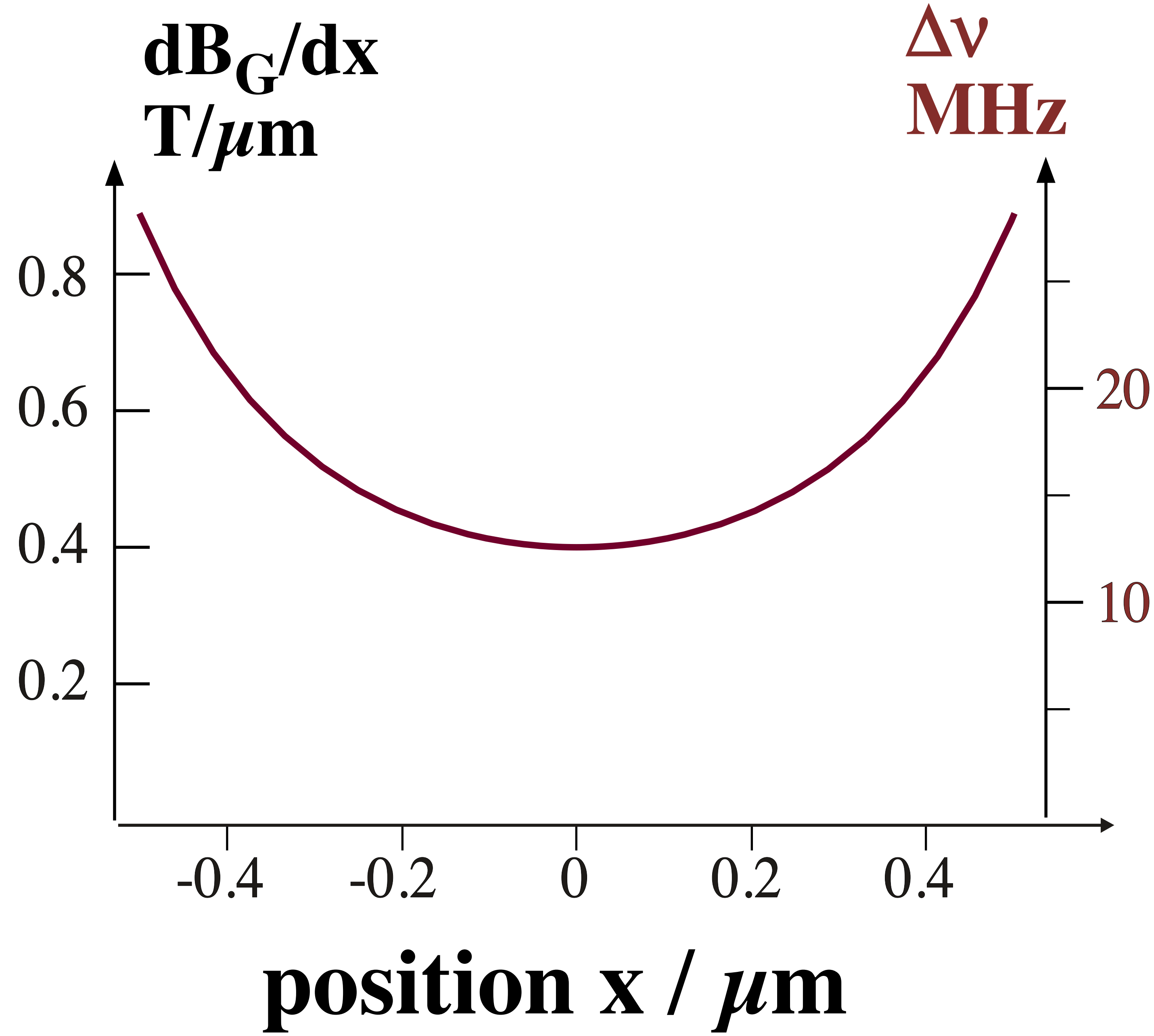
Magnetic Field



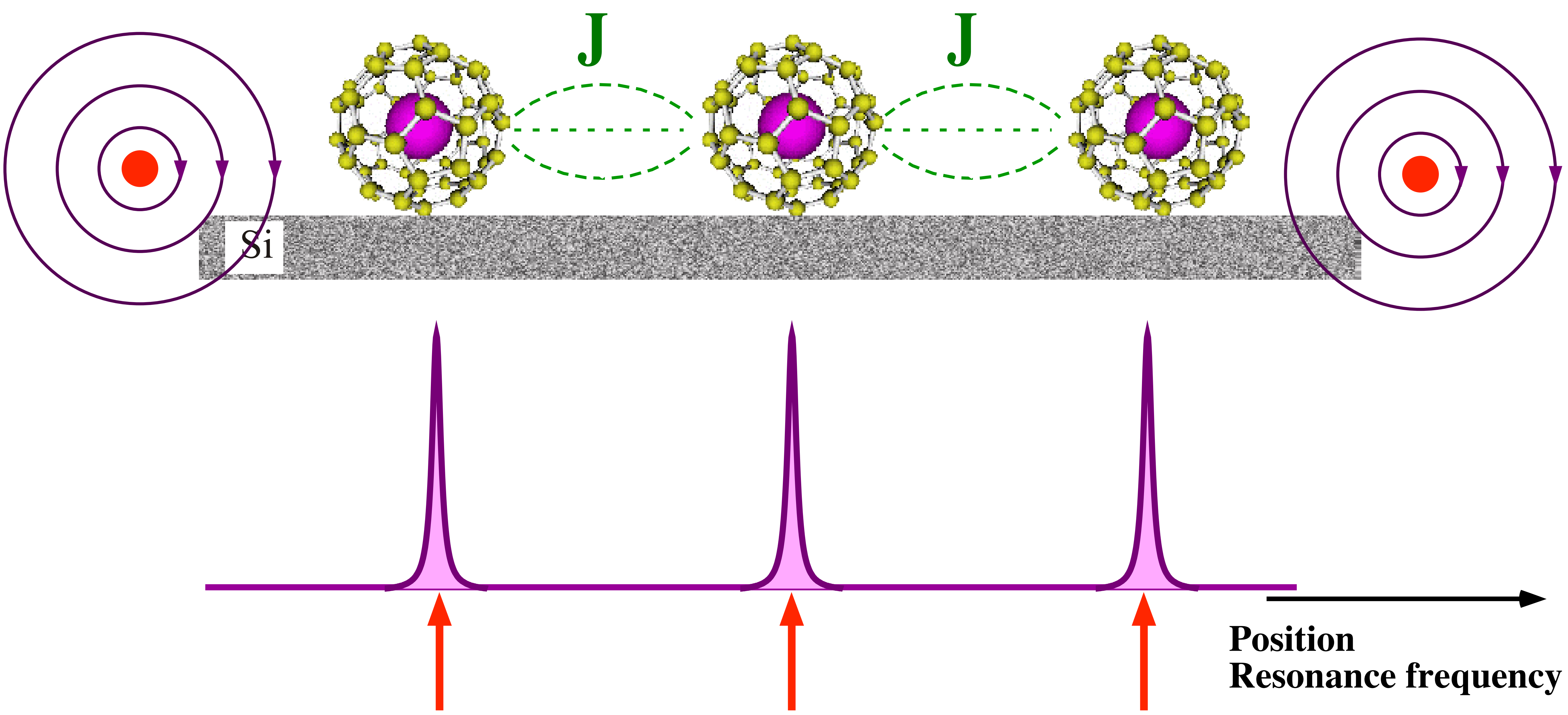
for I = 1A, Δ = 1 μm



Nearest neighbour frequency difference



Frequency Selection



Implement 1-qubit gates by frequency- or field switching

What about 2-qubit gates?

2-Qubit Gates

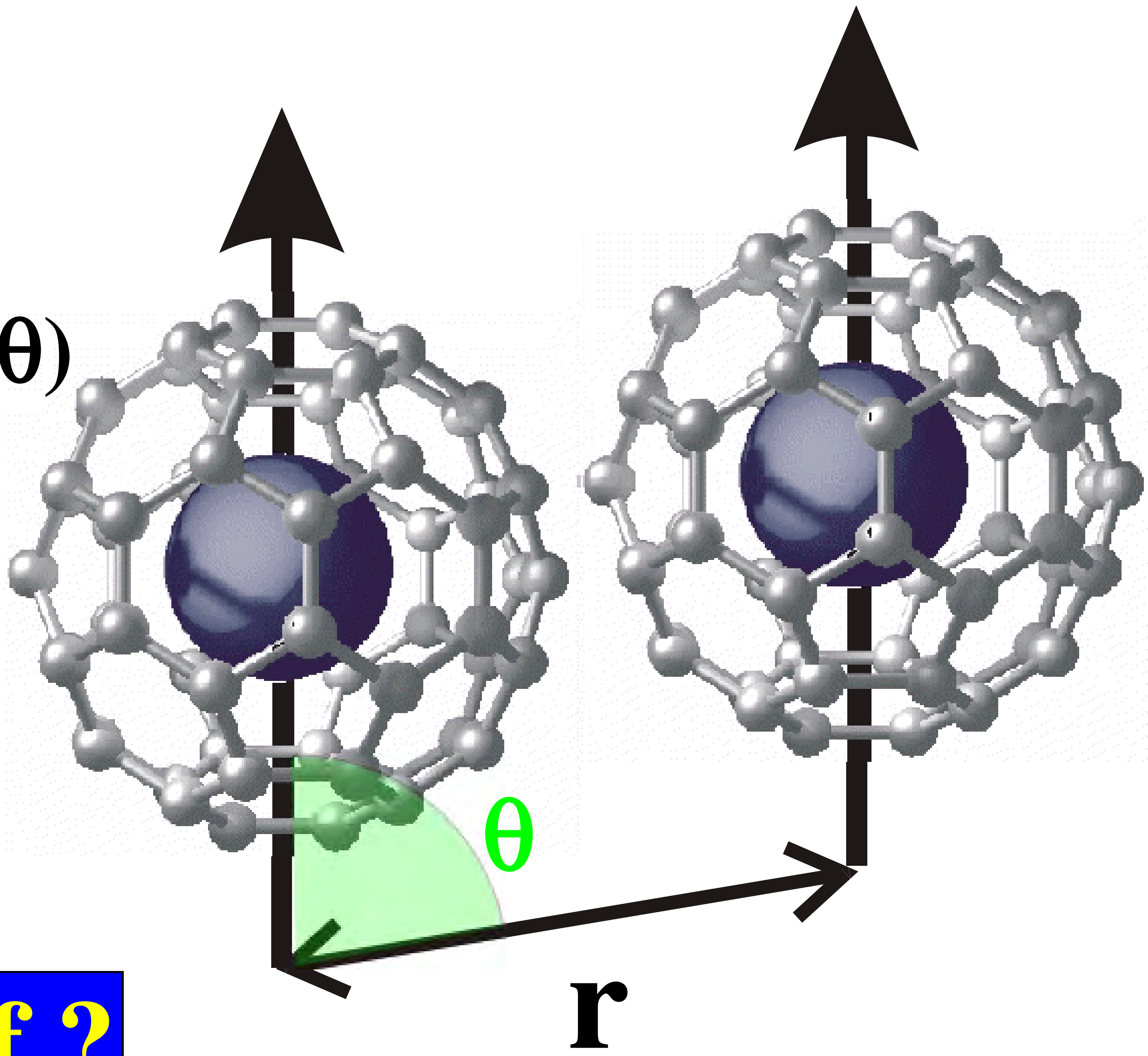
Required: Interaction

Dipole-dipole coupling

$$E_{dd} = \frac{\mu_0}{4\pi}\frac{\gamma_1\gamma_2}{r^3}(1-3\cos^2\theta)$$

N@C_{60}, 1.1 nm distance

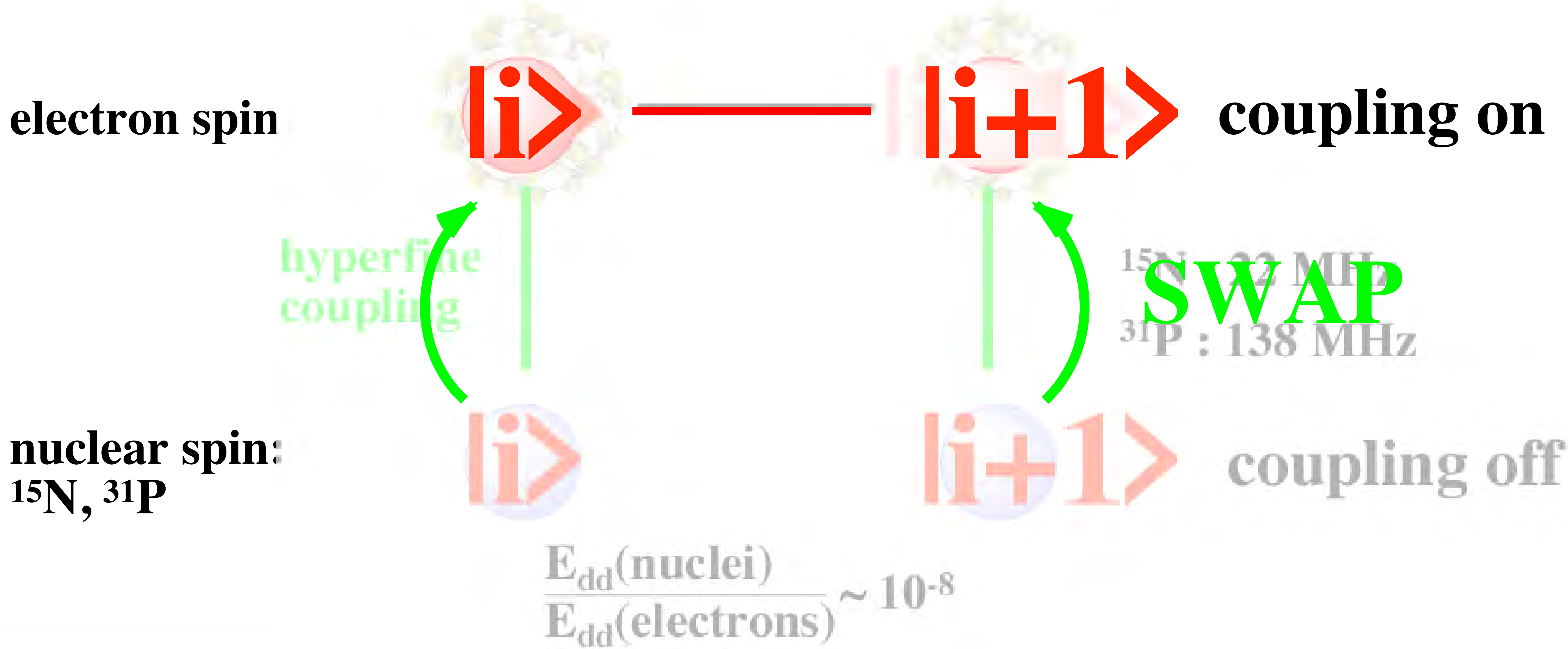
$$\frac{E_{dd}}{h} \sim 50\ \text{MHz}$$



Switch on / off ?

Switchable Coupling

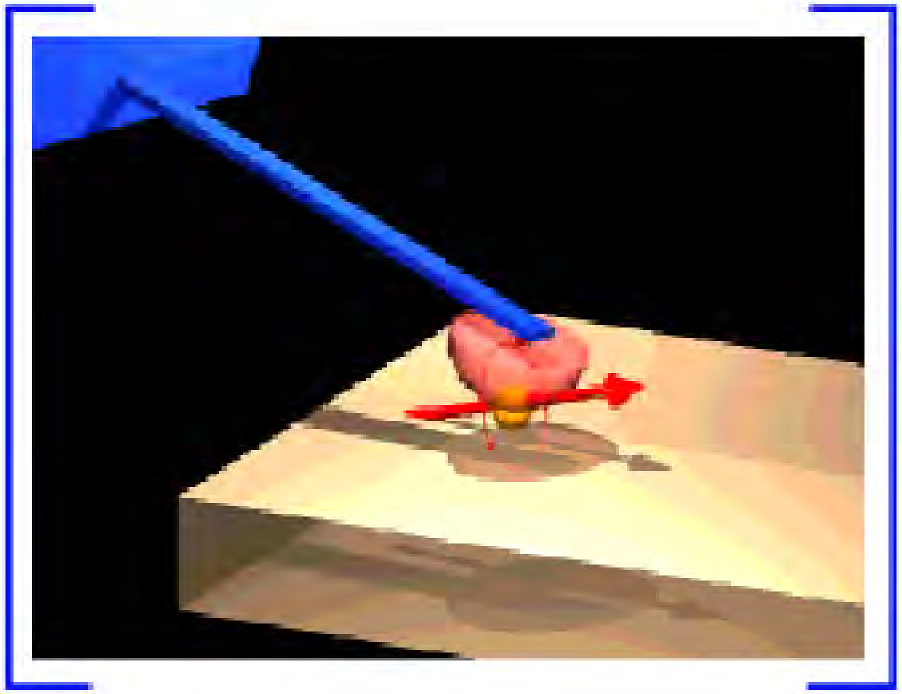
**activate:
SWAP QuInfo**



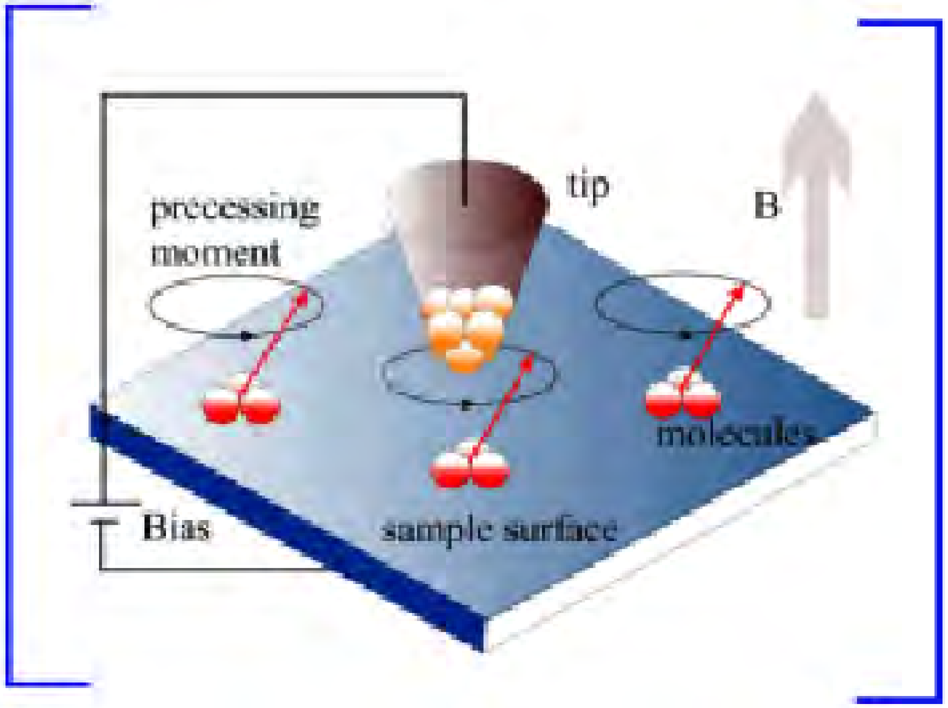
+ (Nuclei) : long decoherence times
no coupling

+ (Electrons) : fast gates
strong coupling

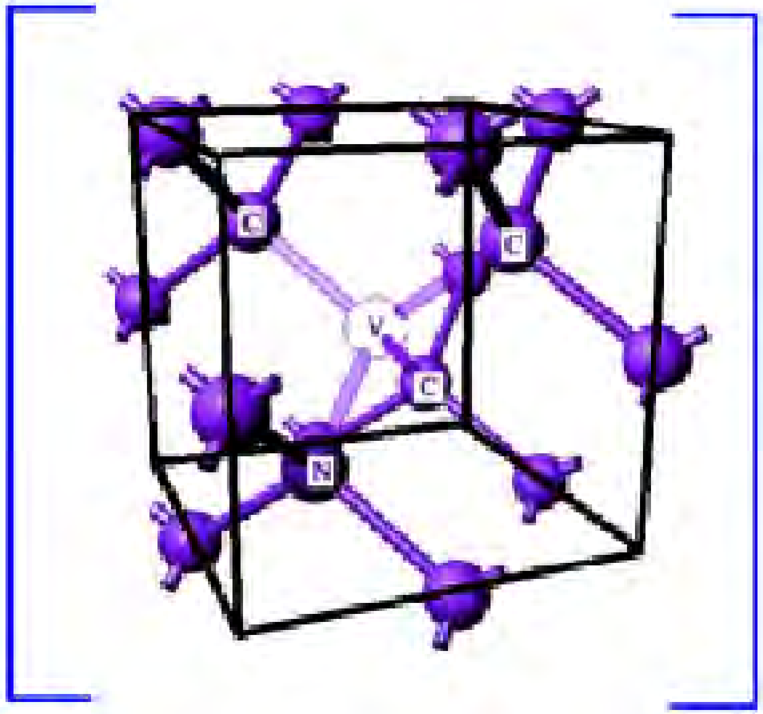
Single-Spin Readout



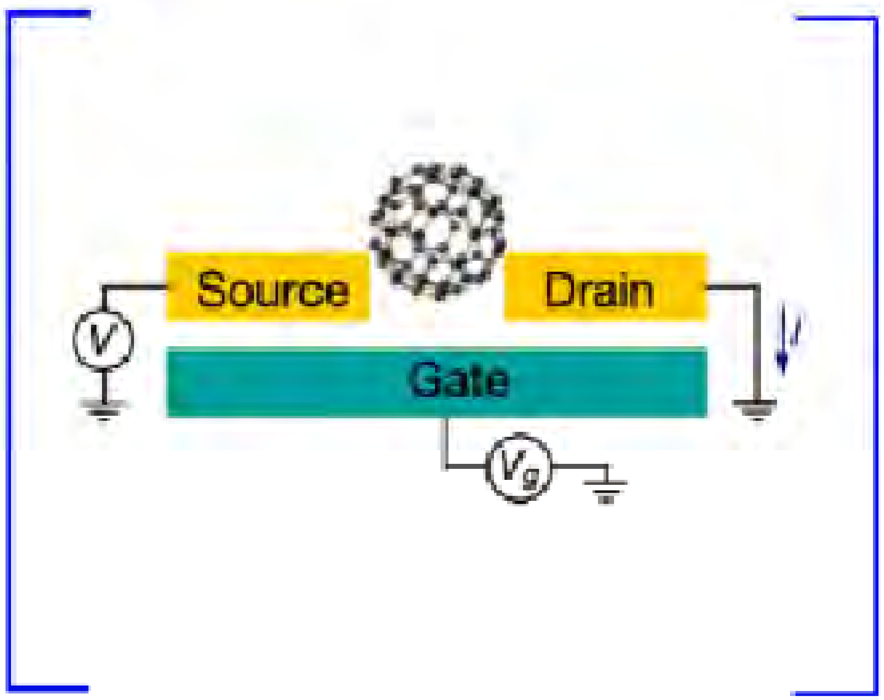
• Magnetic Resonance Force Microscope



• Scanning Tunneling Microscope Electron Spin Resonance



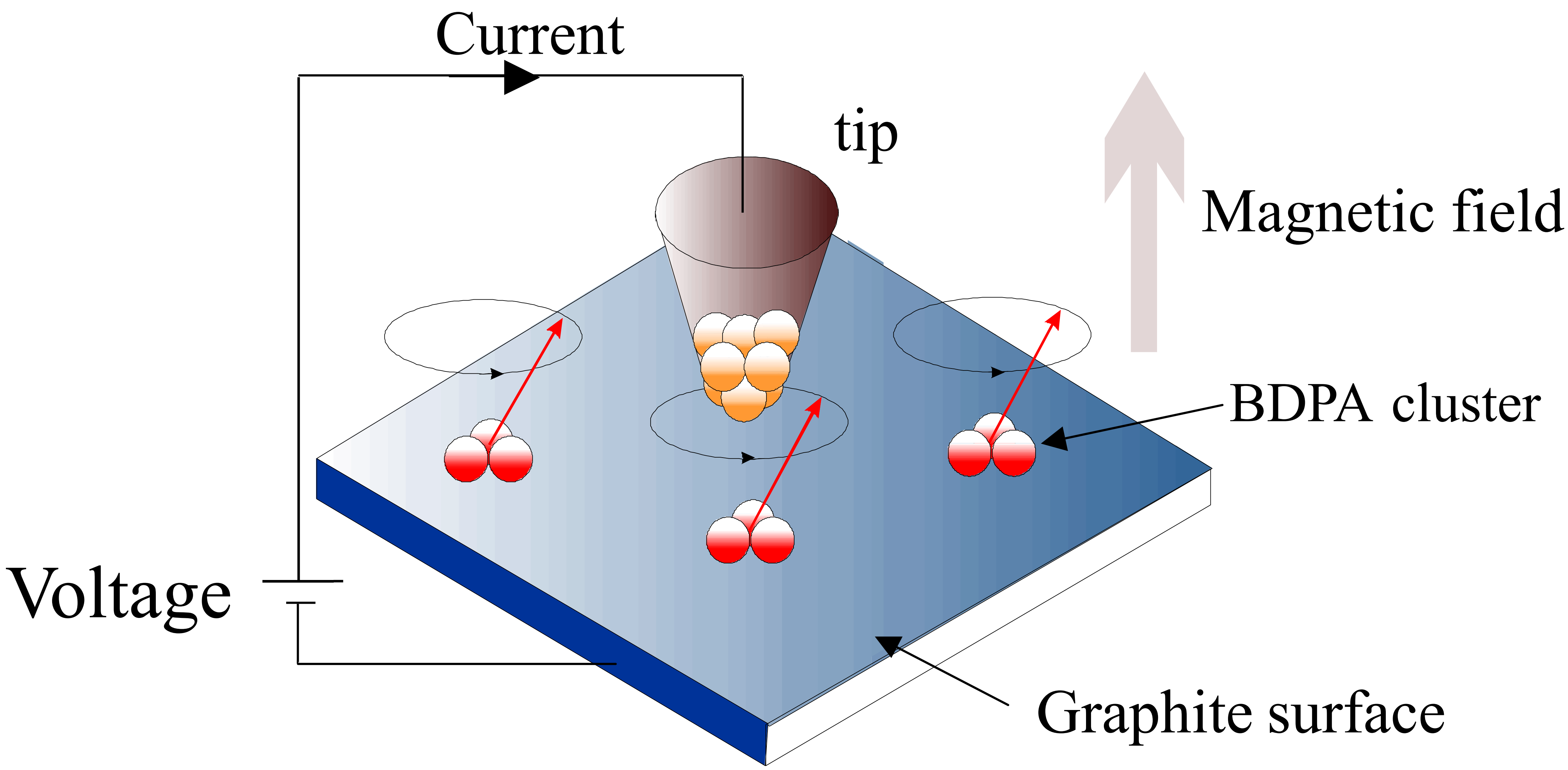
•Optical Detection via Diamond N/V center



• Single Molecule Transistor

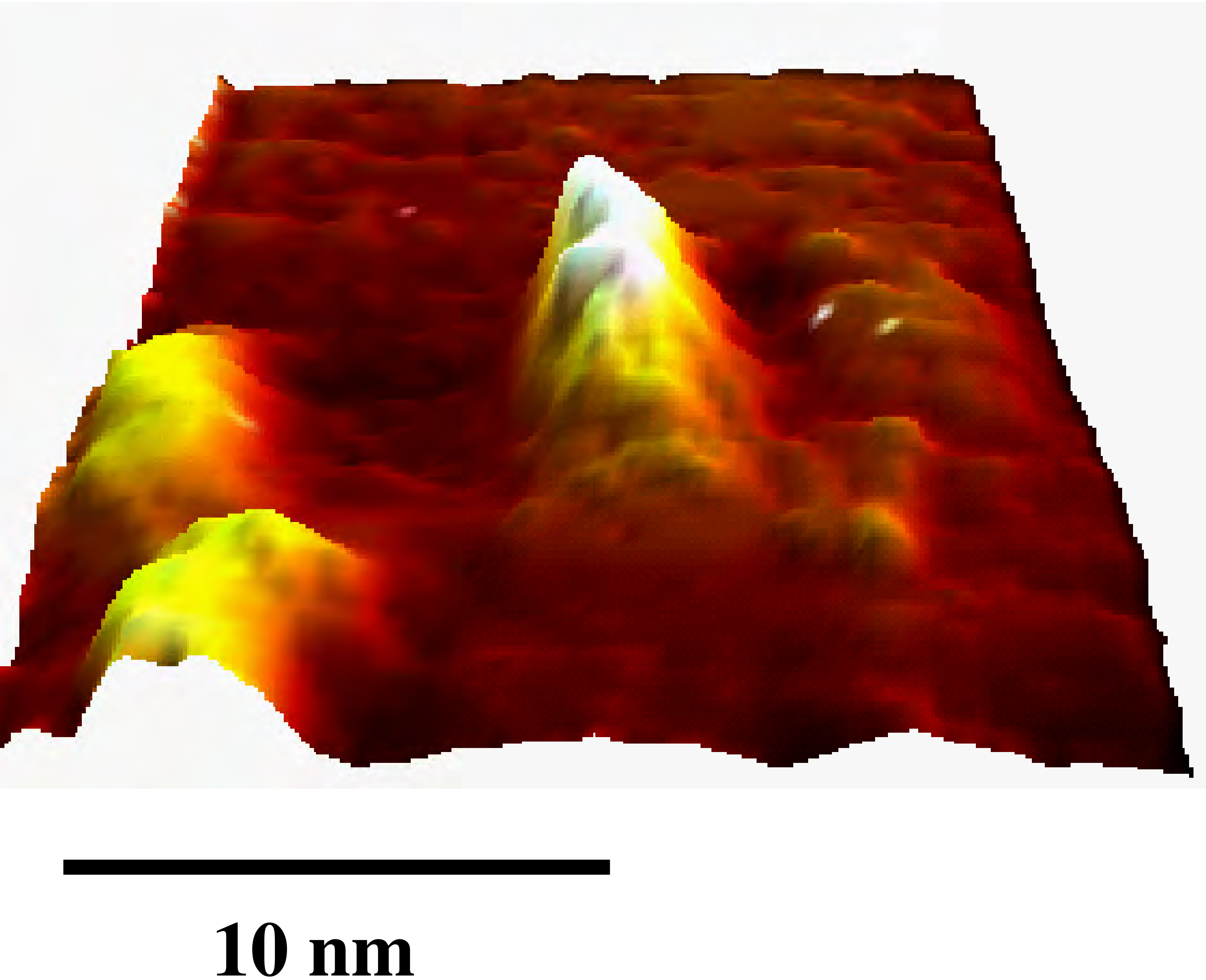
STM EPR

Detect modulation of tunnel current at Larmor frequency

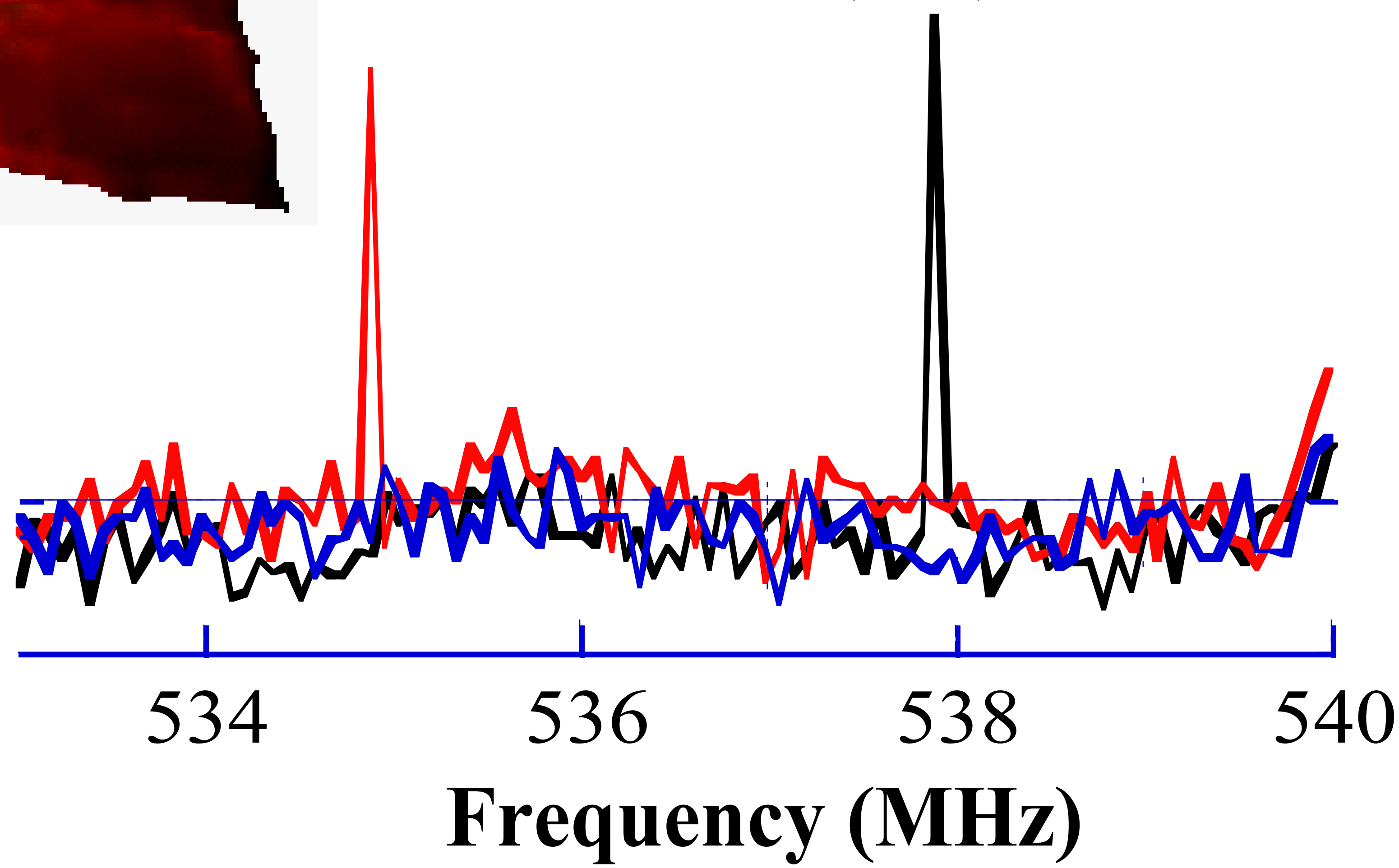


First demonstration: Manassen et al., PRL 62, 2531 (1989).

STM EPR



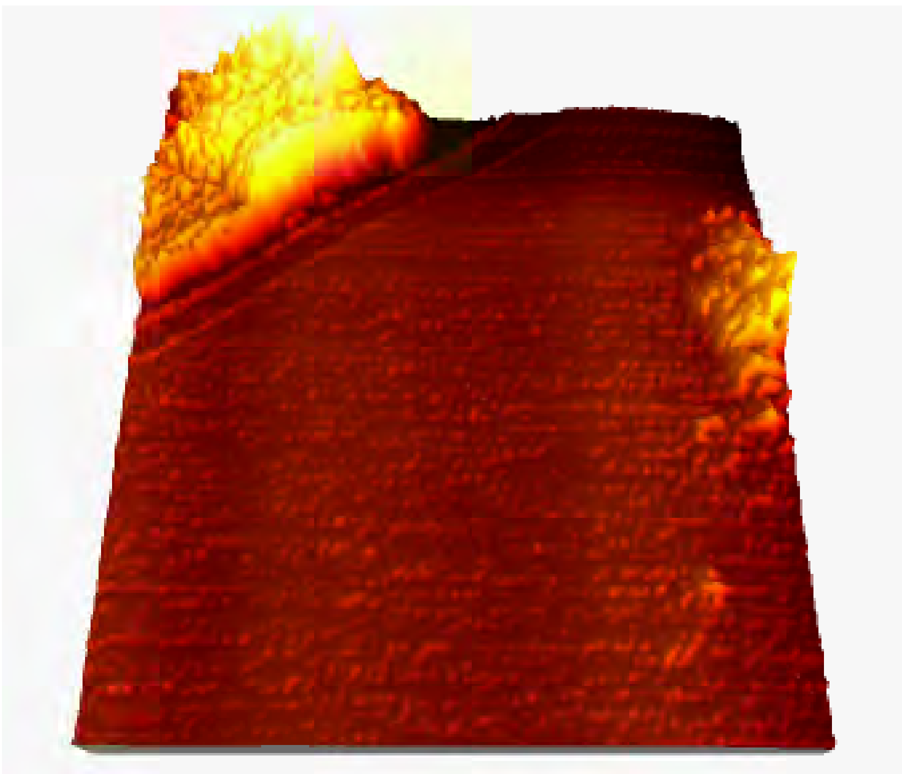
STM-ESR spectra of BDPA on HOPG (red and black) and bare HOPG (blue).



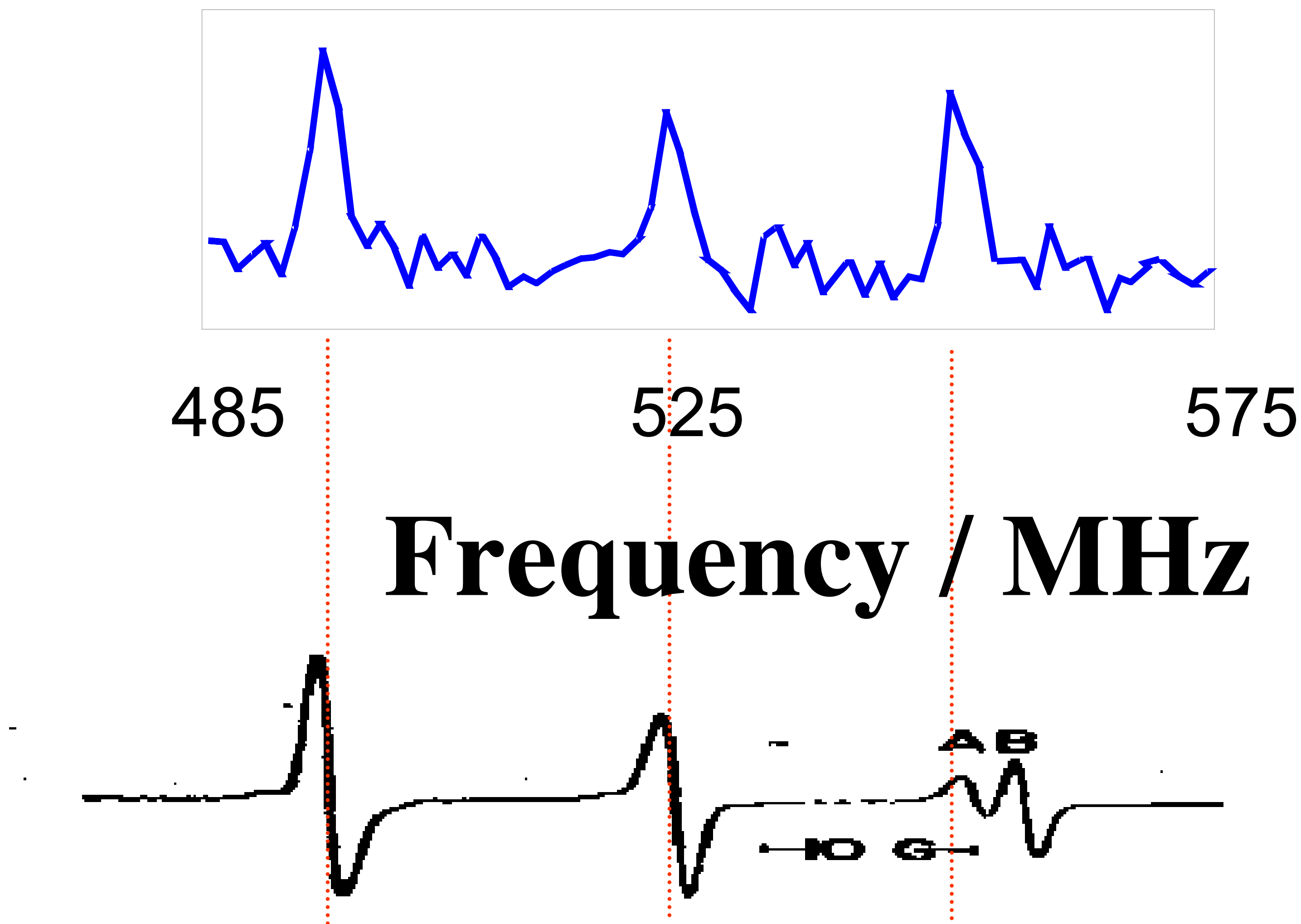
C. Durkan and M. E. Welland, Electronic spin detection in molecules using scanning-tunneling microscopy-assisted electron-spin resonance. *Appl. Phys. Lett.*, *80*, 458 (2002).

STM EPR of TEMPO

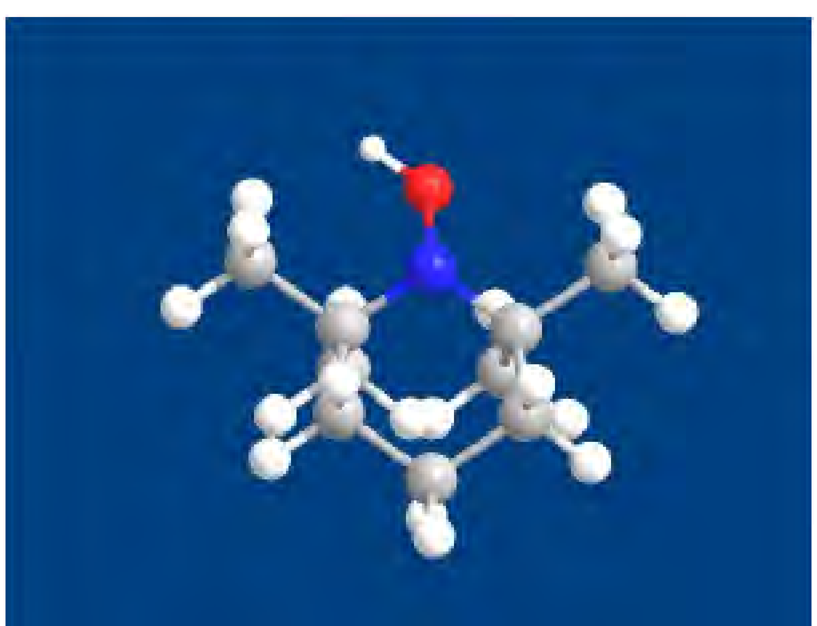
TEMPO on graphite : S=1/2, I=1 : hyperfine splitting



200 nm x 200 nm area



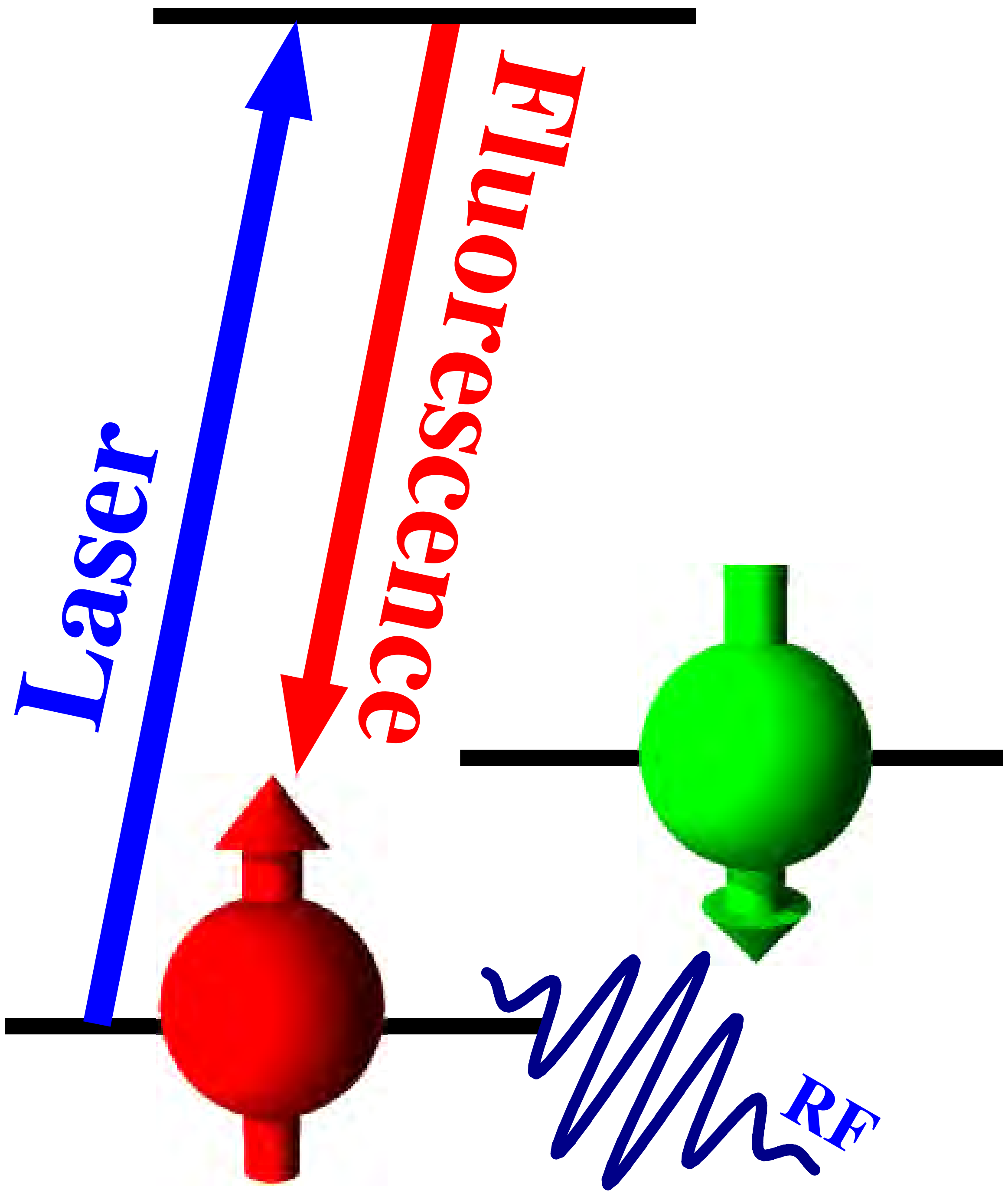
Conventional EPR



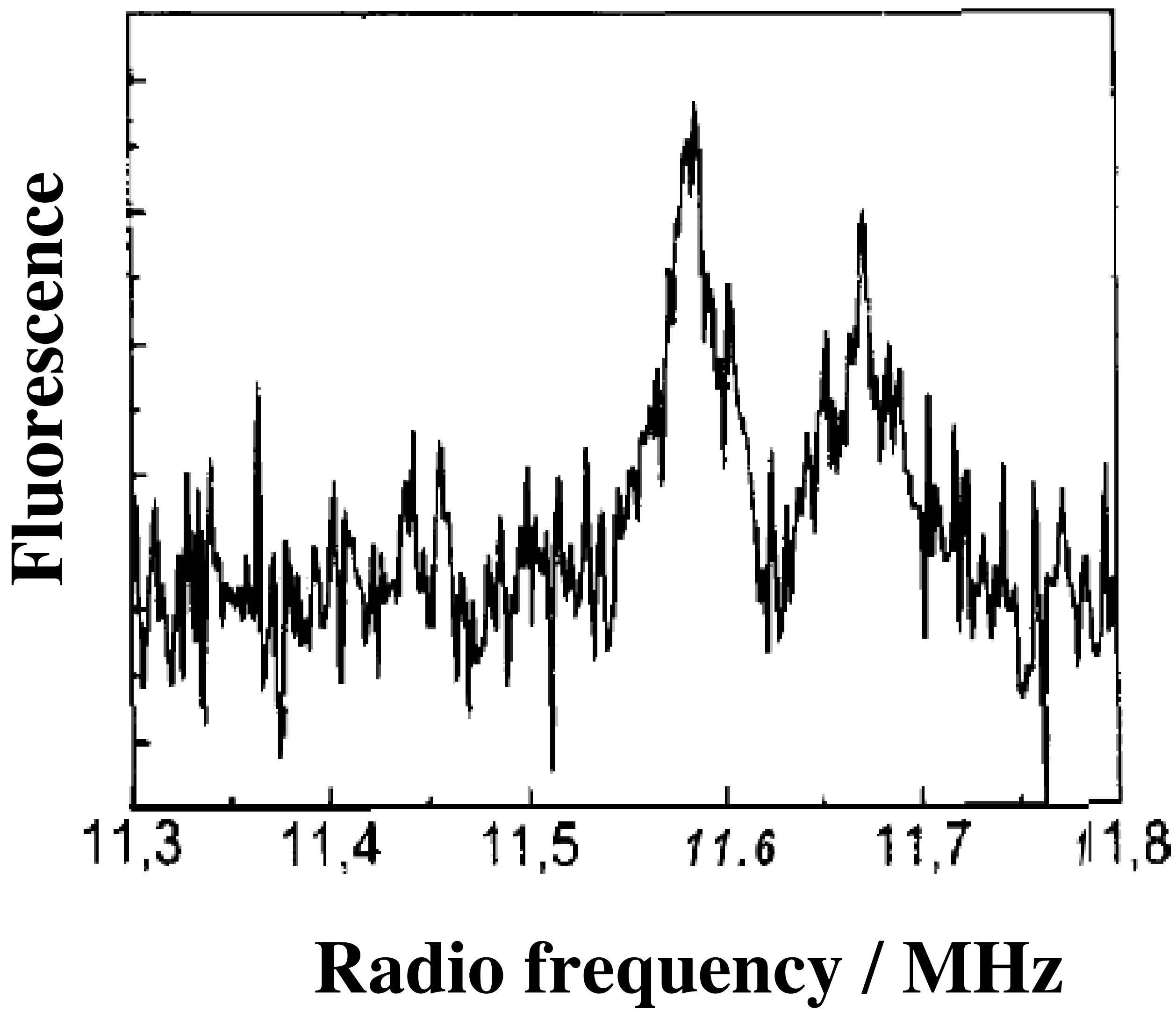
TEMPO

Single-Spin Detection

by optically detected magnetic resonance



single ^{1}H in pentacene

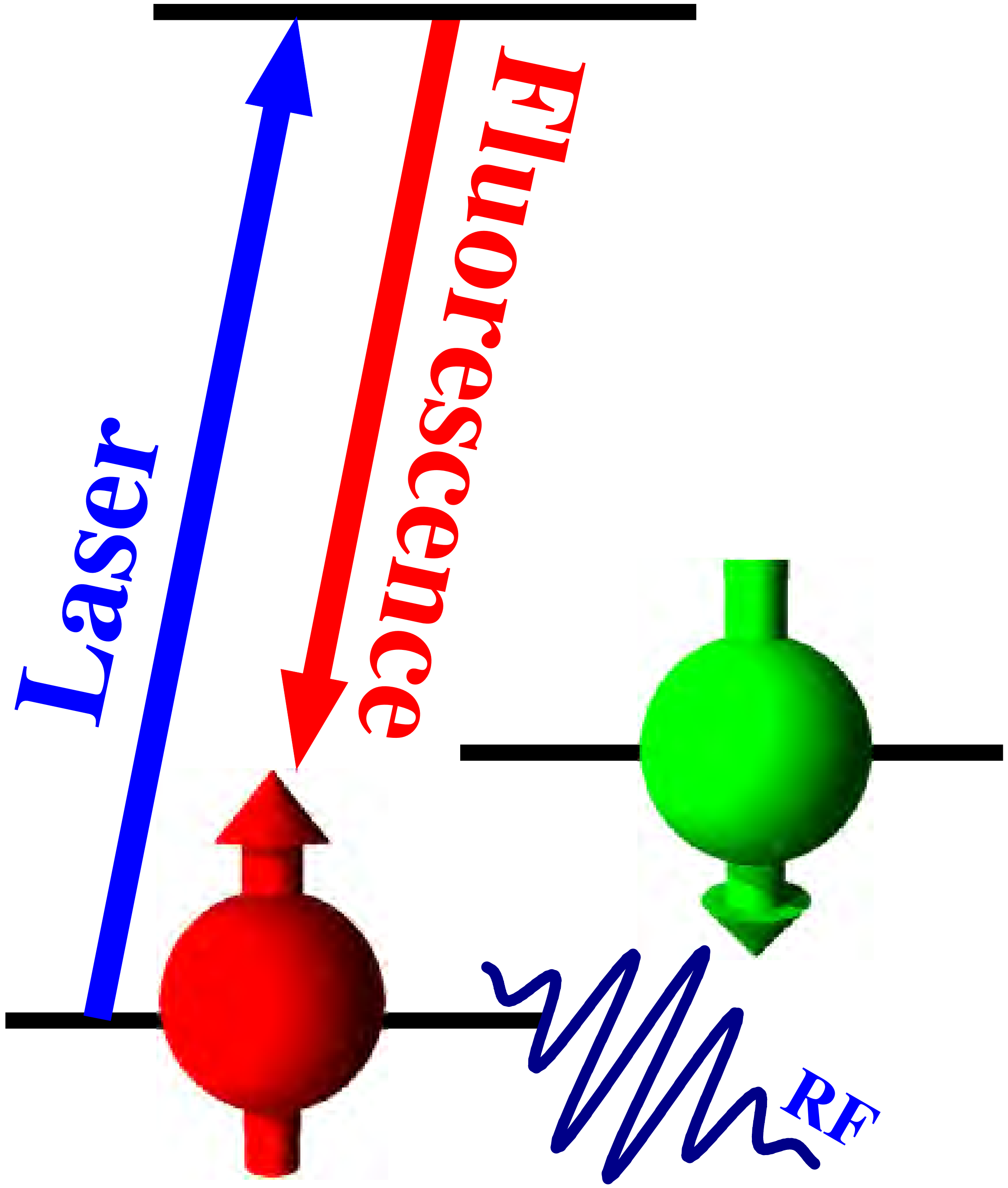


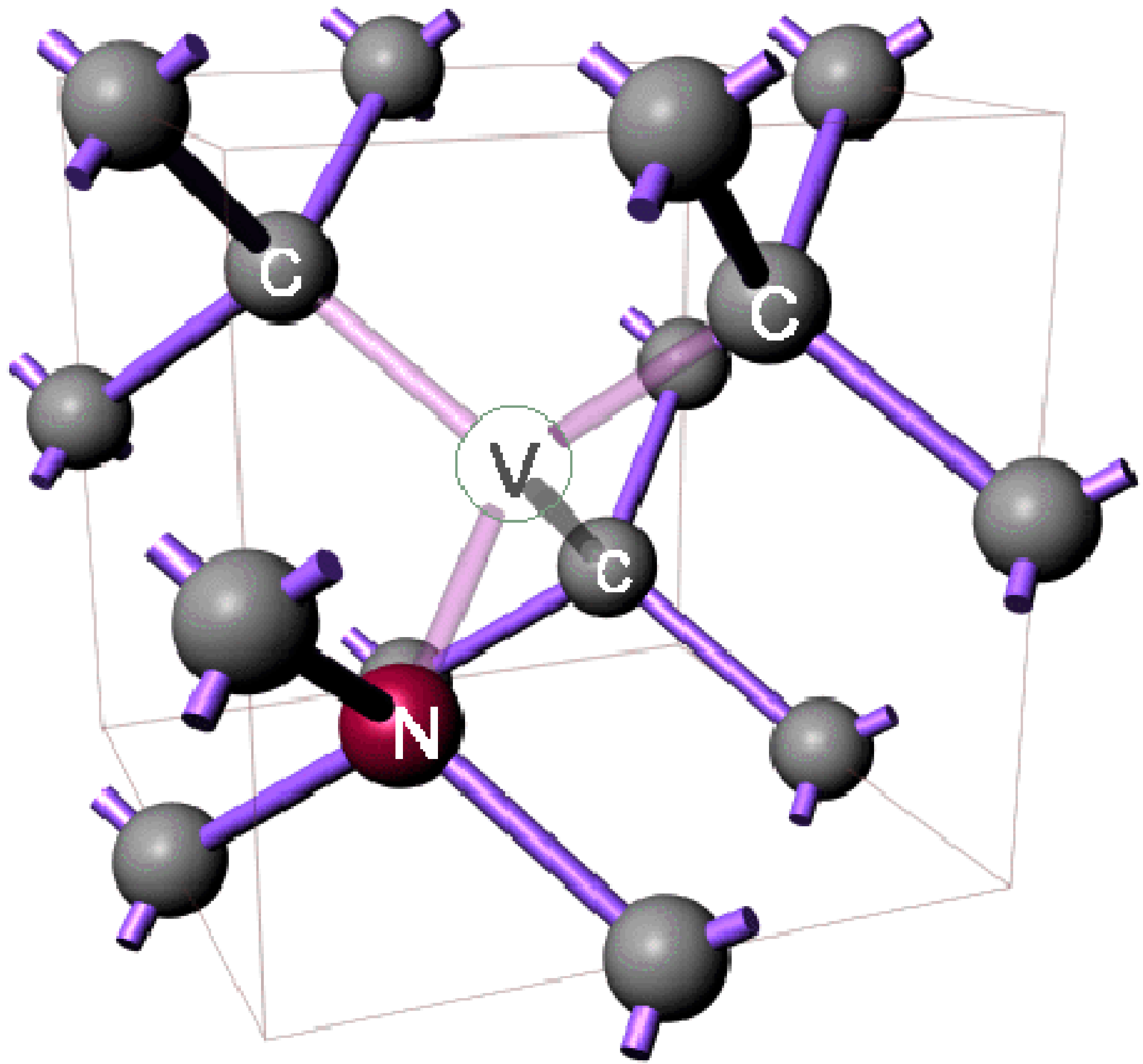
J. Wrachtrup, A. Gruber, L. Fleury, and C.v. Borczyskowski, Chem. Phys. Lett. **267**, 179 (1997).

Single-Spin Detection

by optically detected magnetic resonance

Diamond N/V center

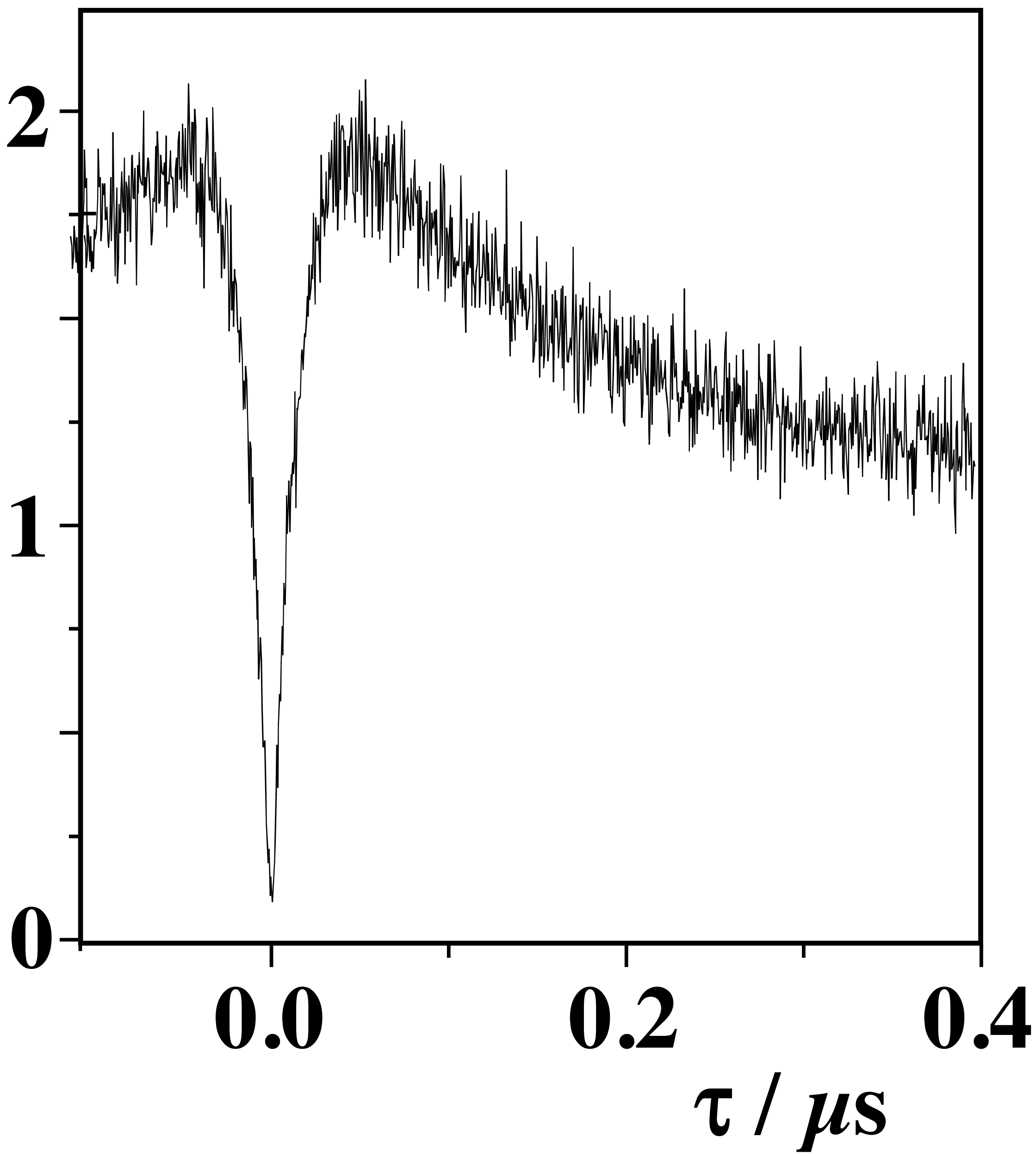


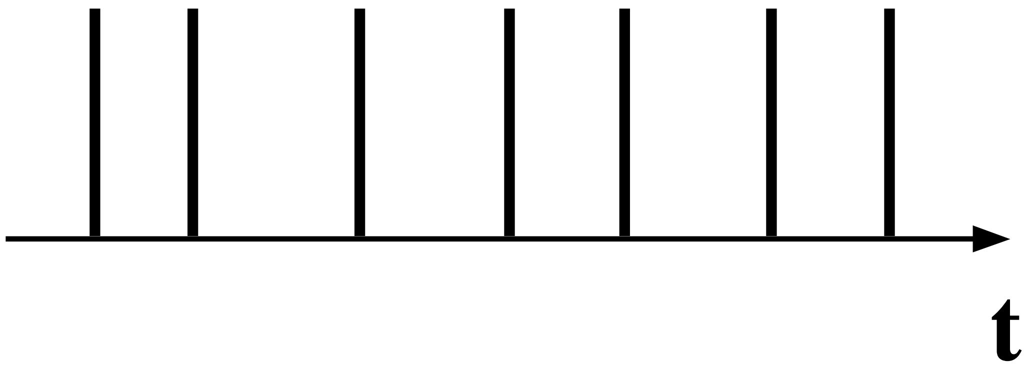


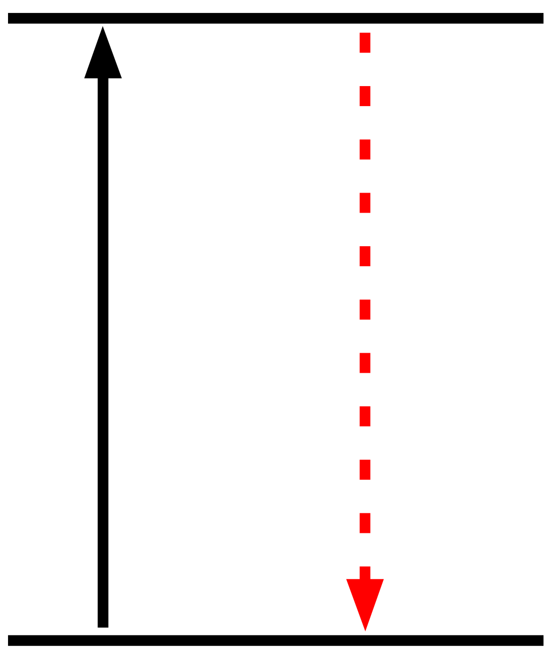
F. Jelezko, C. Tietz, A. Gruber, I. Popa, A. Nizovtsev, S. Kilin, and J. Wrachtrup, Single Mol. **2**, 255 (2001).

Single Center : Photon Antibunching

$$g^{(2)}(\tau) = \frac{\langle I(t)\, I(t+\tau)\rangle}{\langle I(t)\rangle^2}$$



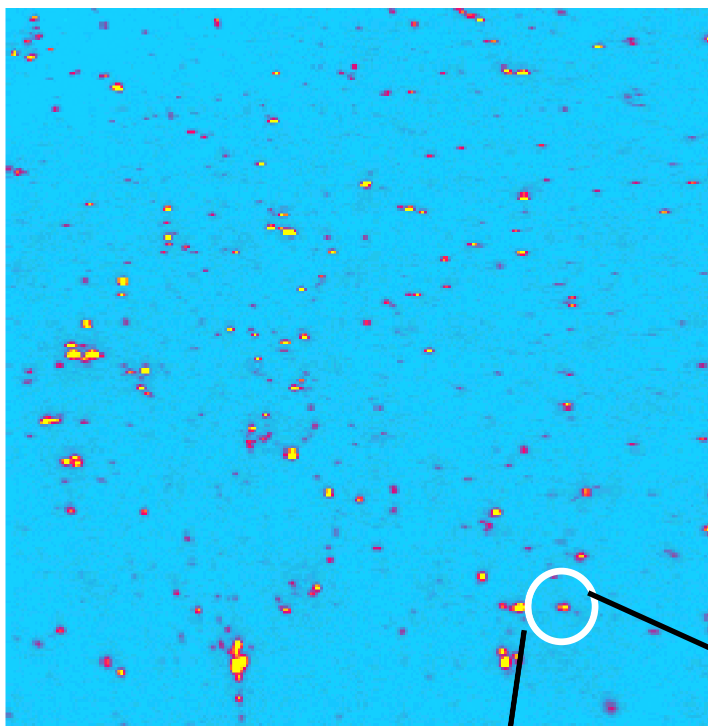




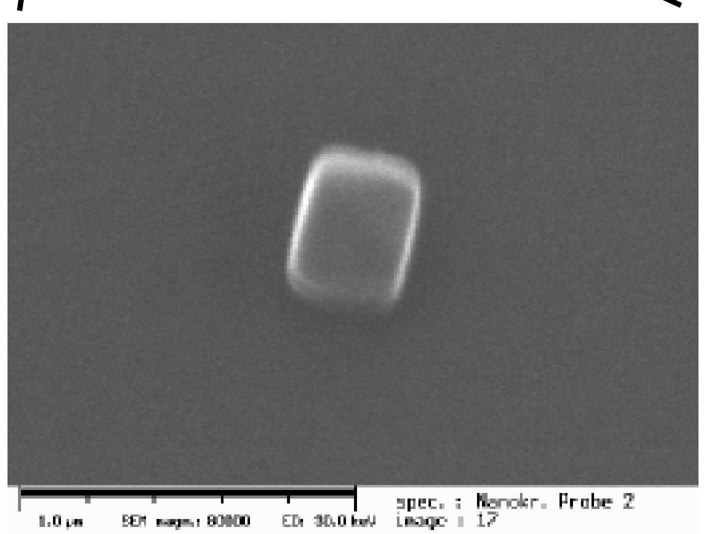
Single Center : Spectroscopy

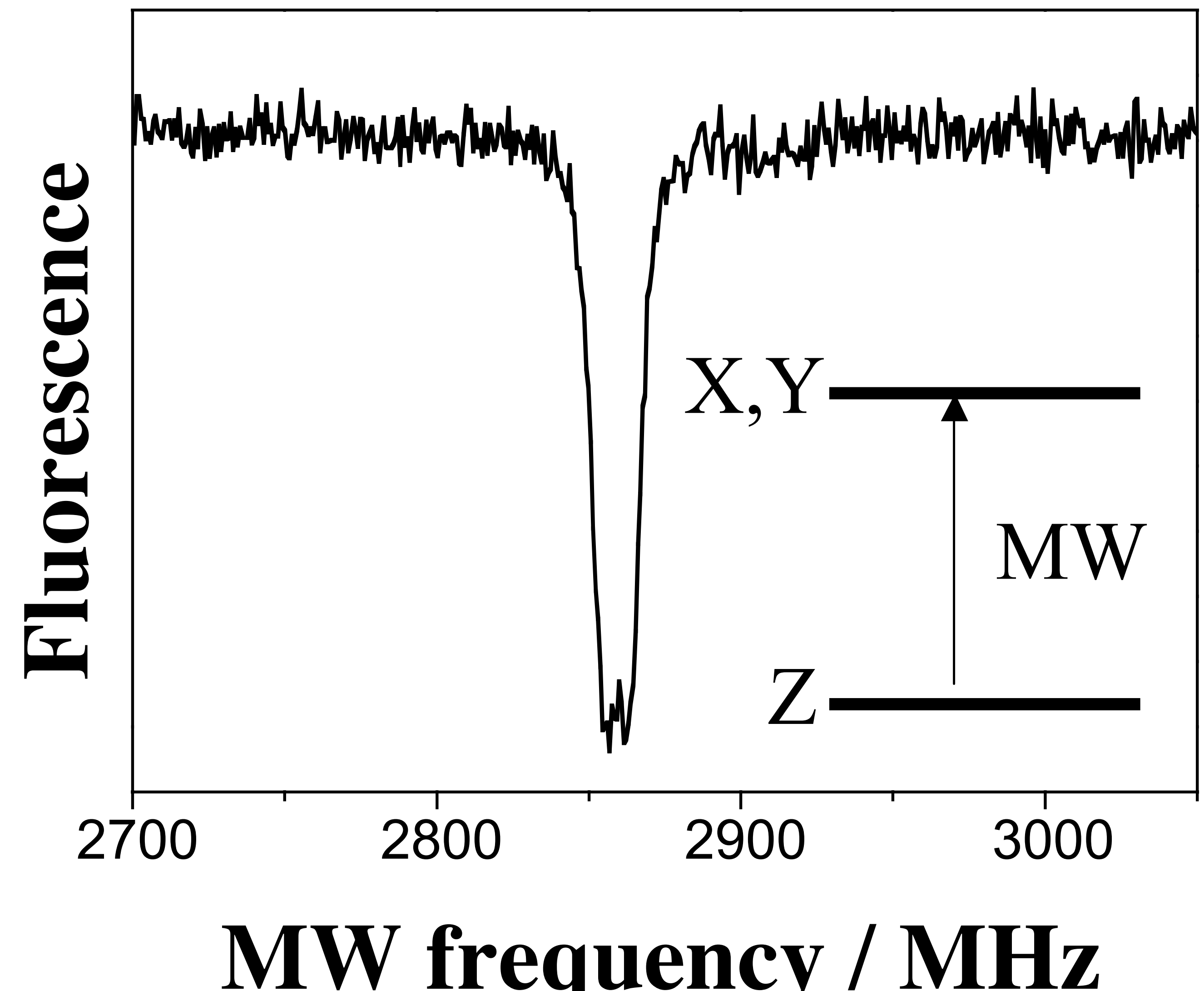
NV - containing nanocrystals

Fluorescence

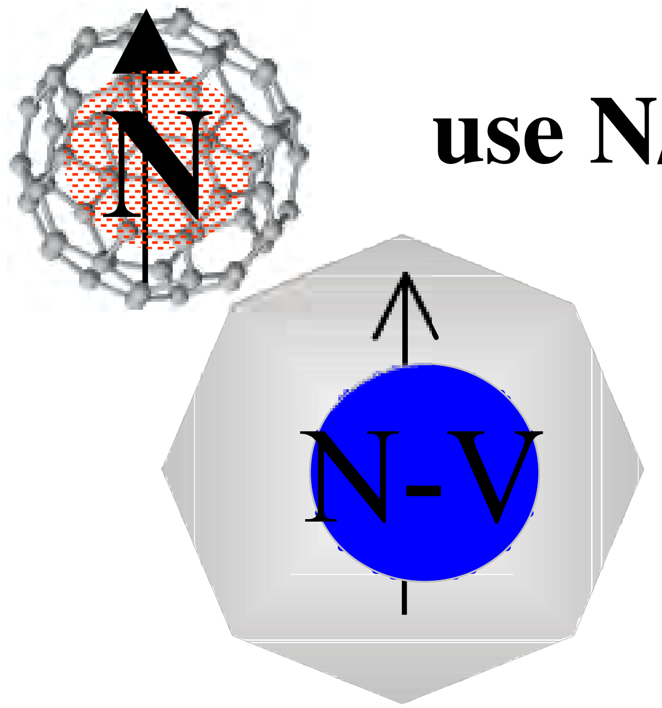


EM image

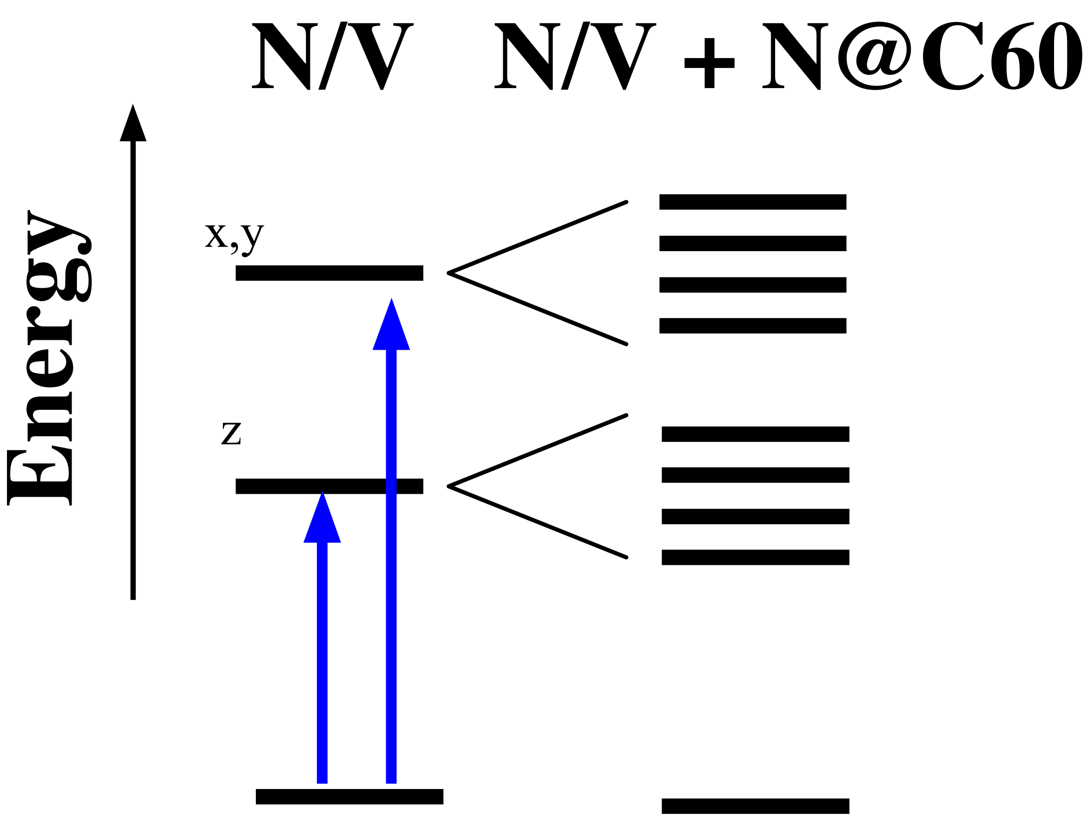


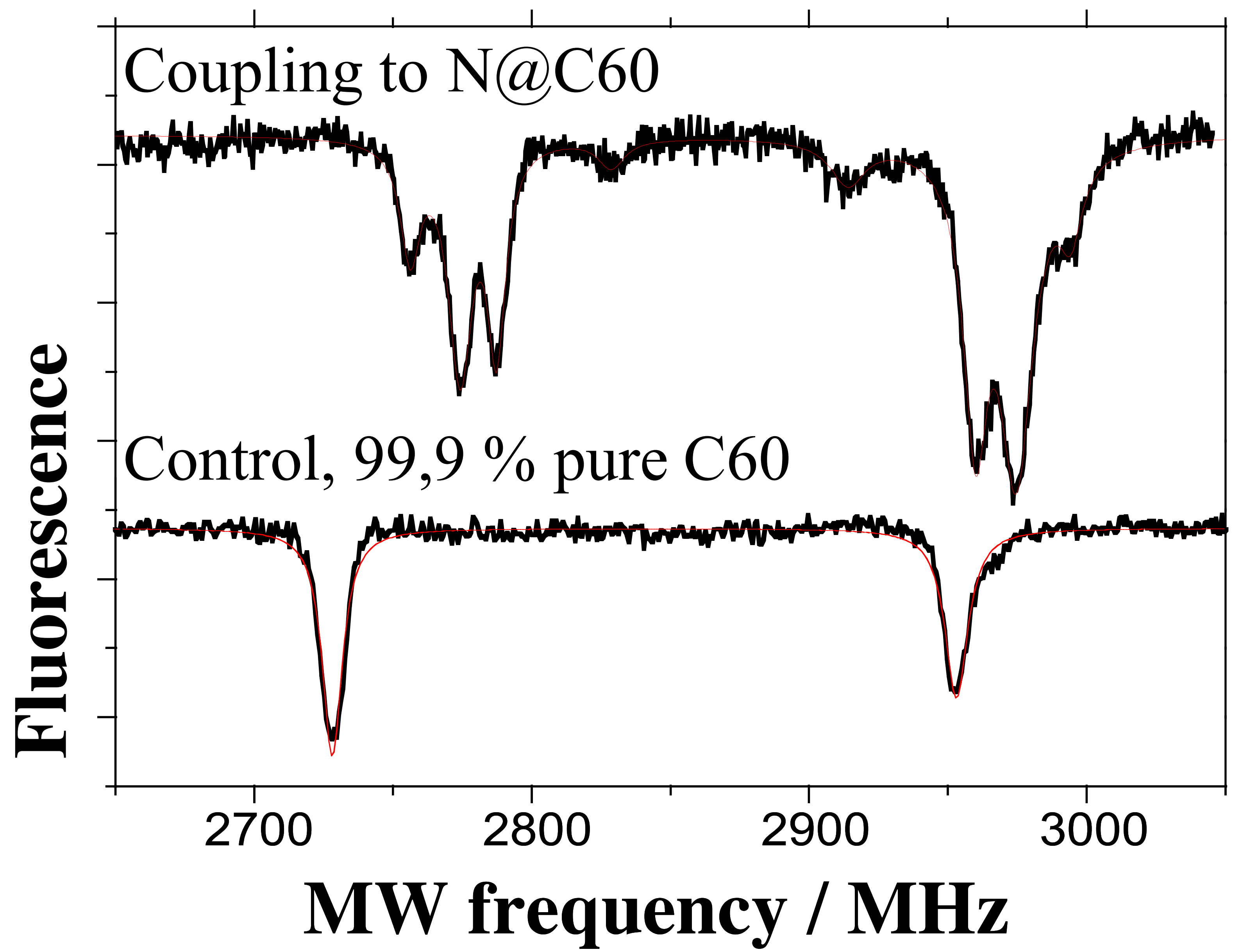


Detecting N@C60 Spins

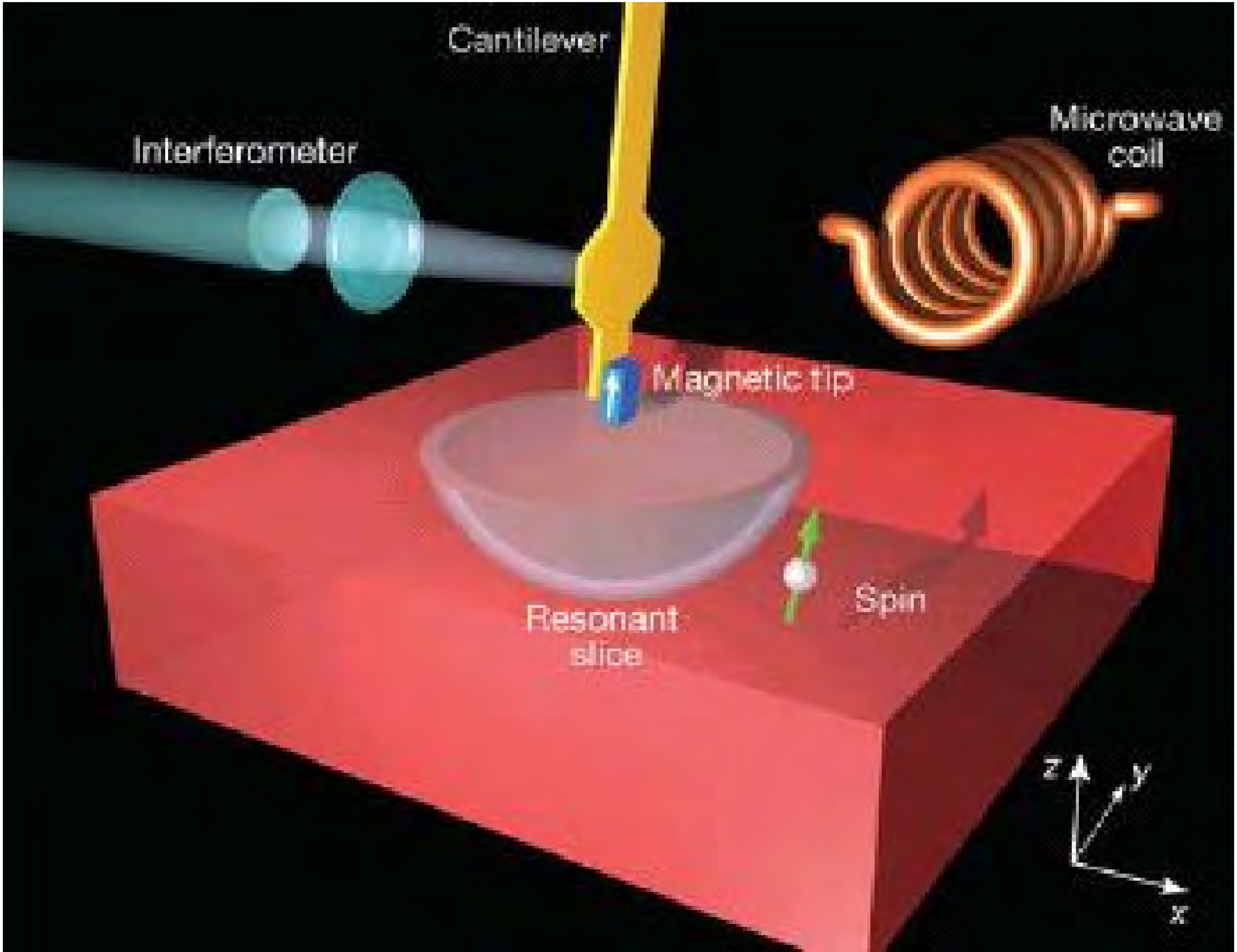


use N/V center as field probe



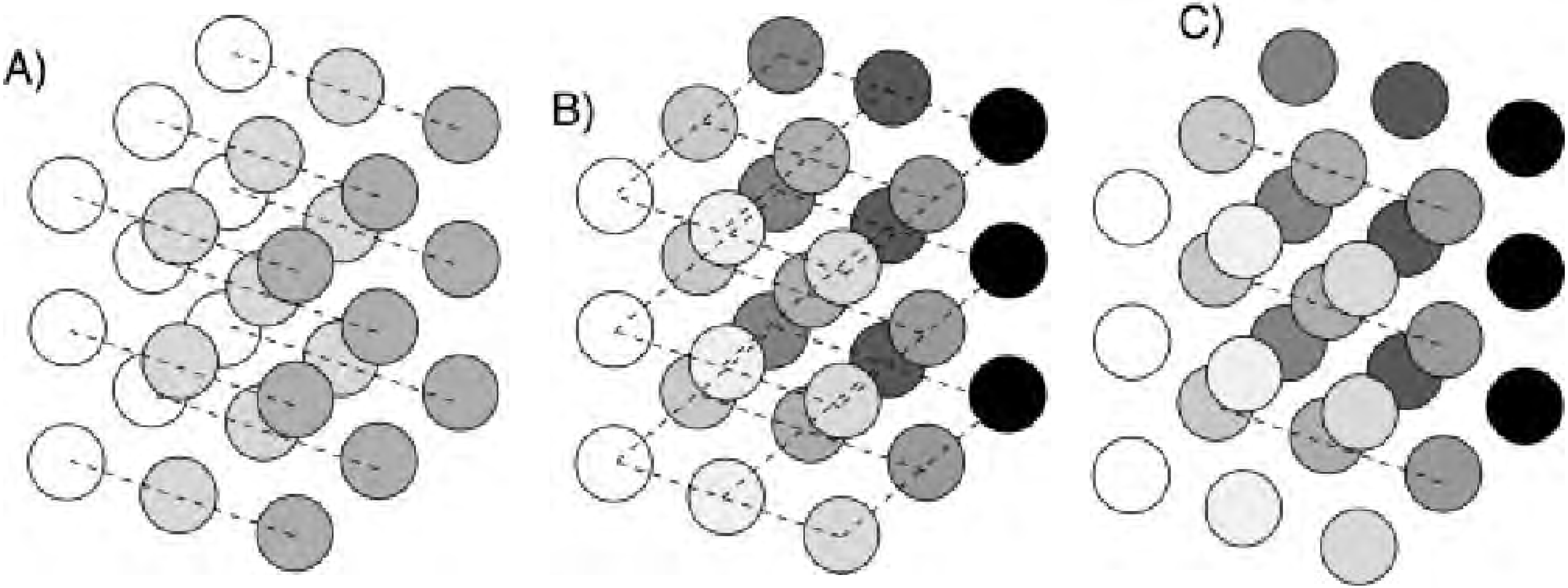


Single Spin Force Detection



Crystal Lattice Quantum Computer

F. Yamaguchi, and Y. Yamamoto, ‘Crystal lattice quantum computer‘, Appl. Phys. A 68, 1 (1999).



Detection e.g. by vibrating cantilever

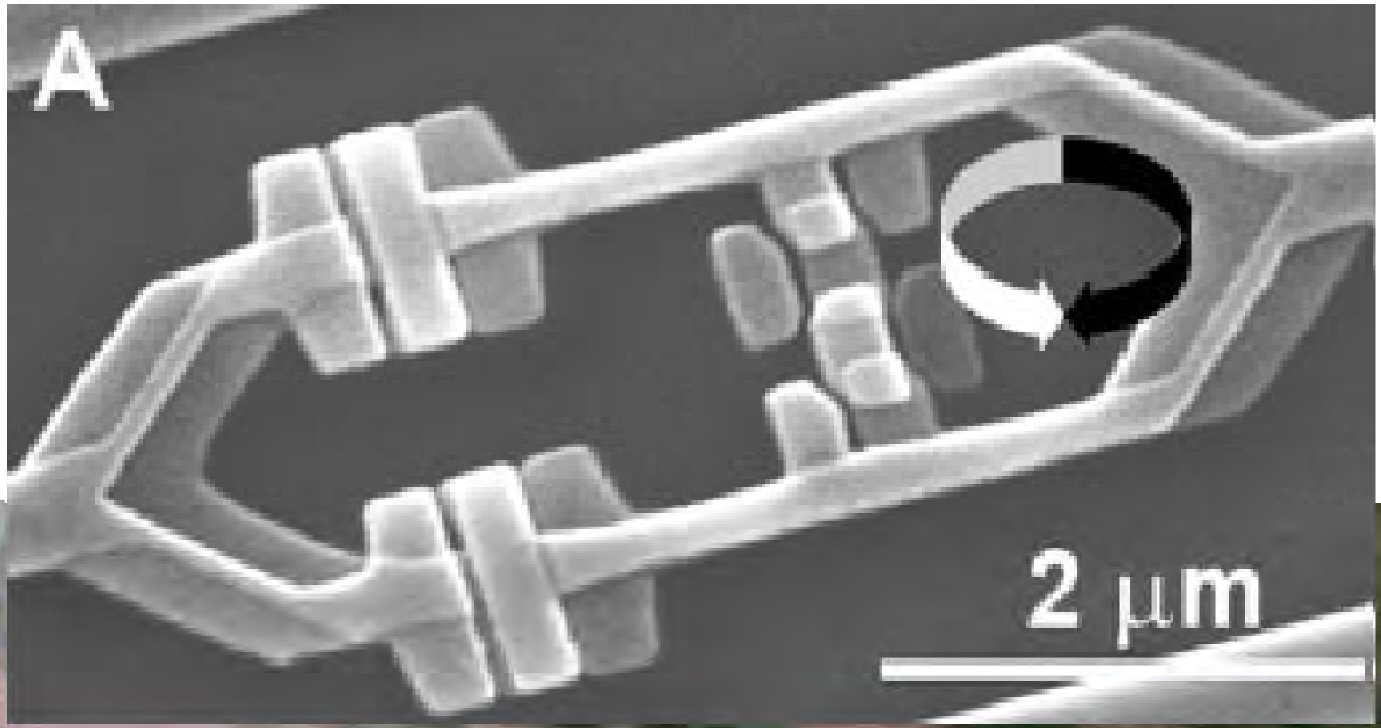
12.2 Superconducting Systems

12.2.1 Charge Qubits

12.2.2 Flux Qubits

12.2.3 Gate Operations

12.2.4 Readout



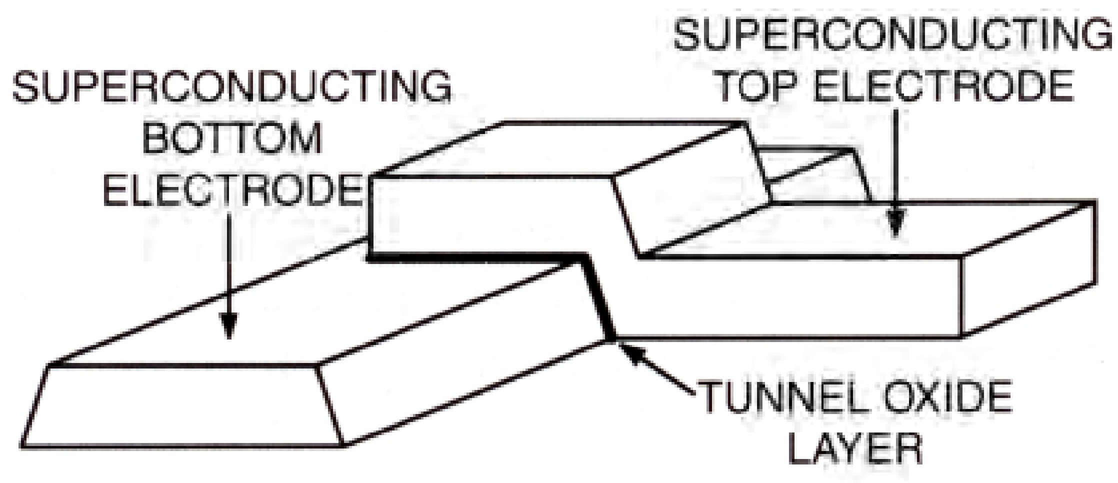
Superconducting Qubits

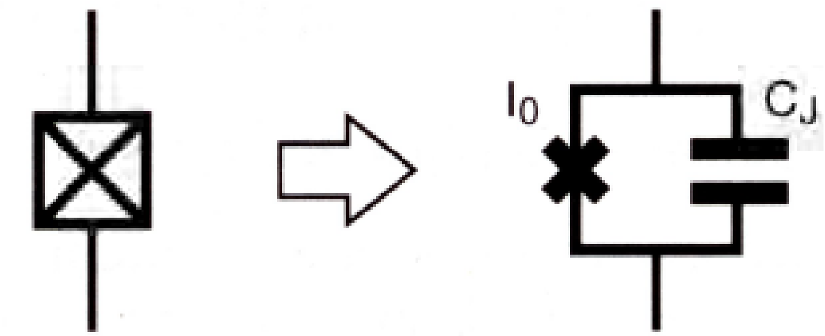
Macroscopic quantum state

Easily coupled to each other

Can be integrated

Josephson junction

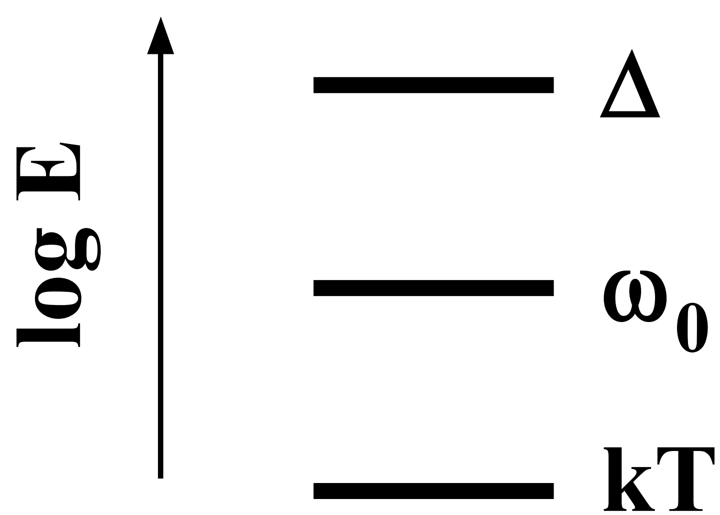




Non-dissipative:

- **Must operate at < 50 mK**
- **Only superconducting elements**
- **Electron temperature < 50 mK**

Energy scales:

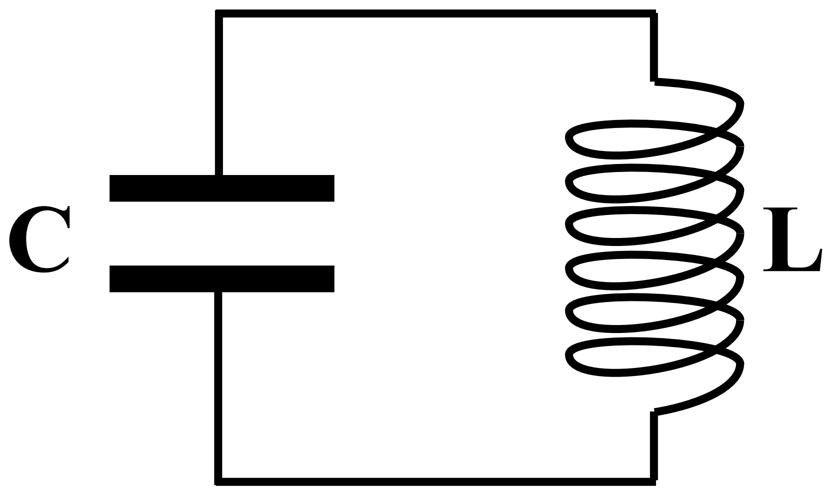


Relevant Observables

Flux Φ = phase difference

Charge Q

Harmonic Oscillator



Classical $$\frac{d^2Q}{dt^2} + \frac{Q}{LC} = 0$$

Quantum $$H = \frac{\Phi^2}{2L} + \frac{Q^2}{2C}$$

$$= \hbar\omega_0(n+\tfrac{1}{2})$$

$$[\Phi, Q] = i\,\hbar$$

~Position ~Momentum

Typical values:

Dimension ~ 10 μm

L ~ 0.1 nH

C ~ 1 pF

$\omega_0/2$ ~ 16 GHz

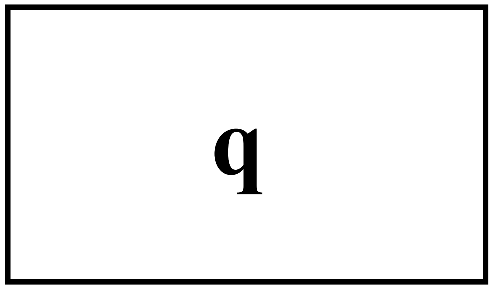
Main challenges:

Coupling to environment

Variability of engineered circuits

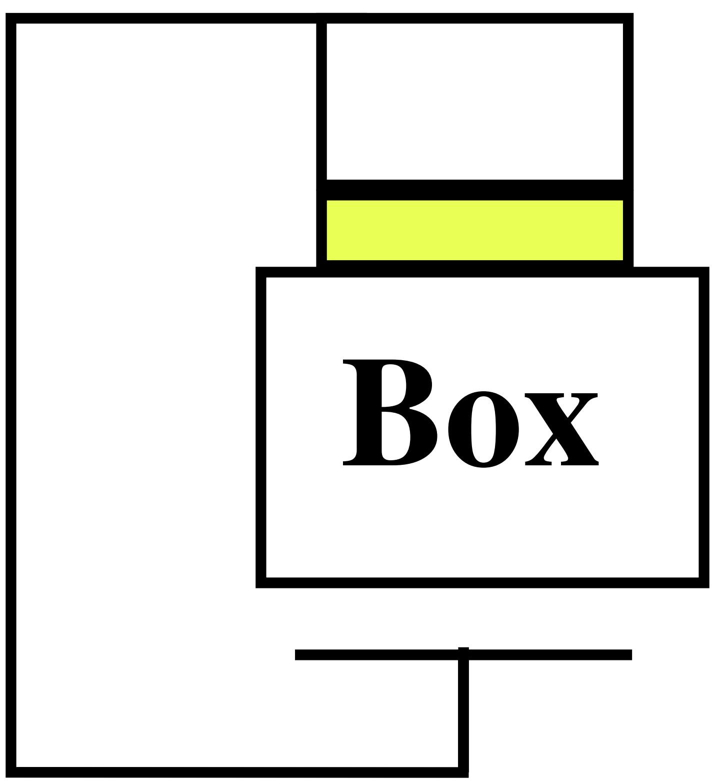
Cooper Pair Box

Coulomb energy of a box:



$$E_C = \frac{q^2}{2C} = \frac{(2ne)^2}{2C} = \frac{2n^2e^2}{C}$$

Hamiltonian including tunnel junction



tunable by offset voltage

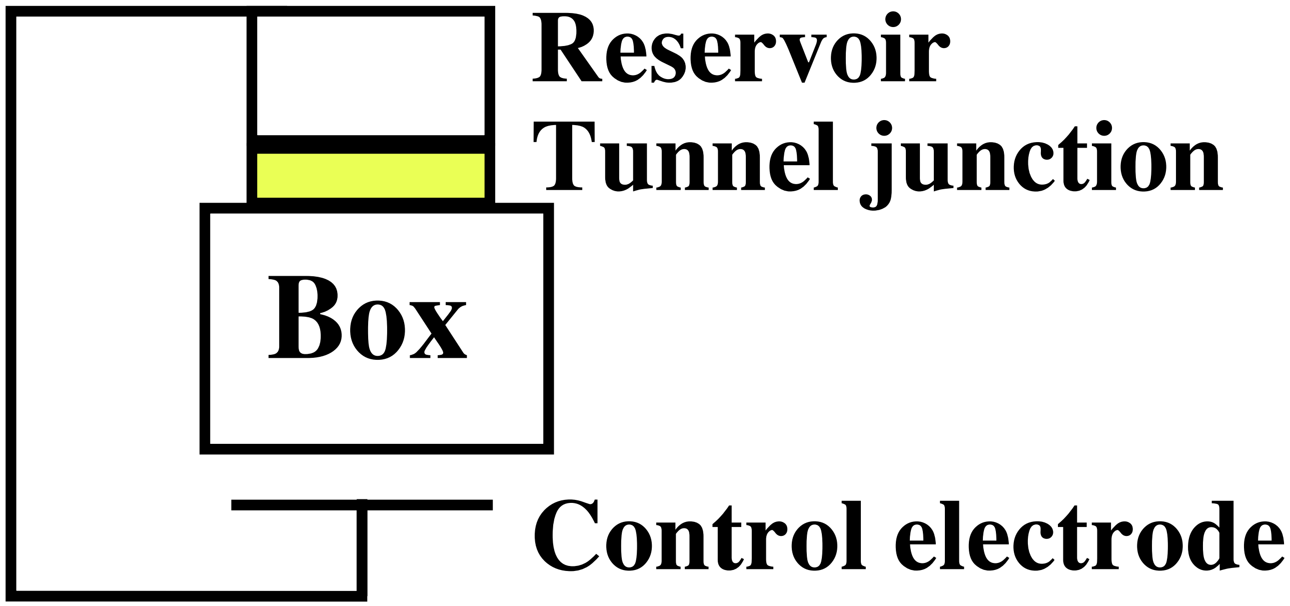
tunable by flux through split junction

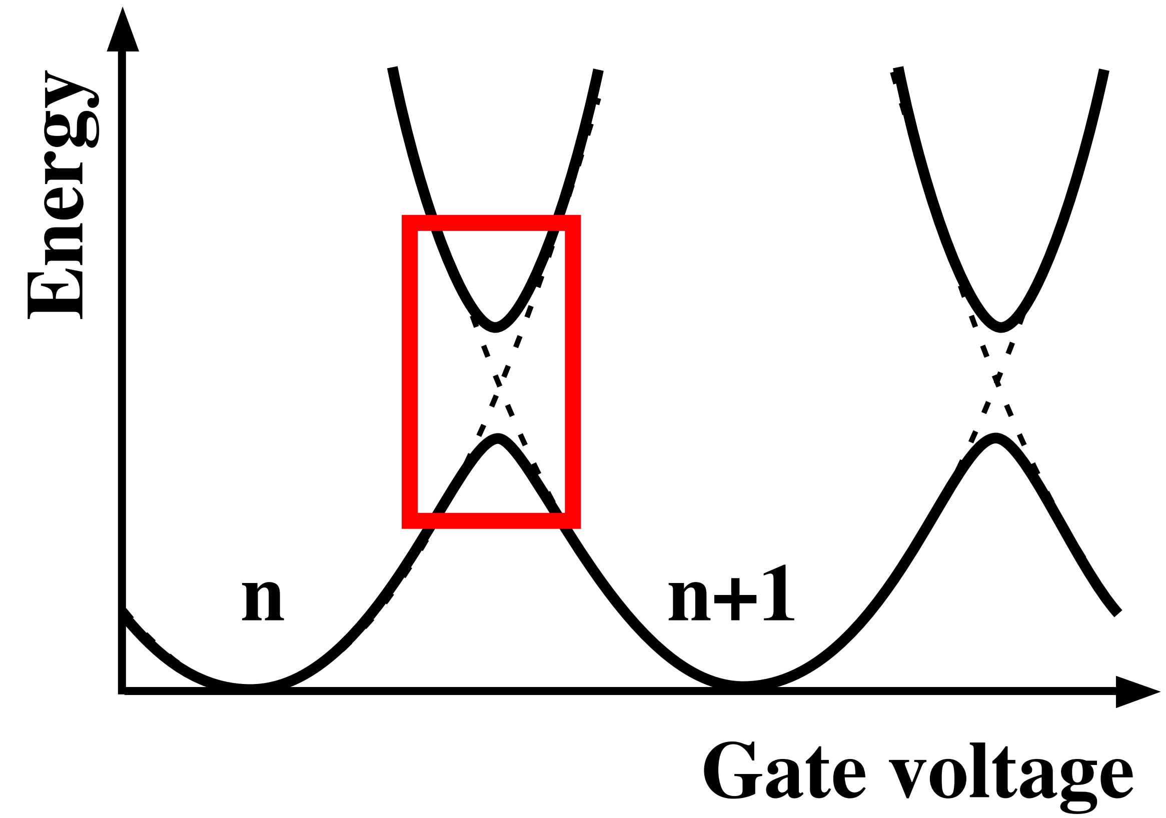
$$H = E_C(N-N_g)^2 - E_J \cos\theta$$

Cooper pairs on island

Phase difference across junction

Charge Qubit





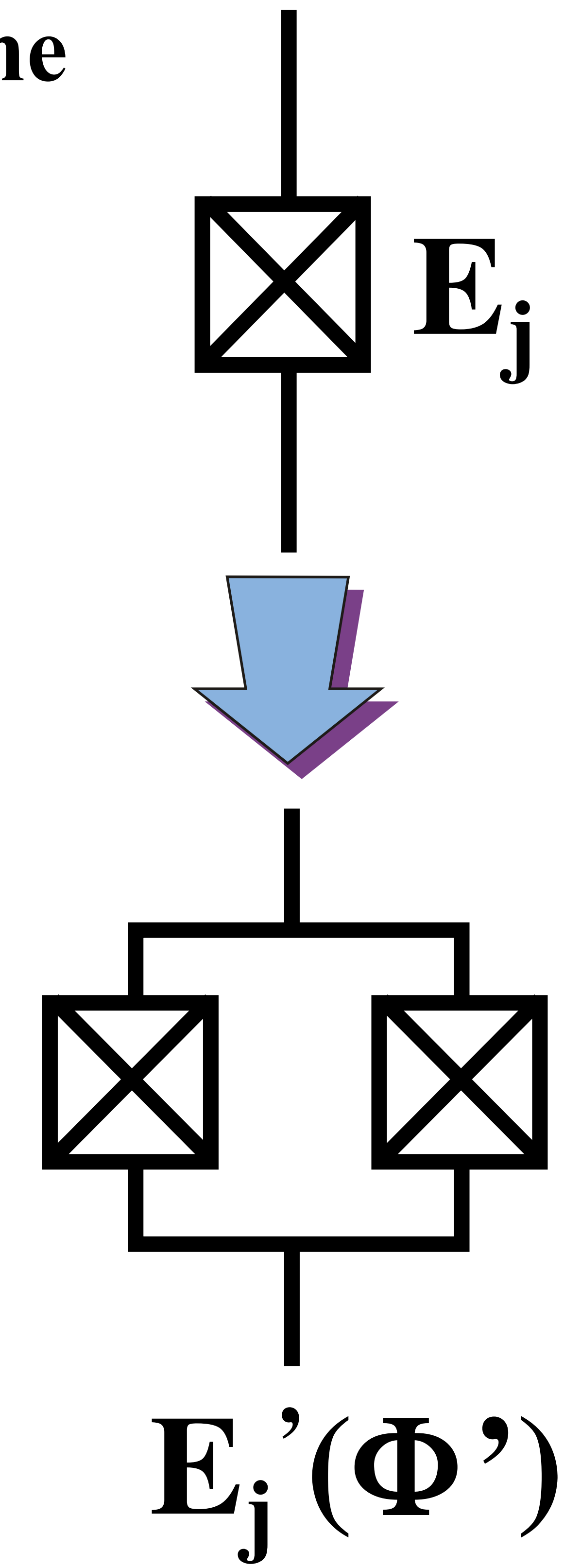
Qubit states: |n>, |n+1>

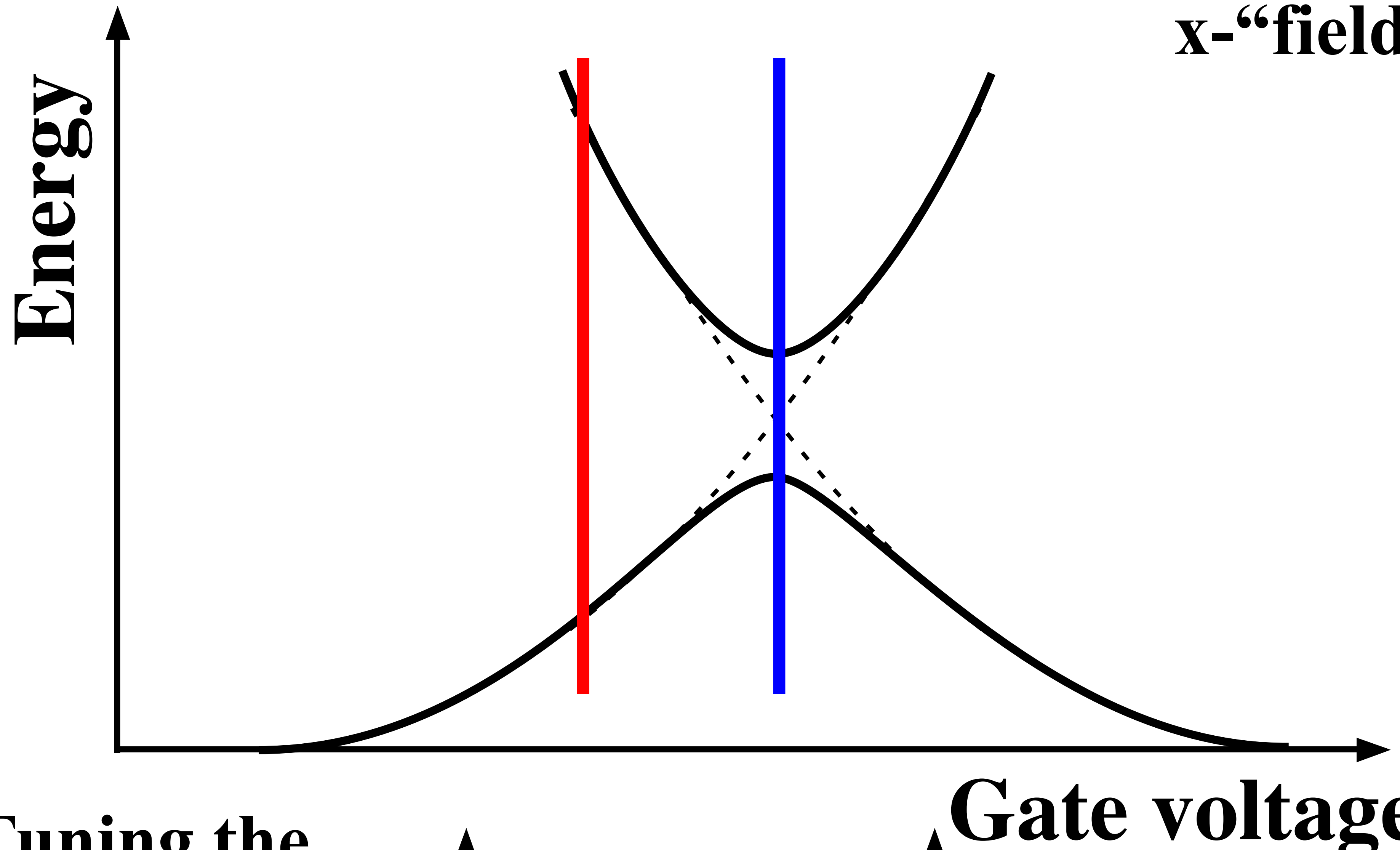
Qubit Hamiltonian:

$$\mathcal{H} = 4\frac{E_C}{\hbar}(1 - 2n_g)\mathbf{S_z} - \frac{E_J}{\hbar}\mathbf{S_x}$$

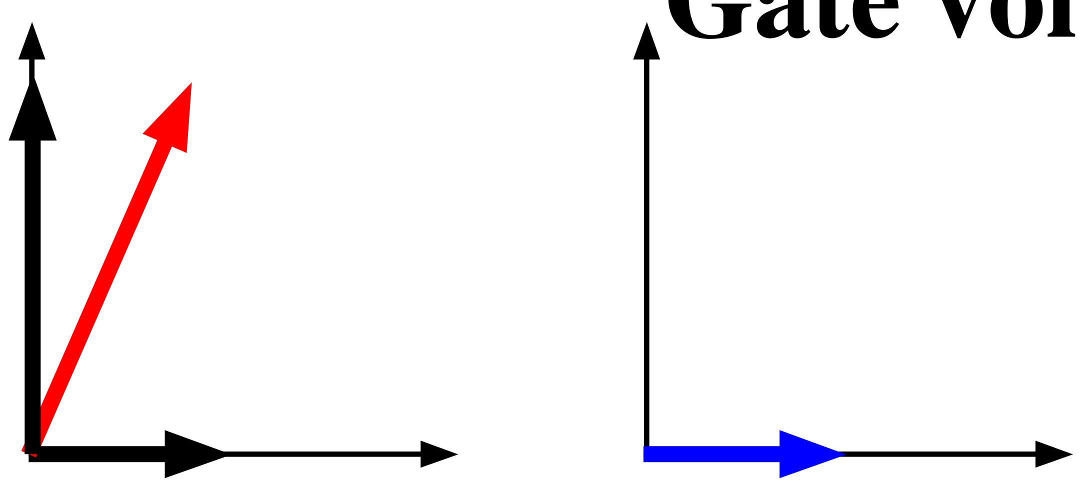
Gate Operations

Tuning the x-"field"



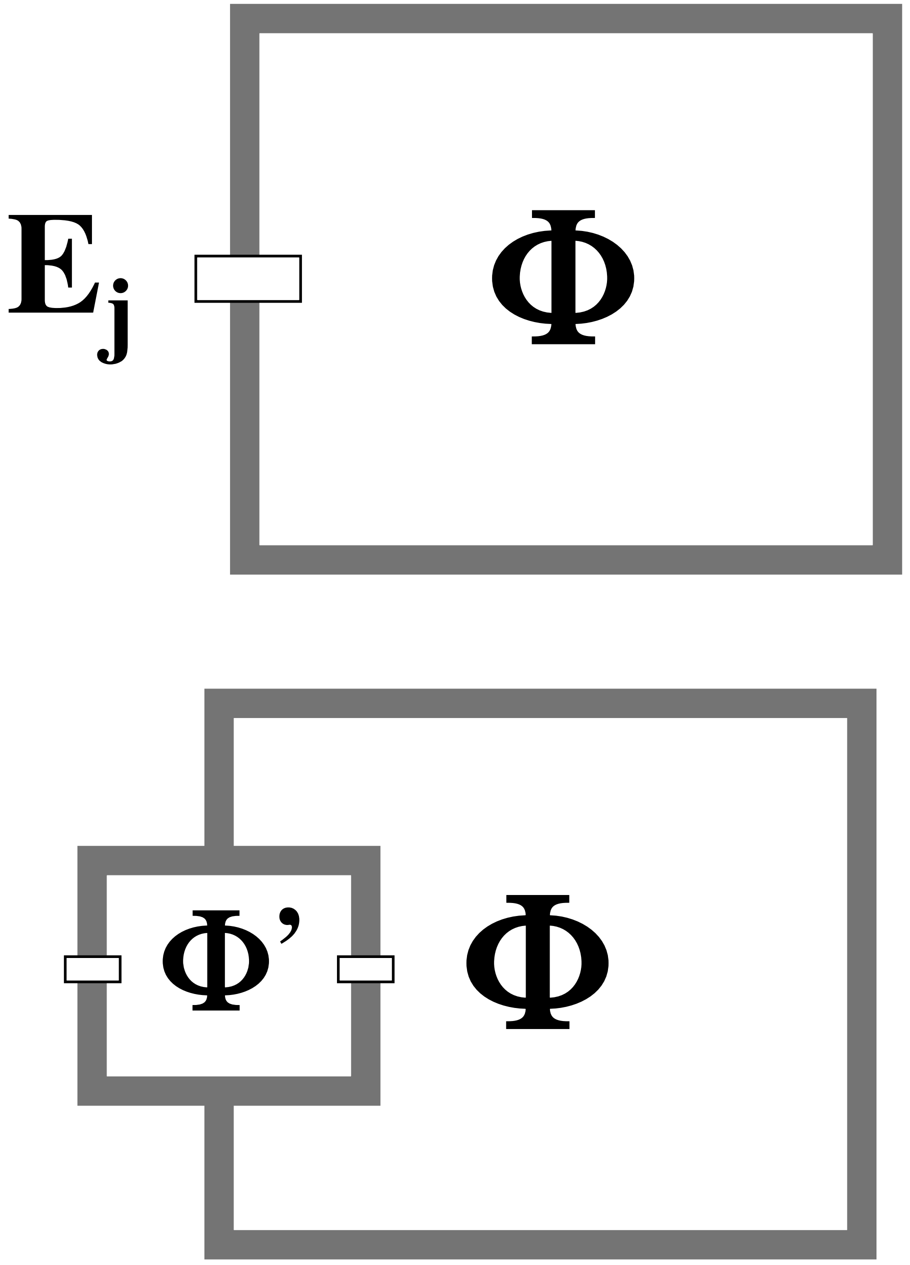


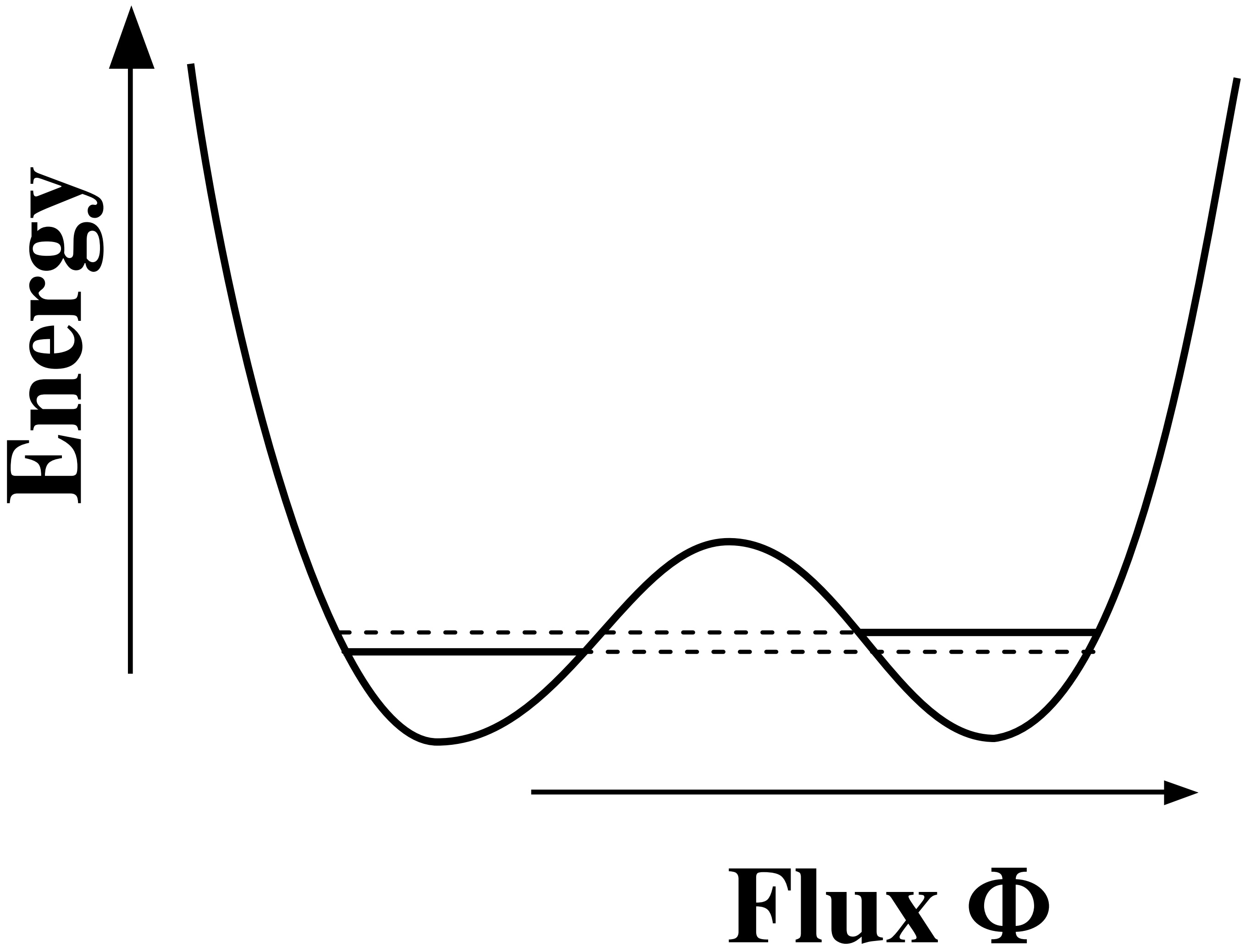
Tuning the z-"field"



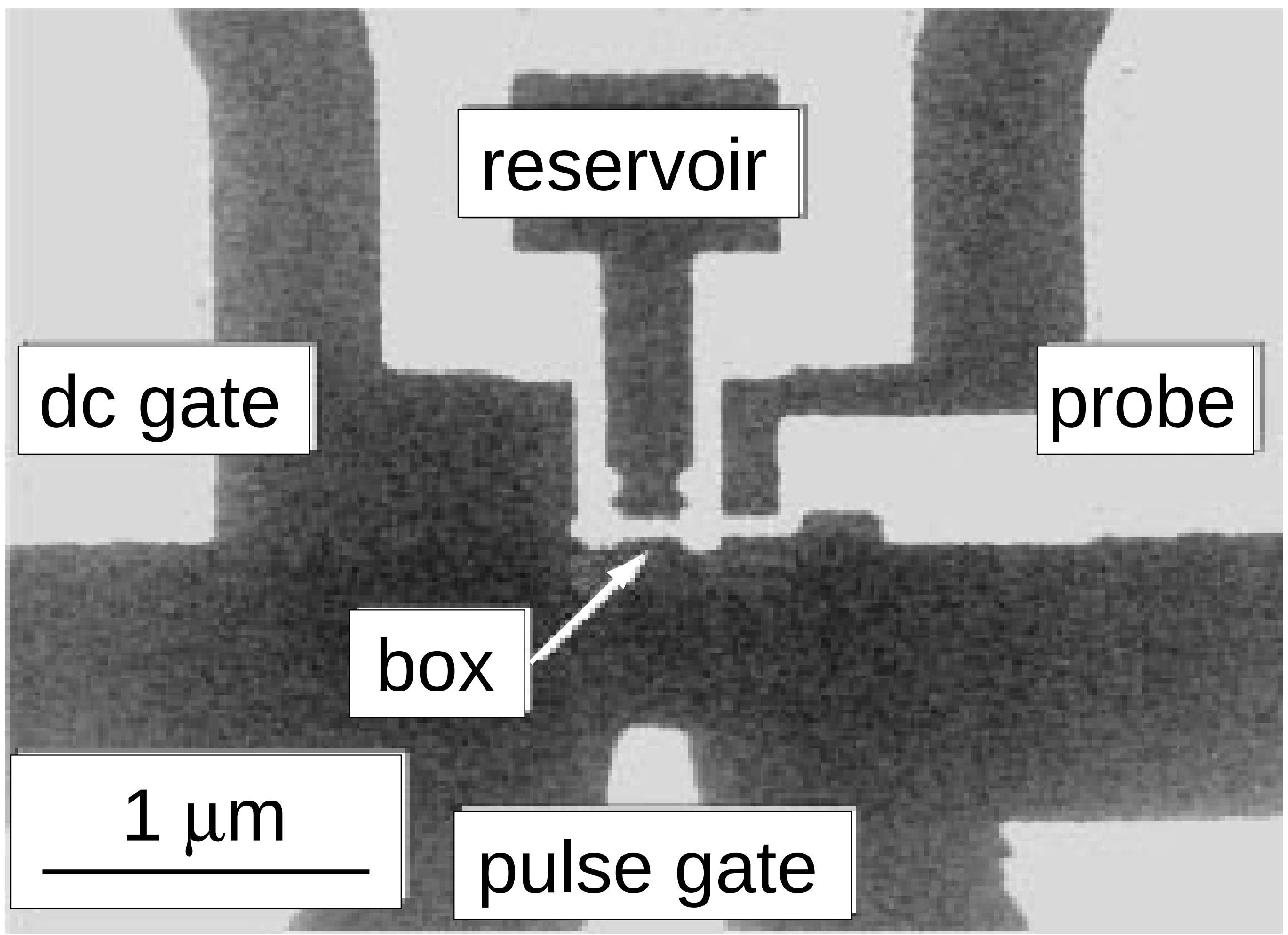
Flux Qubit

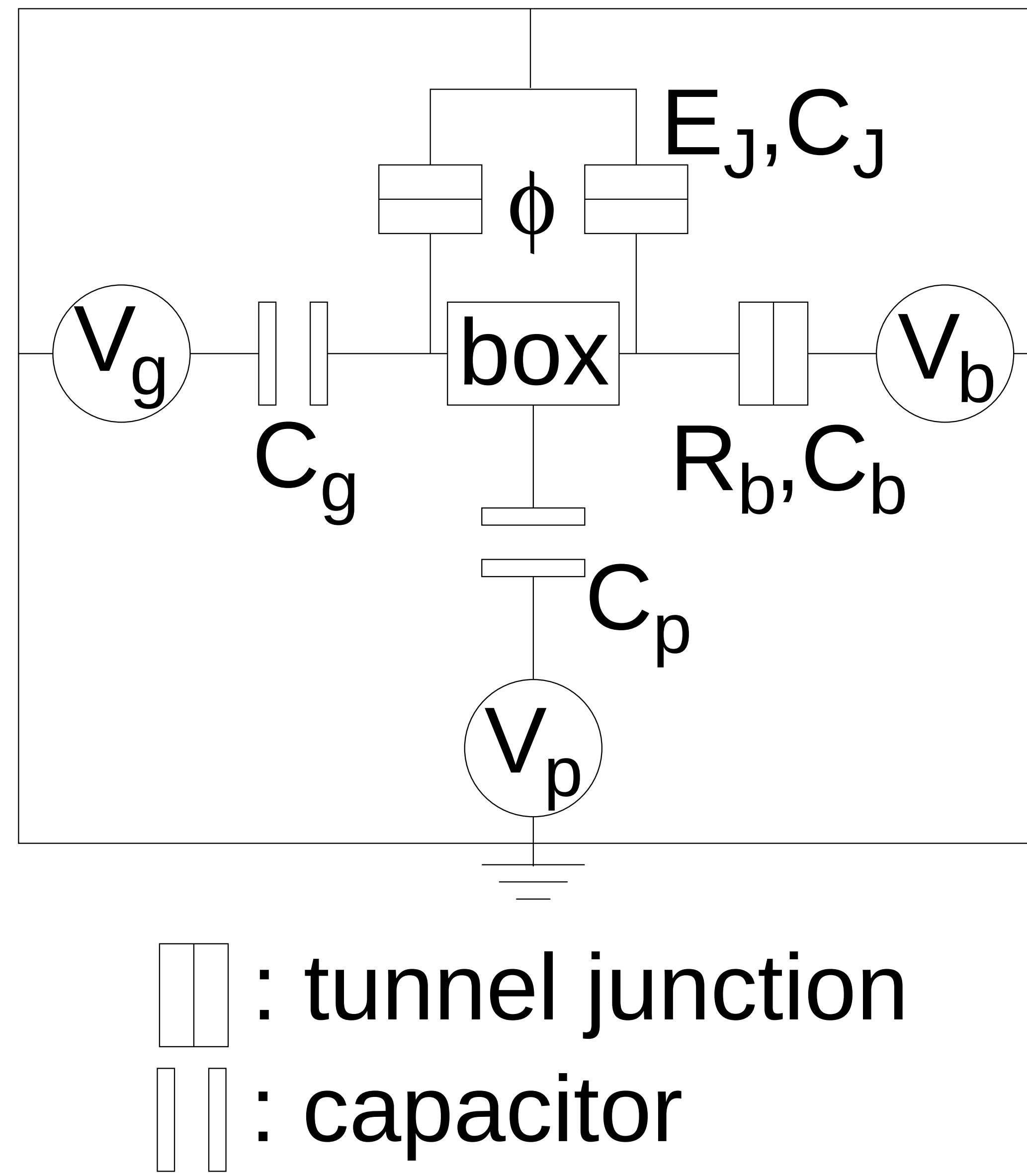
$$\mathcal{H}_{\text{fl}} = -E_J \cos\left(2\pi \frac{\Phi}{\Phi_0}\right) + \frac{(\Phi - \Phi_x)^2}{2L} + \frac{Q^2}{2C_J}$$



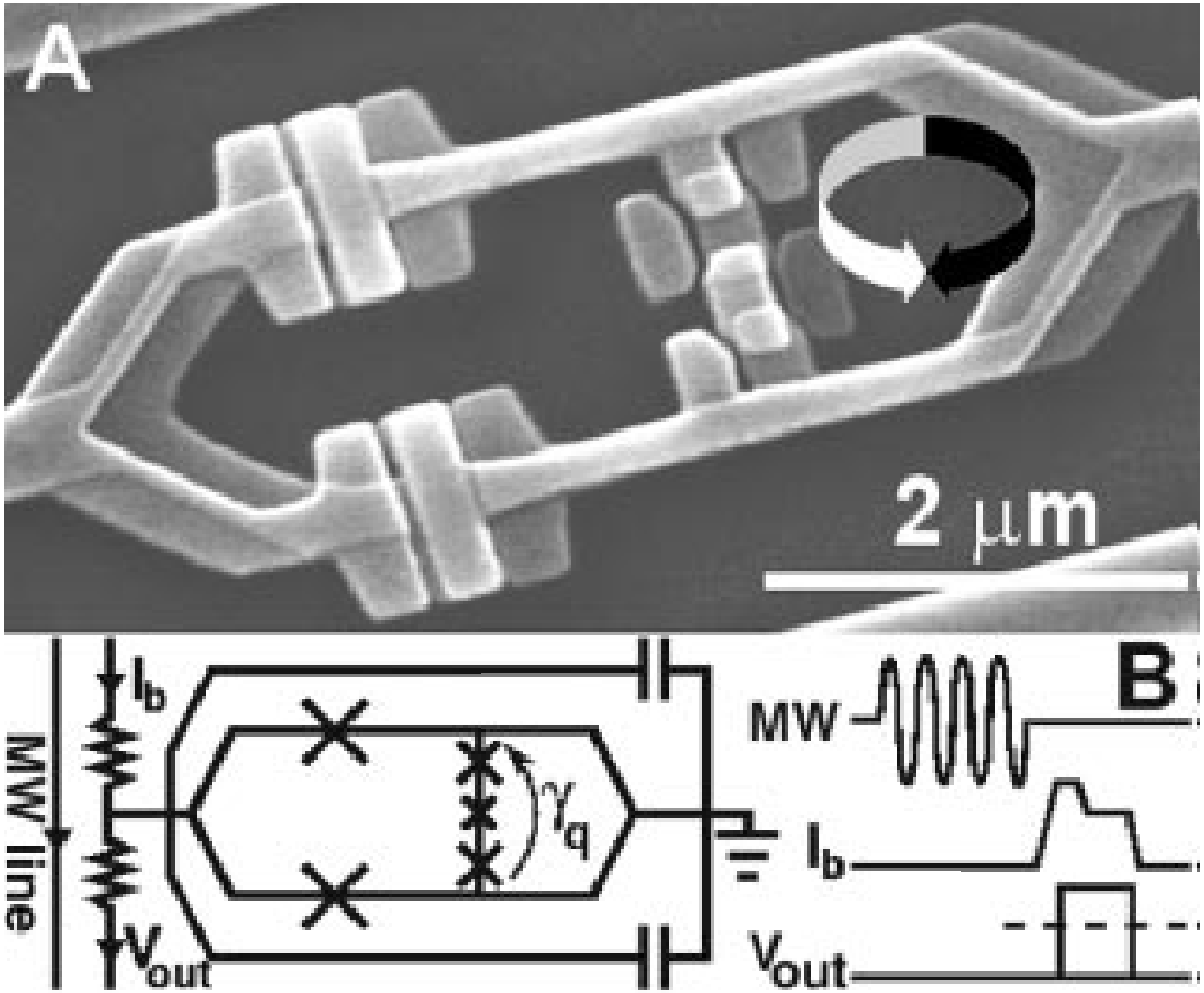


Josephson Qubit

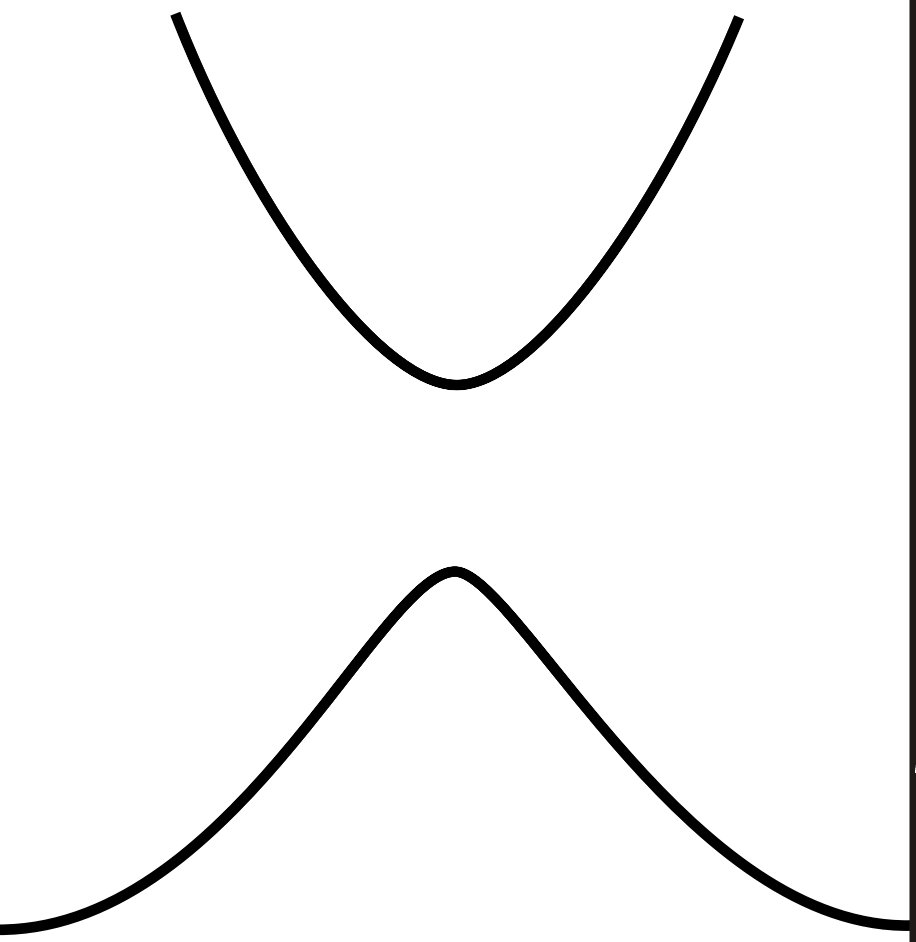


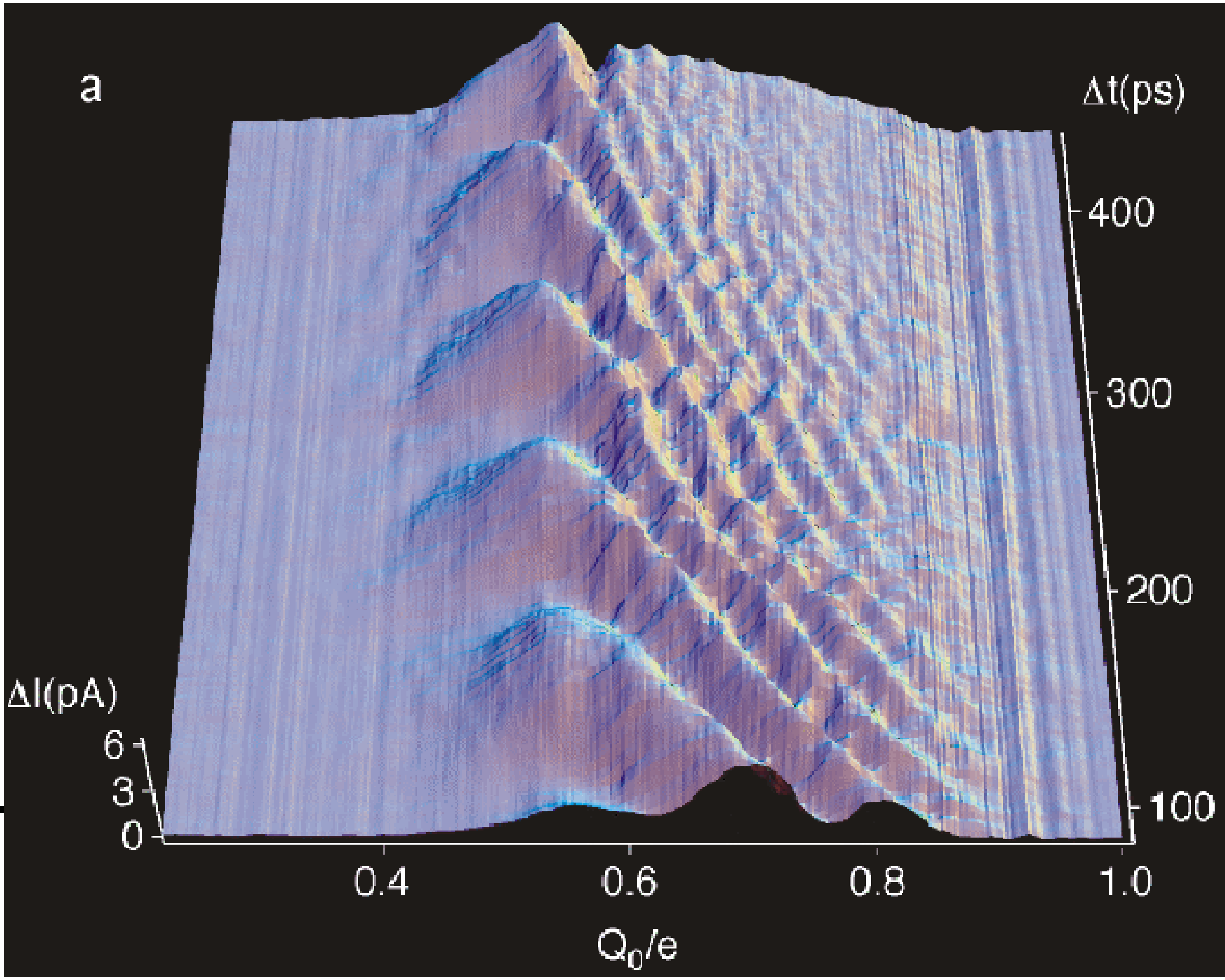


Flux Qubit

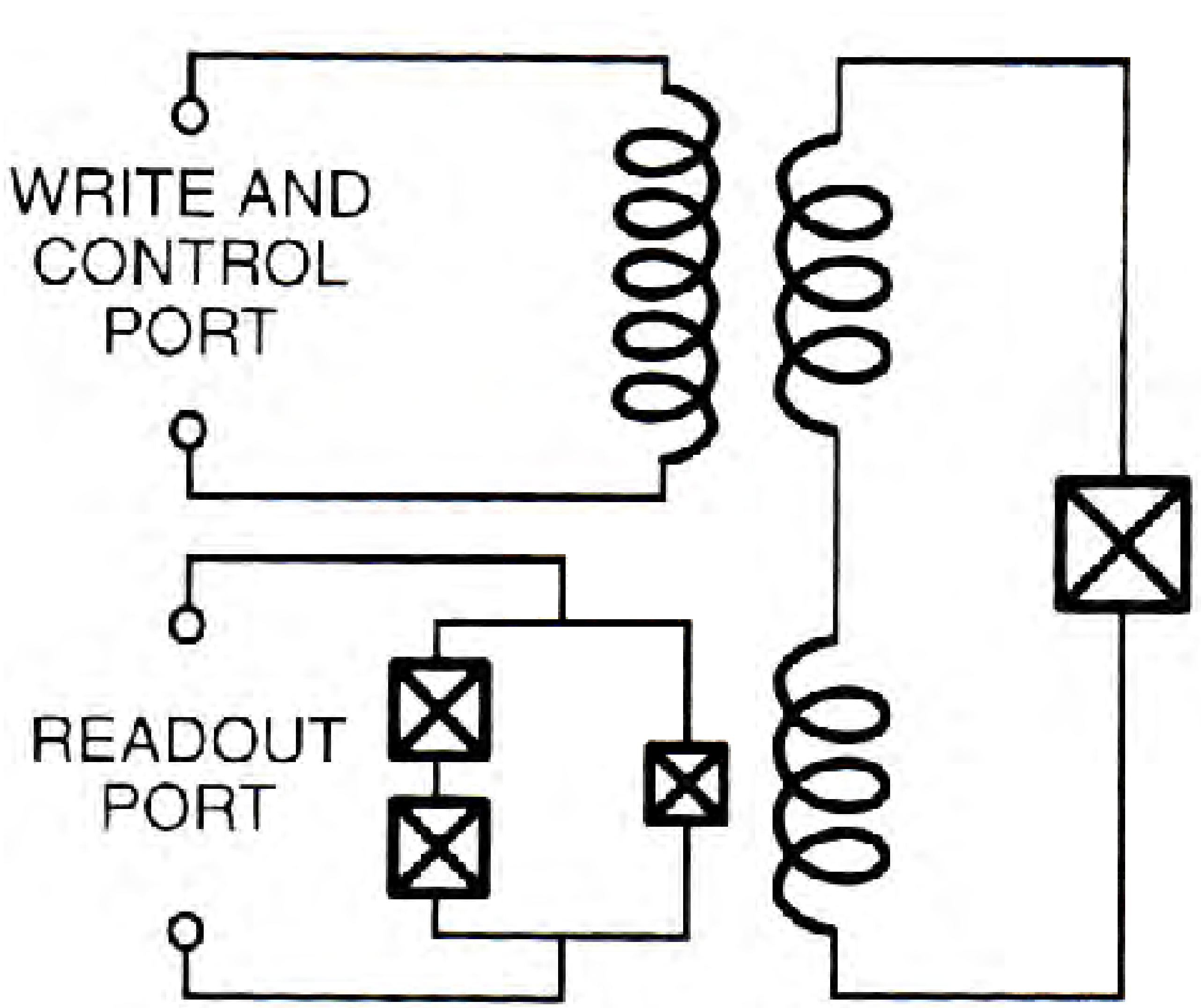


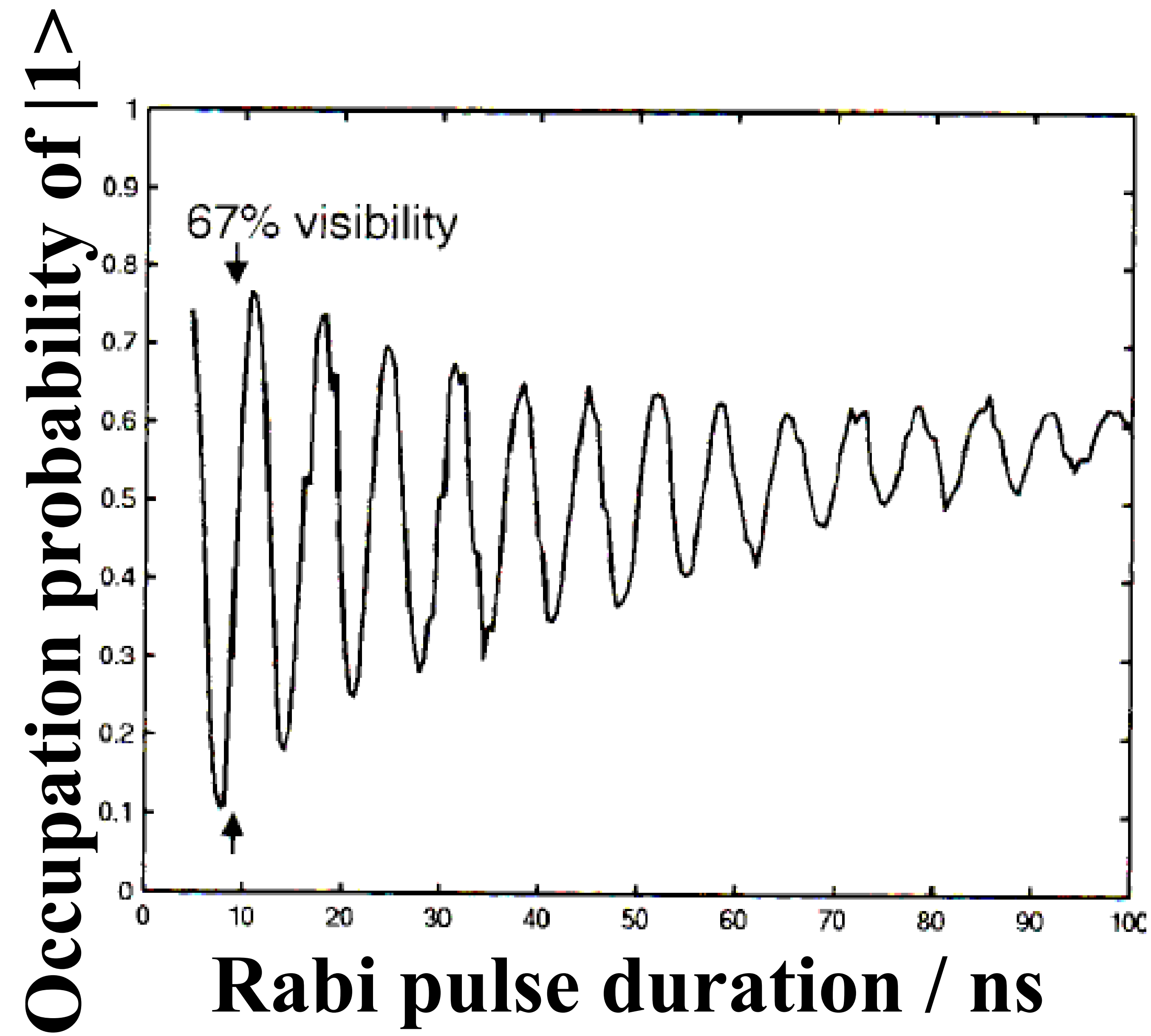
Rabi Oscillations



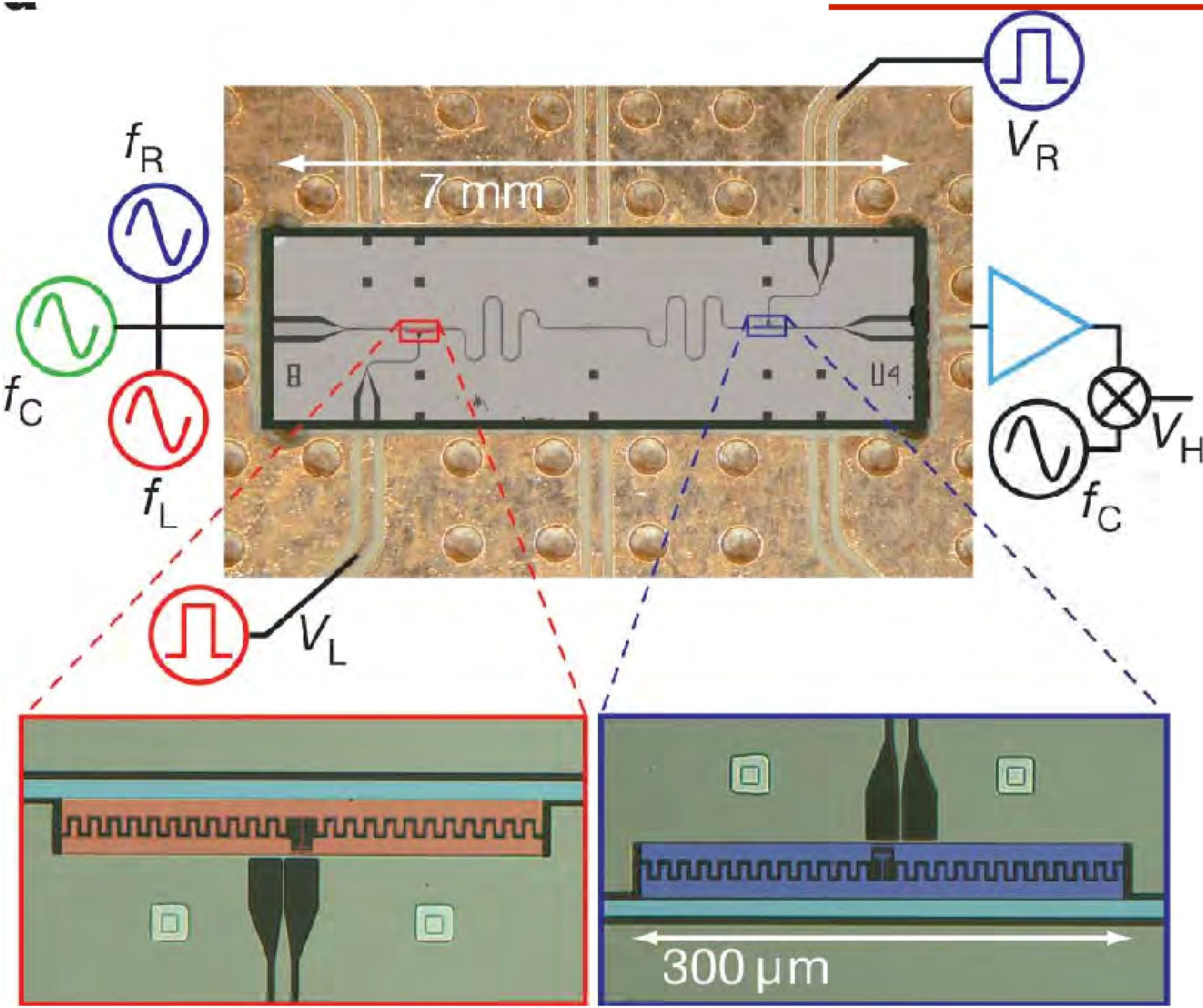


Resonant Excitation



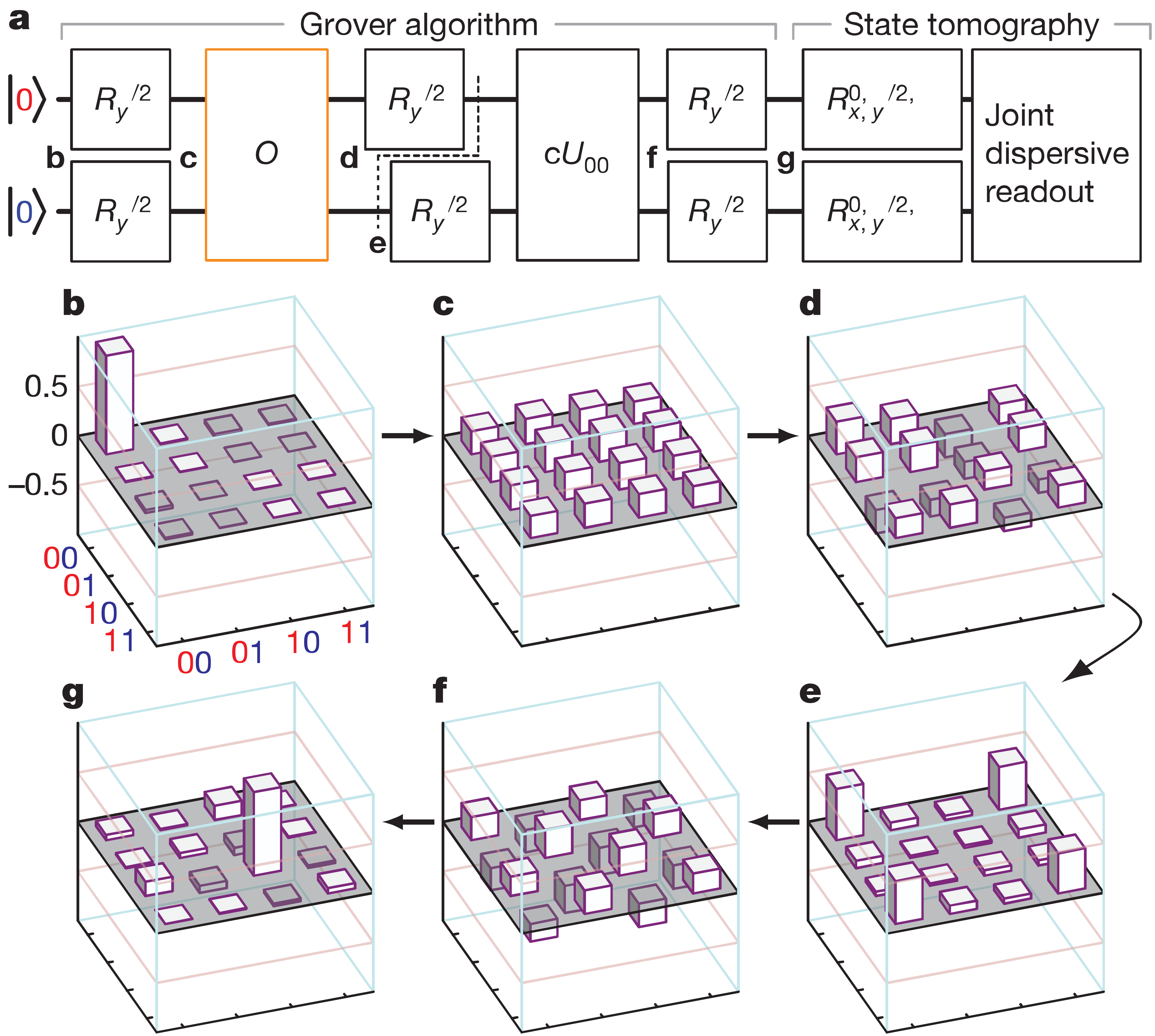


Current Device



DiCarlo et al., Nature, 460, 240 (2009).

Grover Search

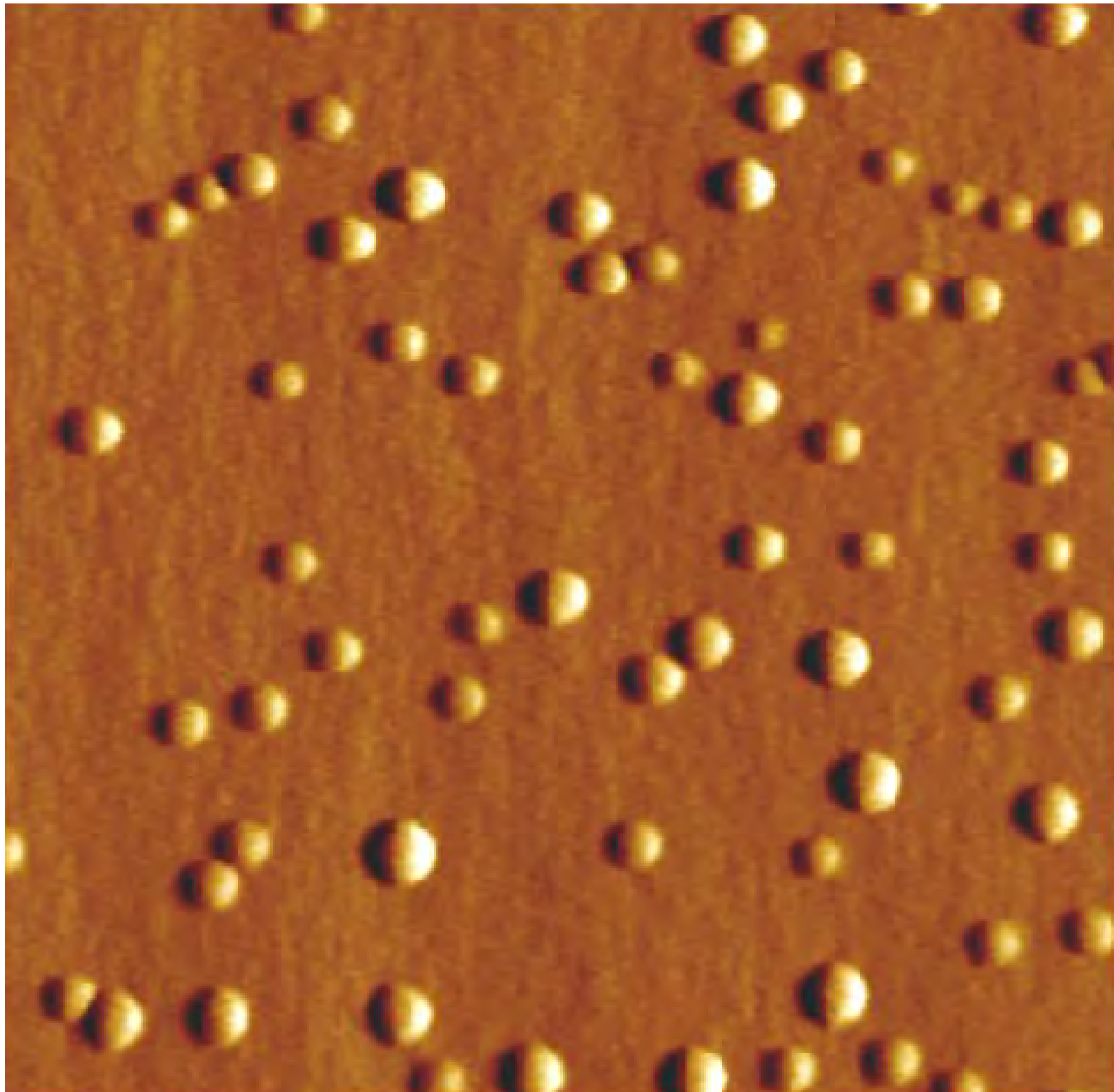


Semiconductor Qubits

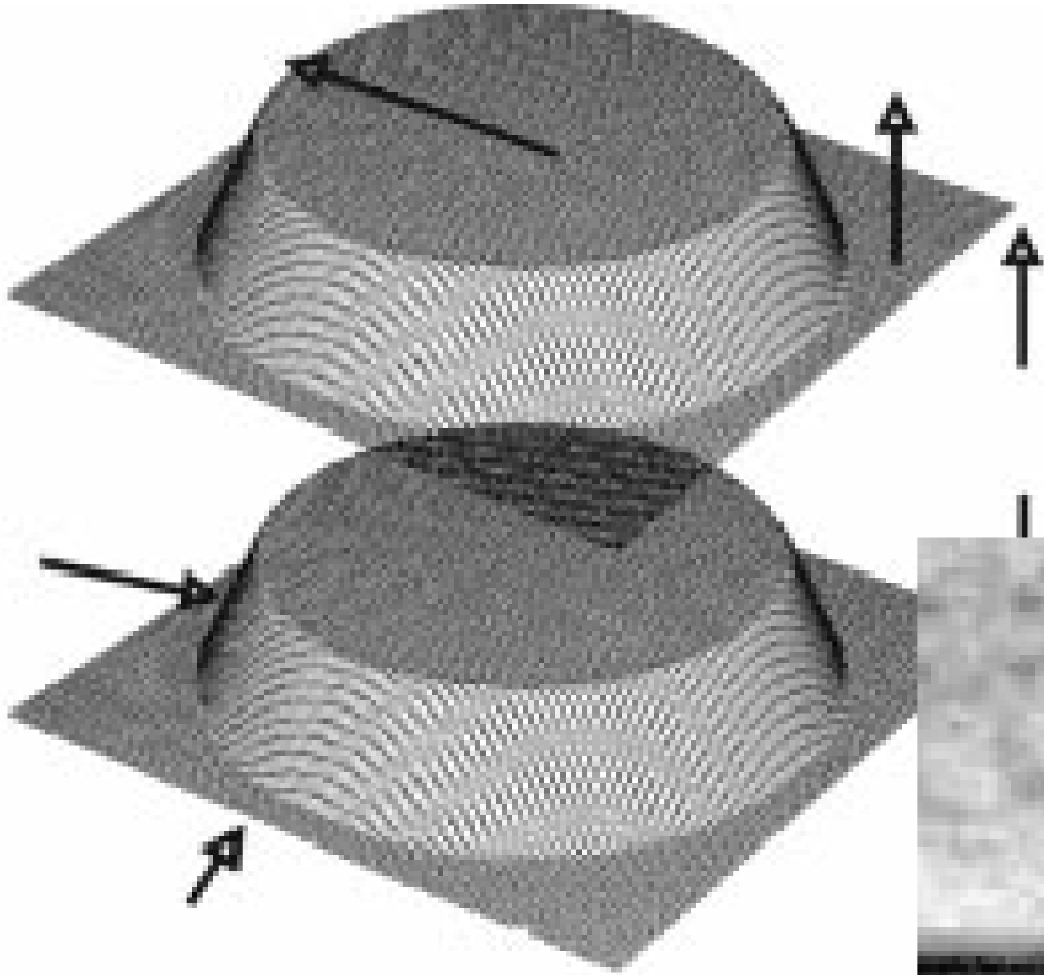
12.3.1 Materials

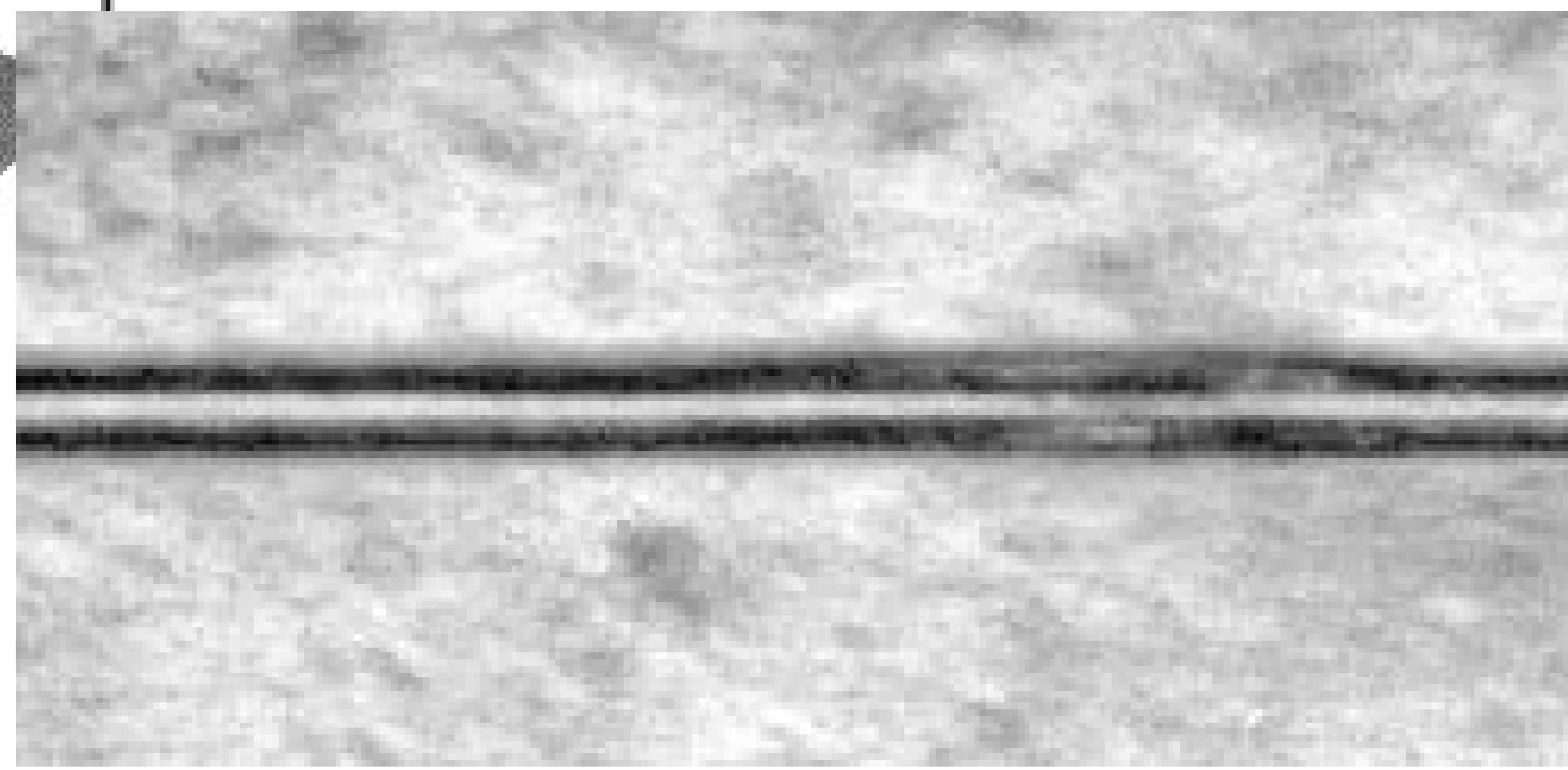
12.3.2 Excitons in quantum dots

12.3.3 Electron spin qubits

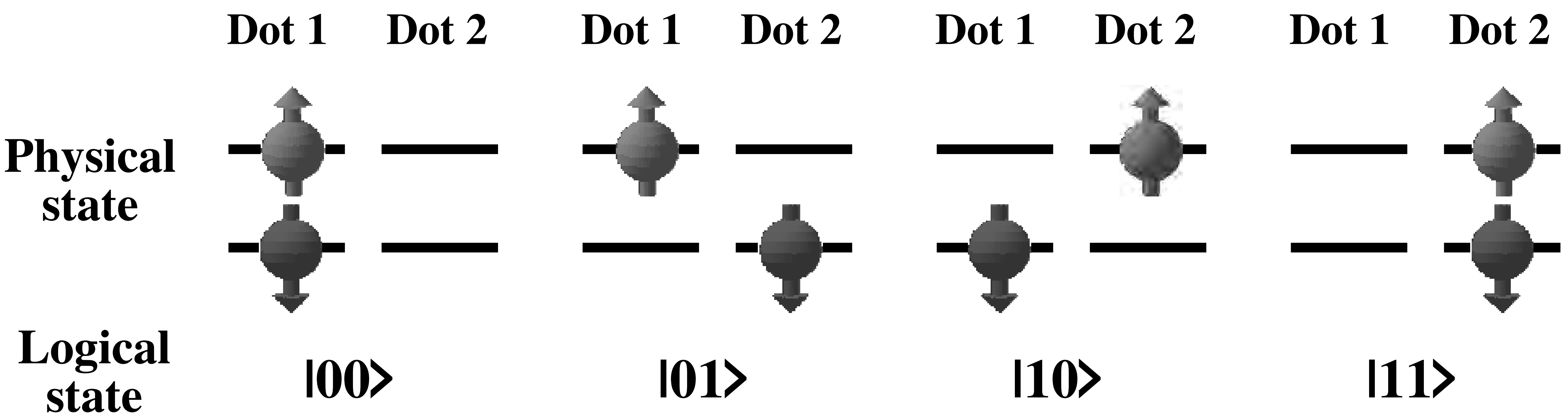


Coupled Quantum Dots





Qubits

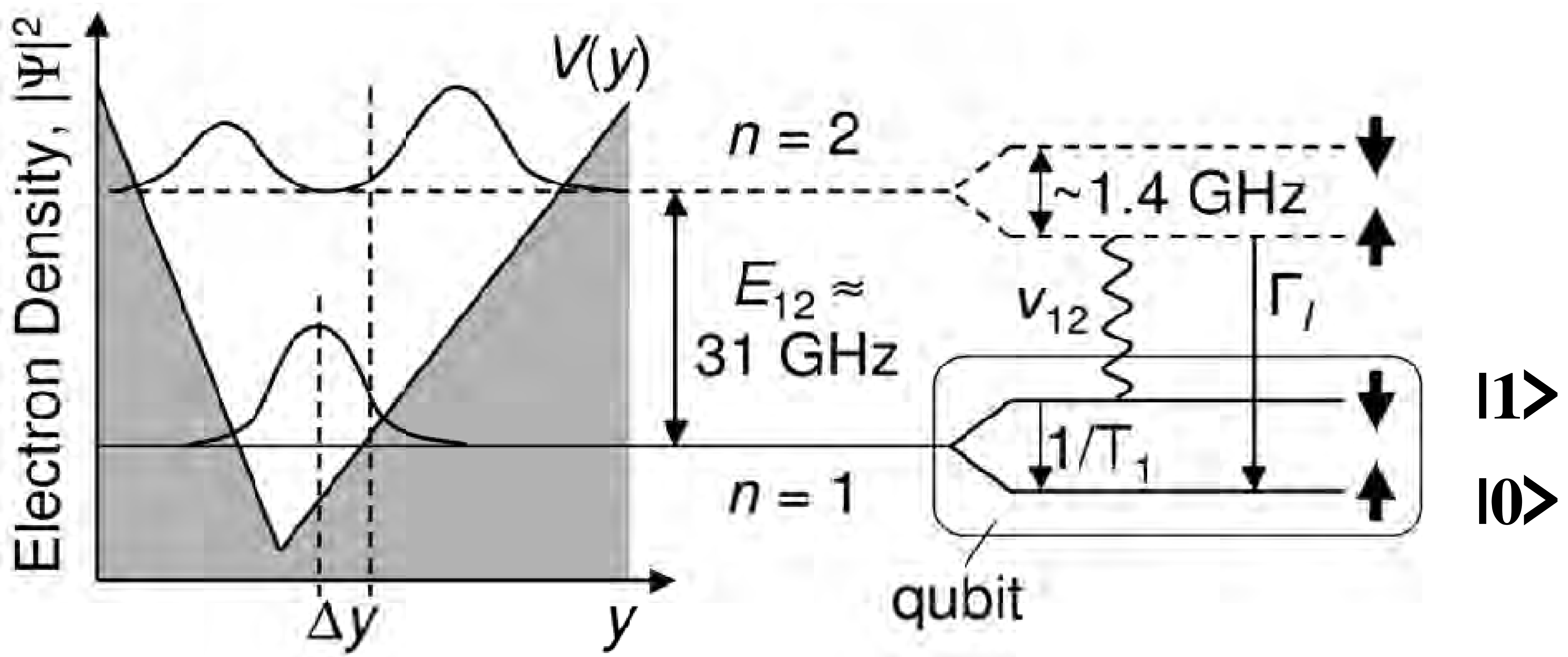

Dot 1
Dot 2
Dot 1
Dot 2
Dot 1
Dot 2
Dot 1
Dot 2
Physical state
Logical state
|00›
|01›
|10›
|11›

Single-step readout by microwave excitation

QDot Readout

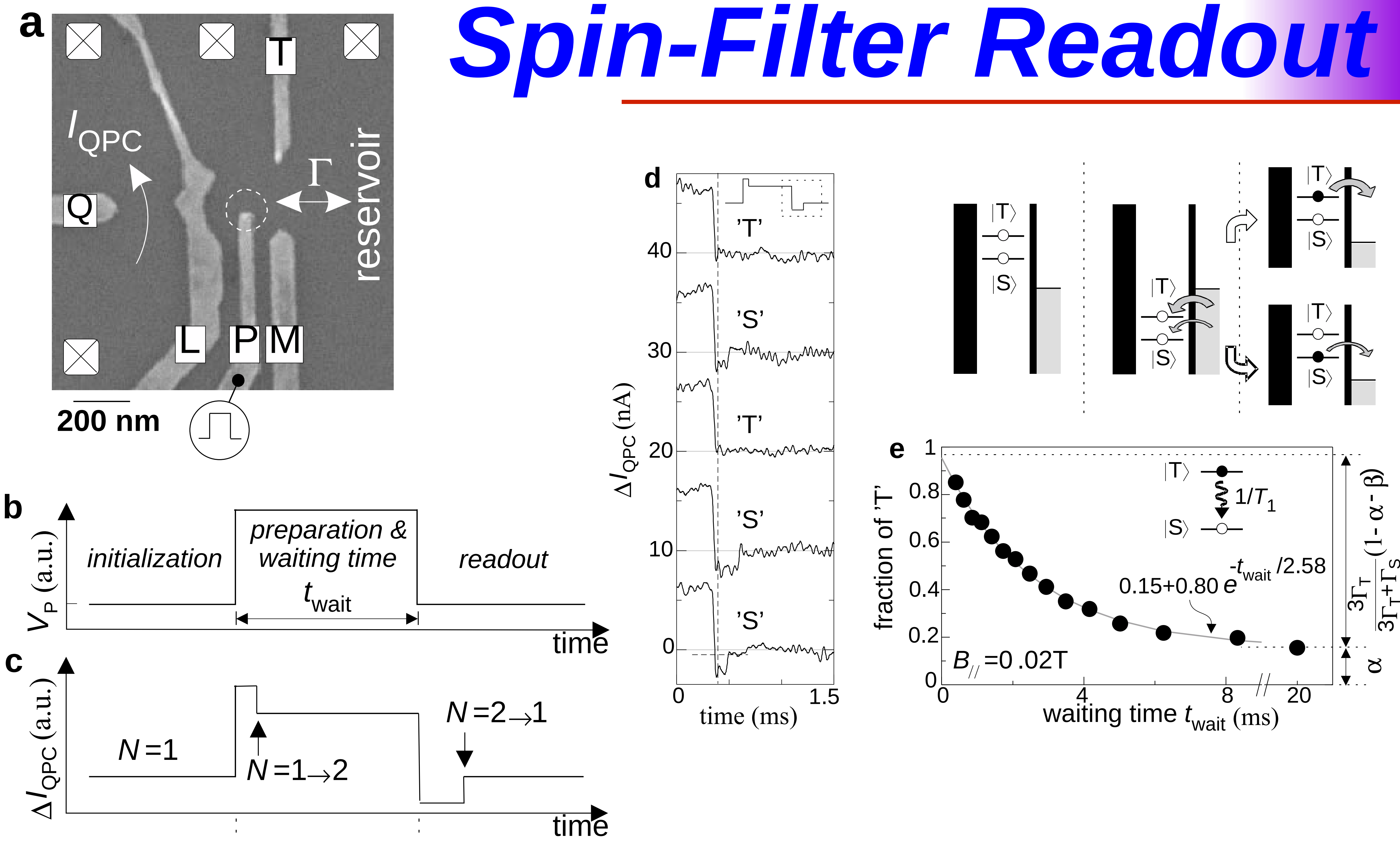
M. Friesen et al., Phys. Rev. Lett. 92, 037901 (2004).

Asymmetric QW



- **Irradiation at ν_{12} creates charge oscillation if qubit is in |1> state**
- **Can also be used for initialization**

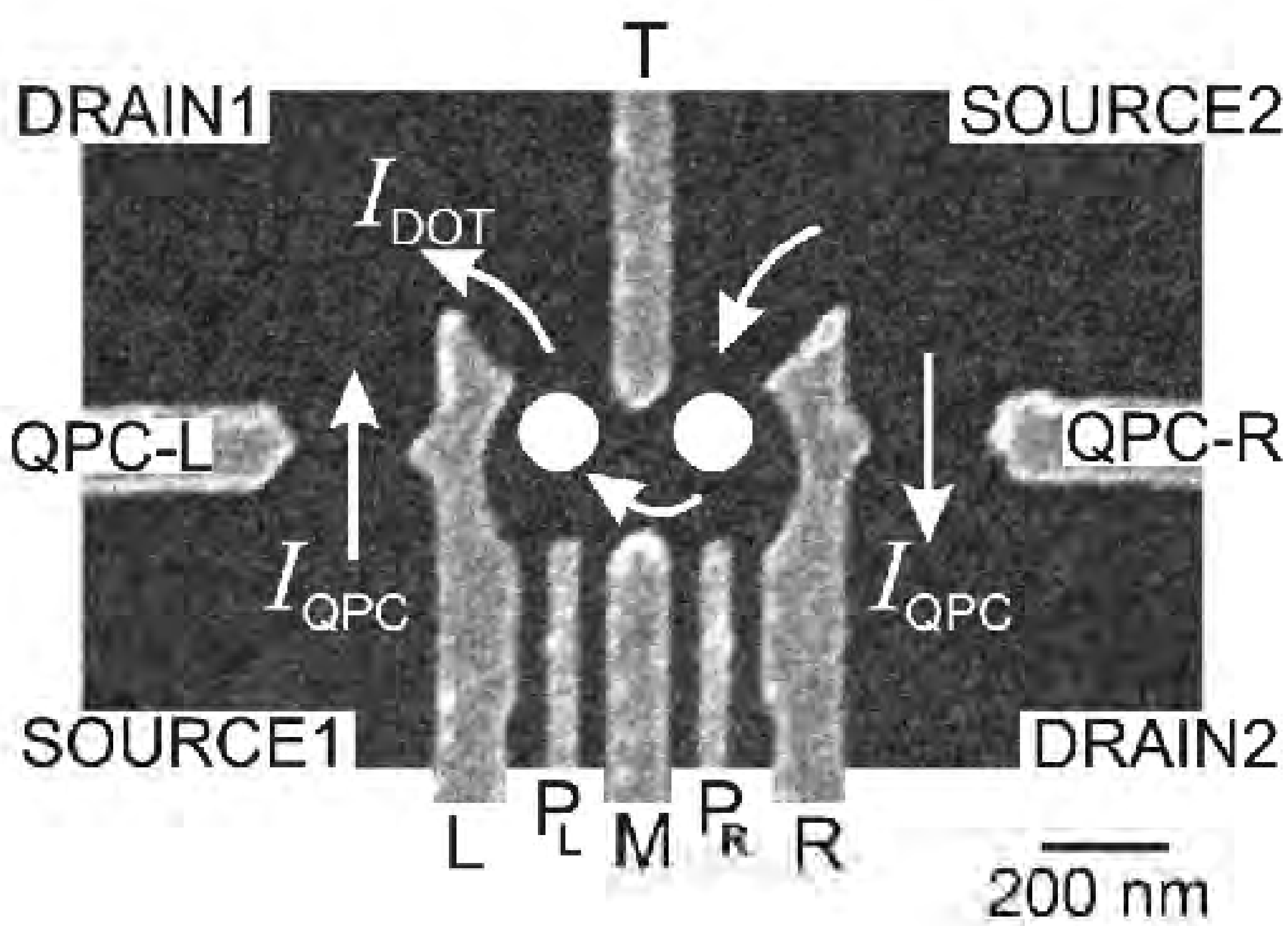
Spin-Filter Readout



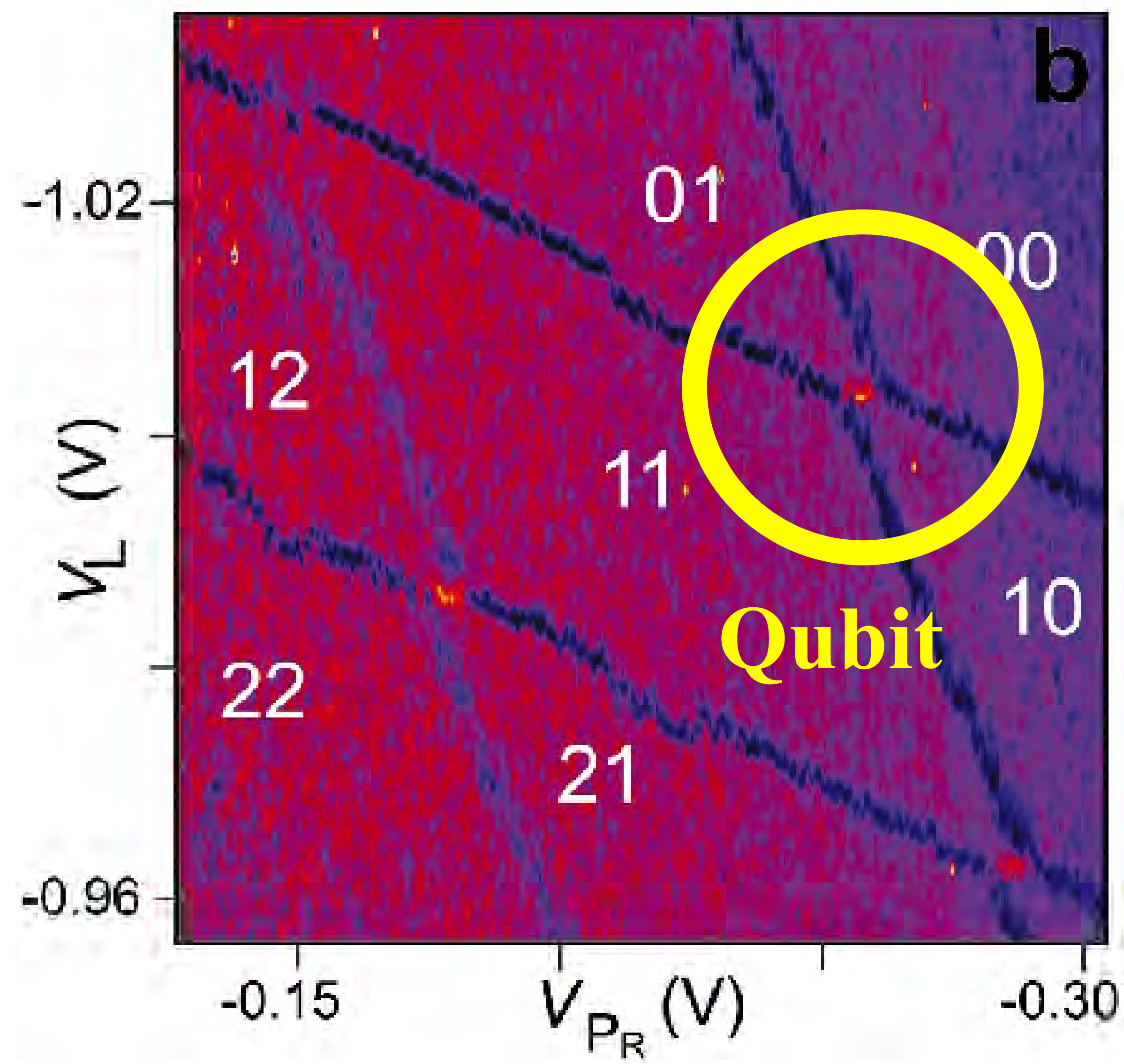
R. Hanson, L.H.W.v. Beveren, I.T. Vink, J.M. Elzerman, W.J.M. Naber, F.H.L. Koppens, L.P. Kouwenhoven, and L.M.K. Vandersypen, 'Single-Shot Readout of Electron Spin States in a Quantum Dot Using Spin-Dependent Tunnel Rates', Phys. Rev. Lett. 94, 196802 (2005).

Qubits in Quantum Dots

Electrostatically controlled pair of quantum dots



Occupation numbers



[1] J.M. Elzerman, R. Hanson, J.S. Greidanus, L.H.W.v. Beveren, S.D. Franceschi, L.M.K. Vandersypen, S. Tarucha, and L.P. Kouwenhoven, 'Few-electron quantum dot circuit with integrate charge read out', PRB 67, 161308 (2003).