Spin Blockade, Spin Relaxation and Spin Dephasing, in ^{12}C and ^{13}C Nanotubes

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David Reilly

Theory:

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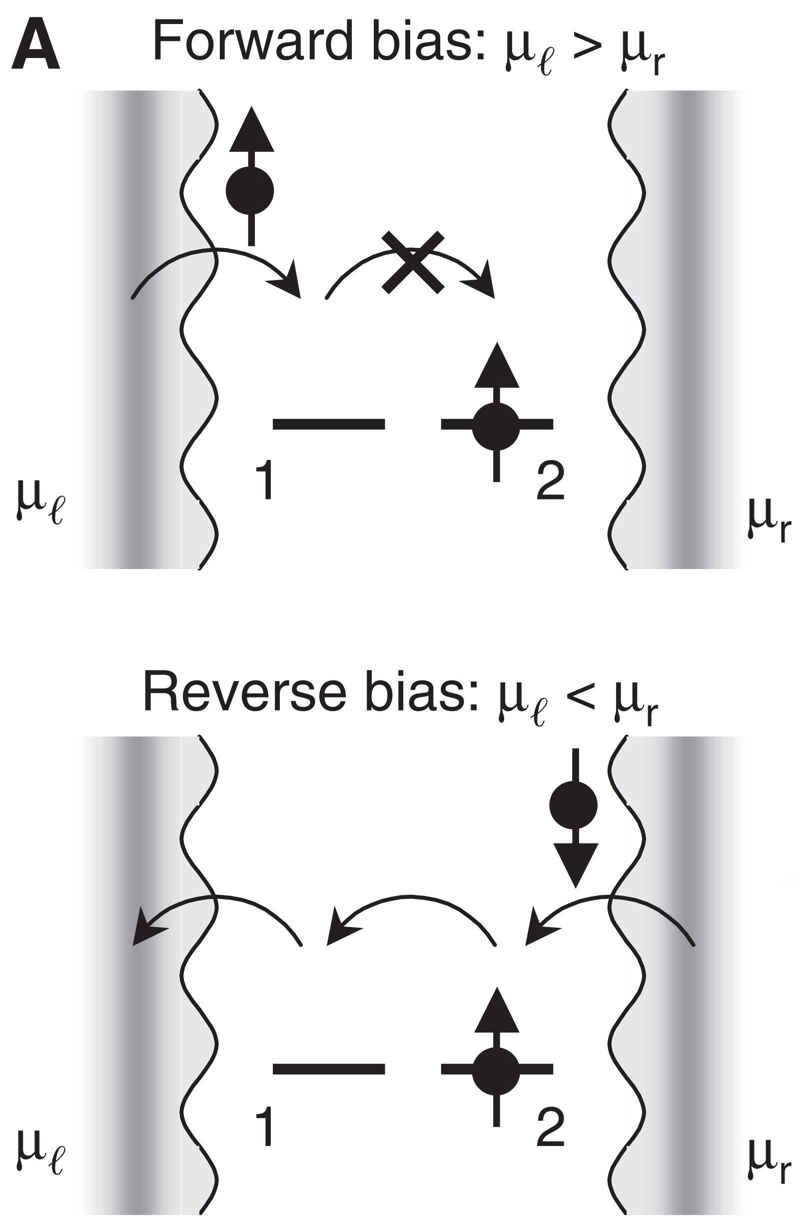
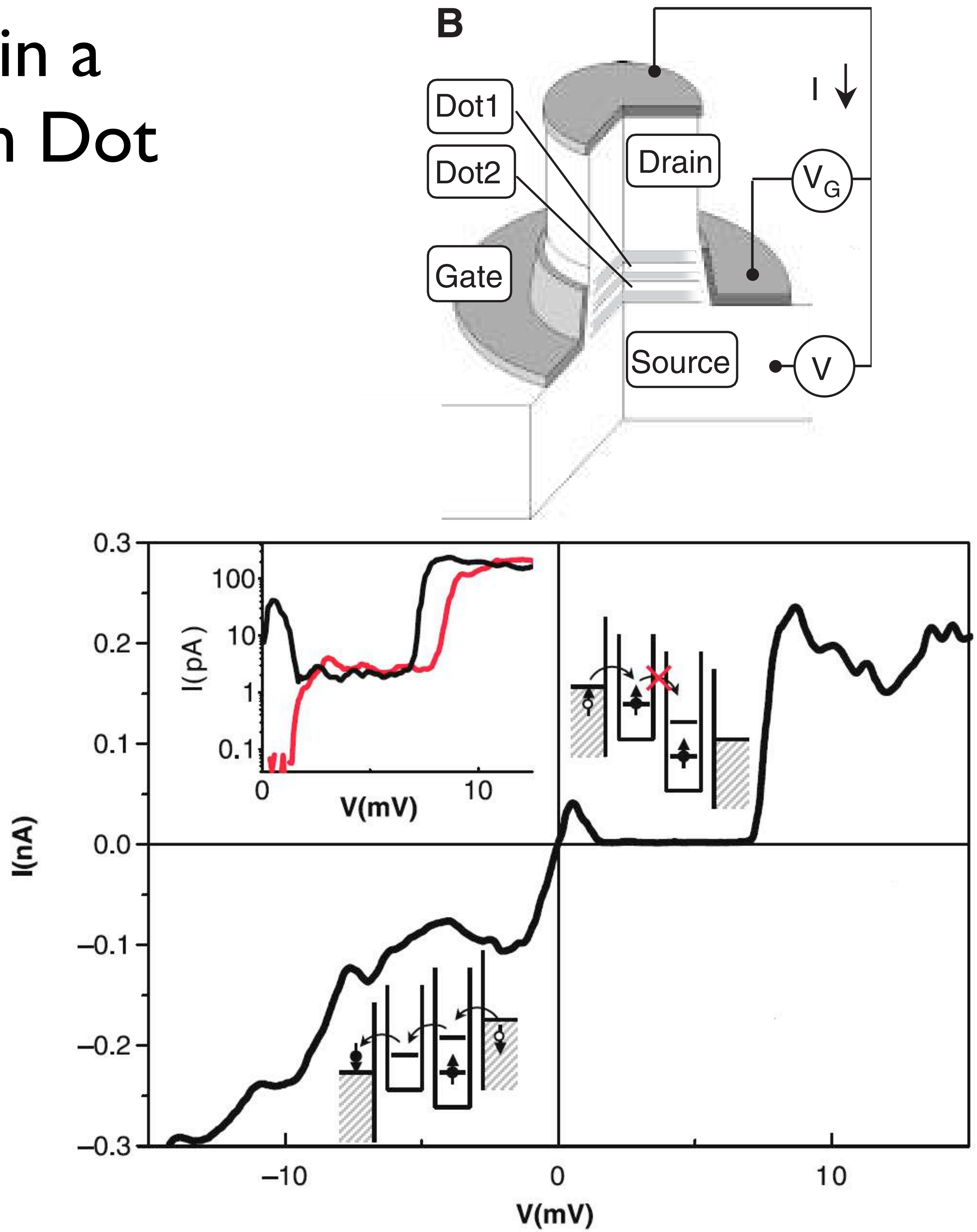
Emmanuel Rashba (Harvard)

Support: NSF, Harvard NSEC, ARO/iARPA, DoD, Harvard CNS

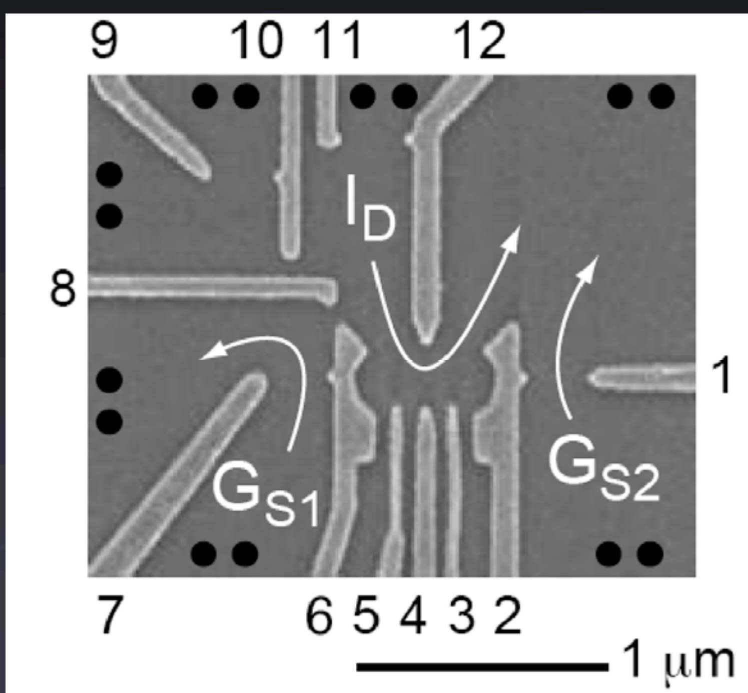
Pauli Blockade in a Double Quantum Dot

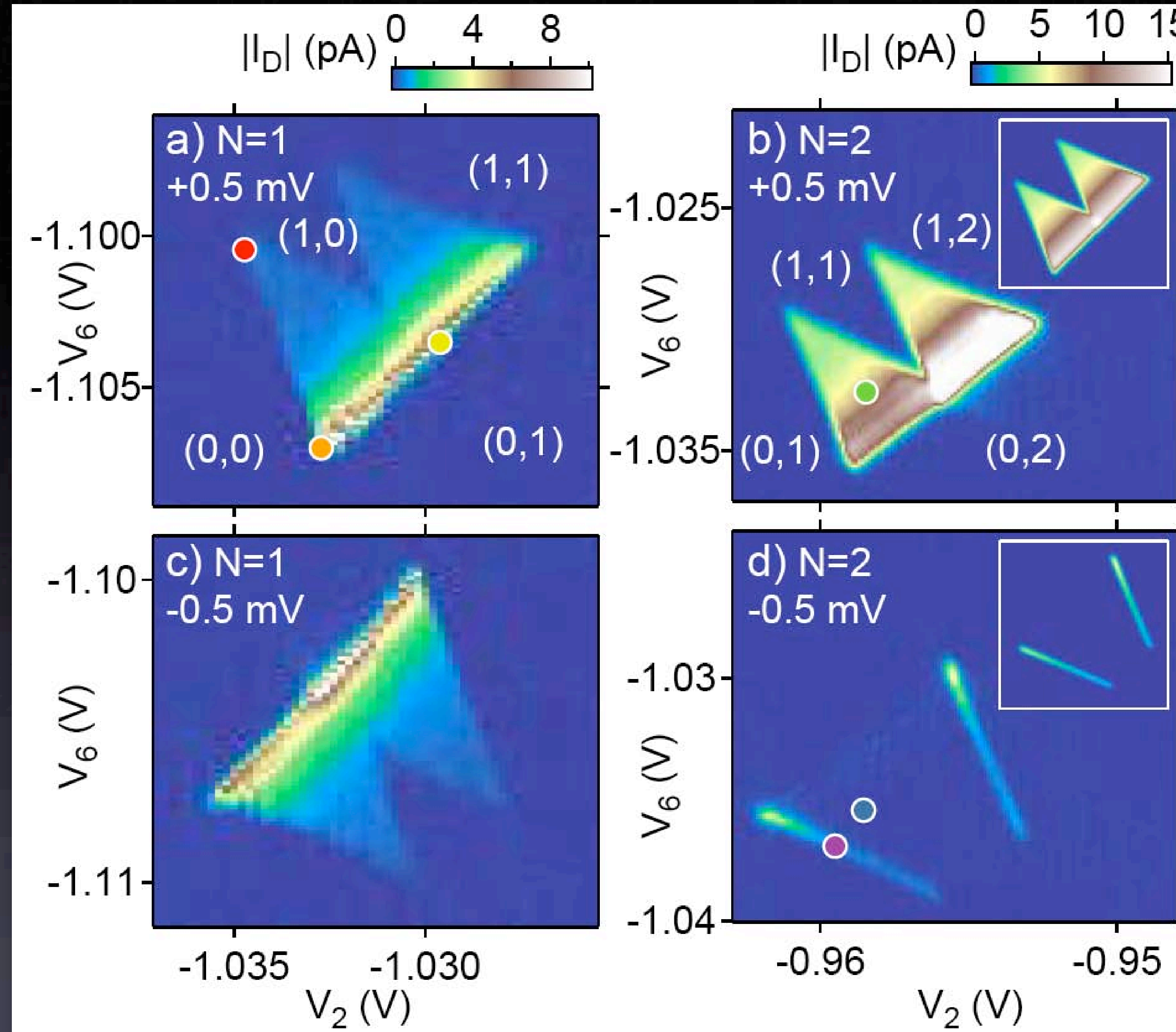


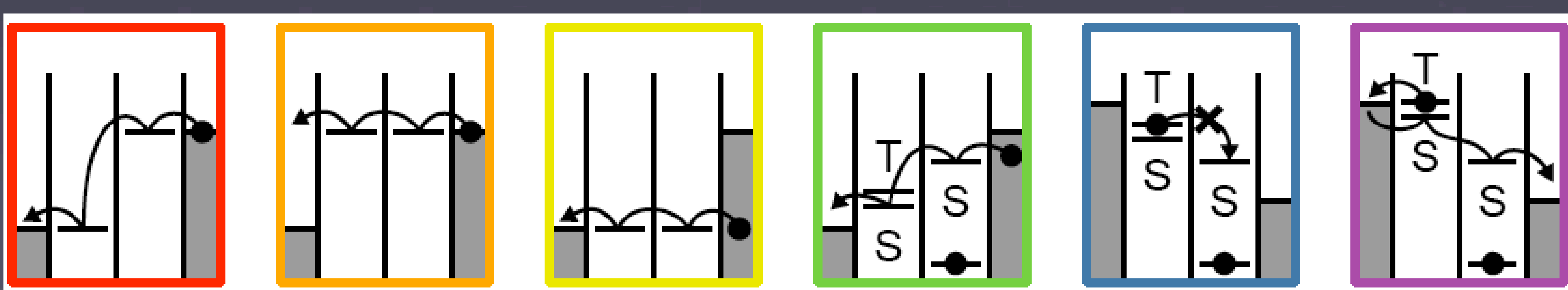


Ono, Tarucha, et al.
Science **297**, 1313 (2002).

Spin Blockade in a Double Dot

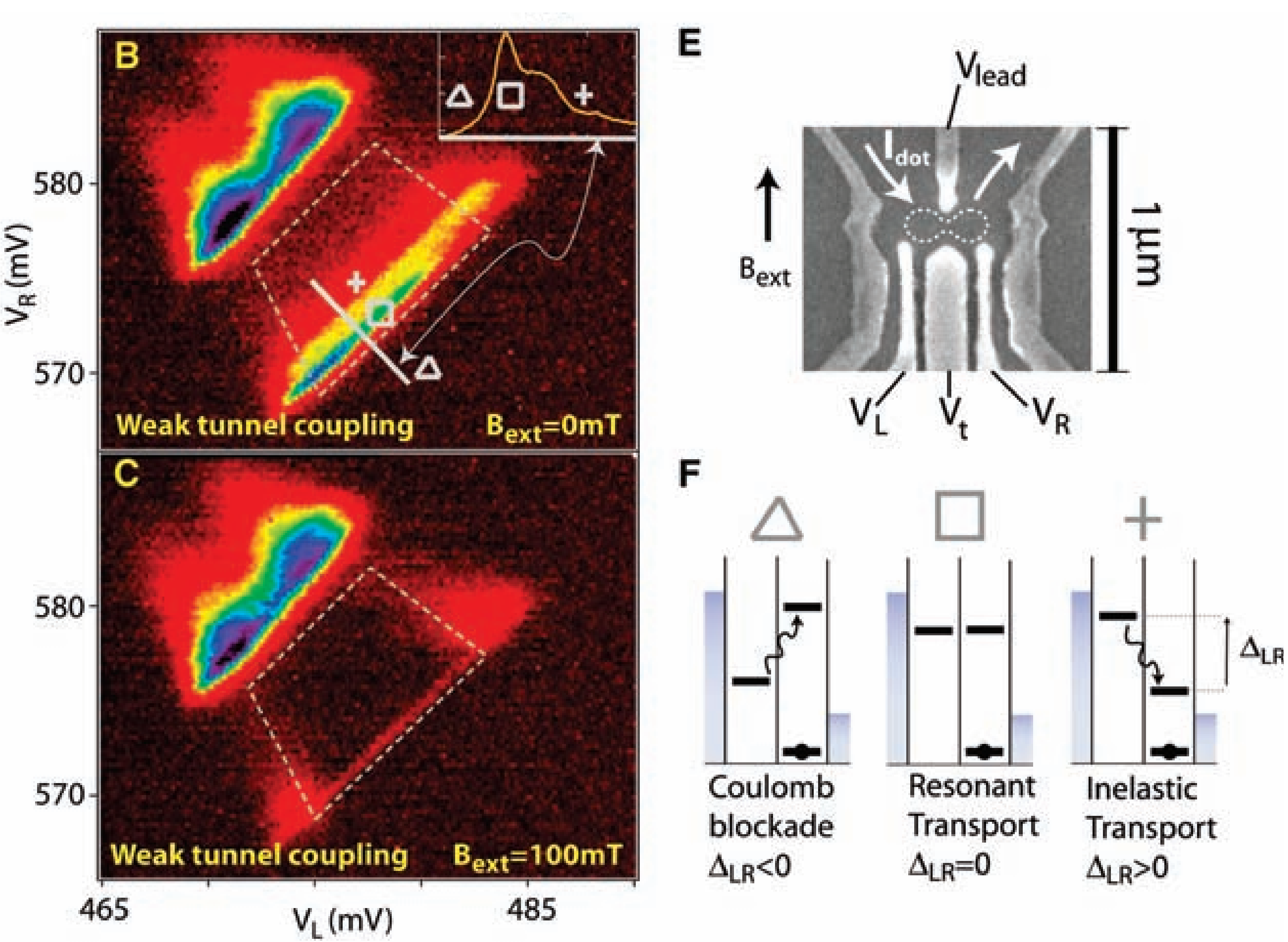


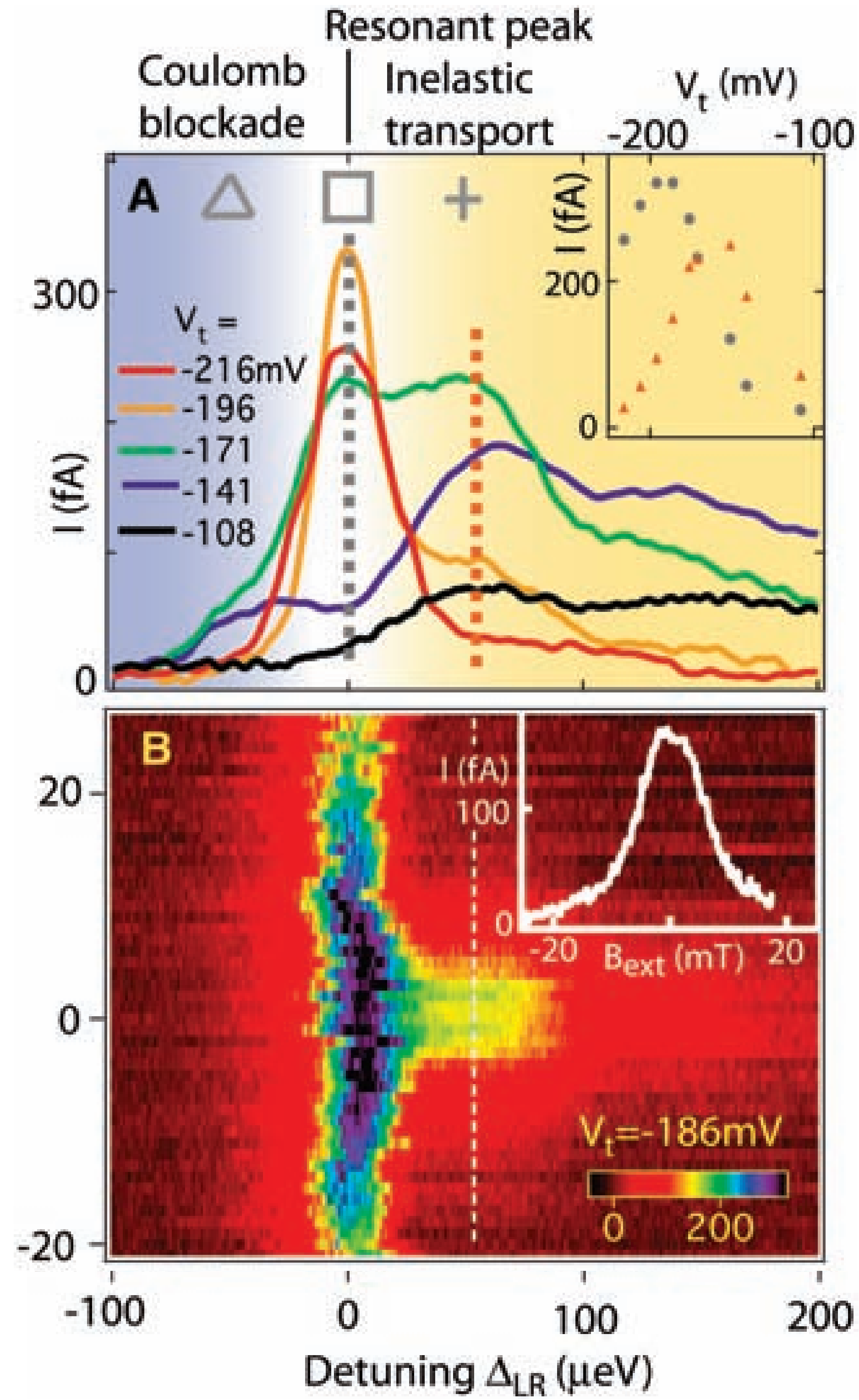




Control and Detection of Singlet-Triplet Mixing in a Random Nuclear Field

F. H. L. Koppens,[1*] J. A. Folk,[1*] J. M. Elzerman,[1] R. Hanson,[1]
L. H. Willems van Beveren,[1] I. T. Vink,[1] H. P. Tranitz,[2]
W. Wegscheider,[2] L. P. Kouwenhoven,[1] L. M. K. Vandersypen[1]†





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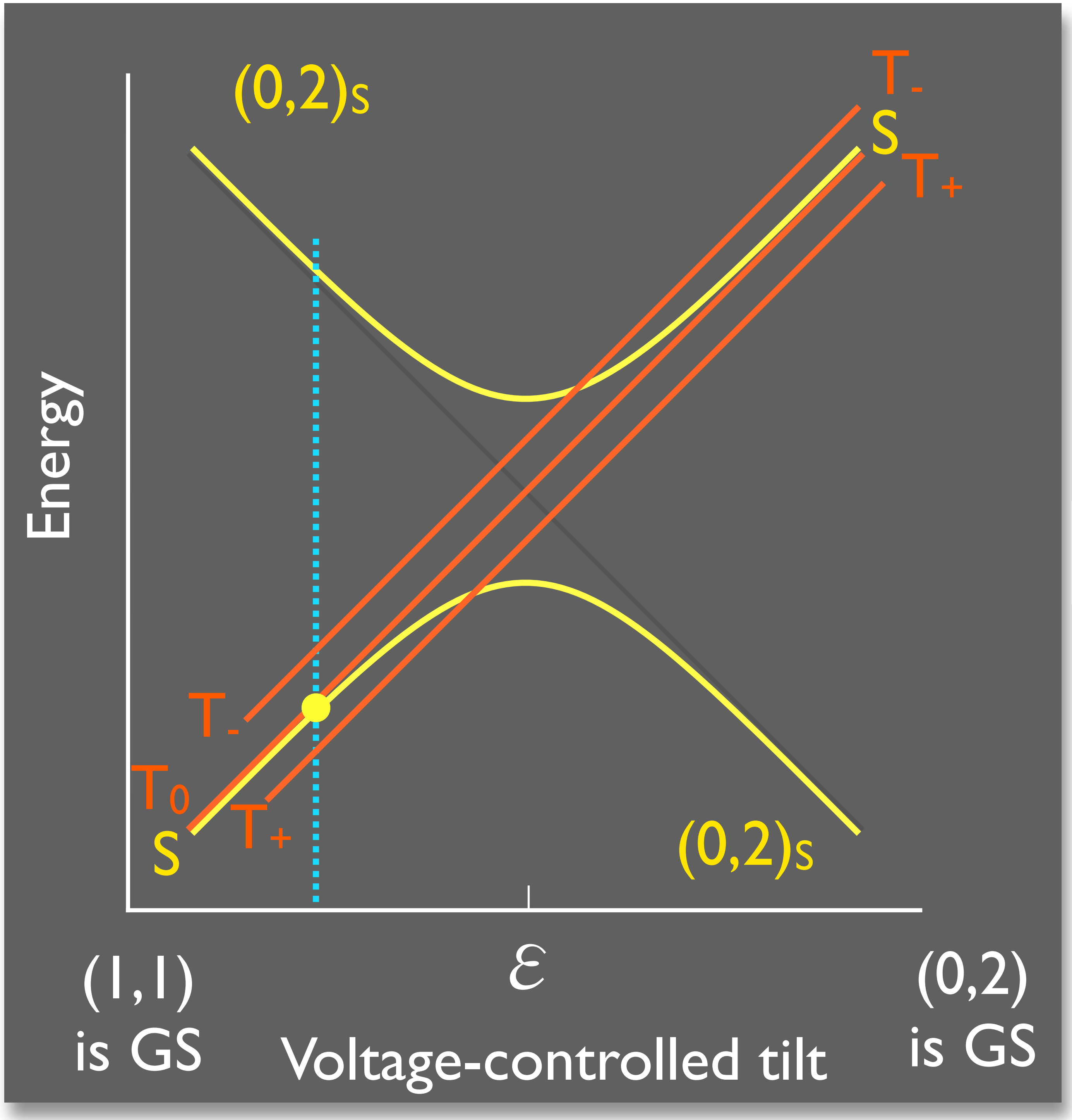
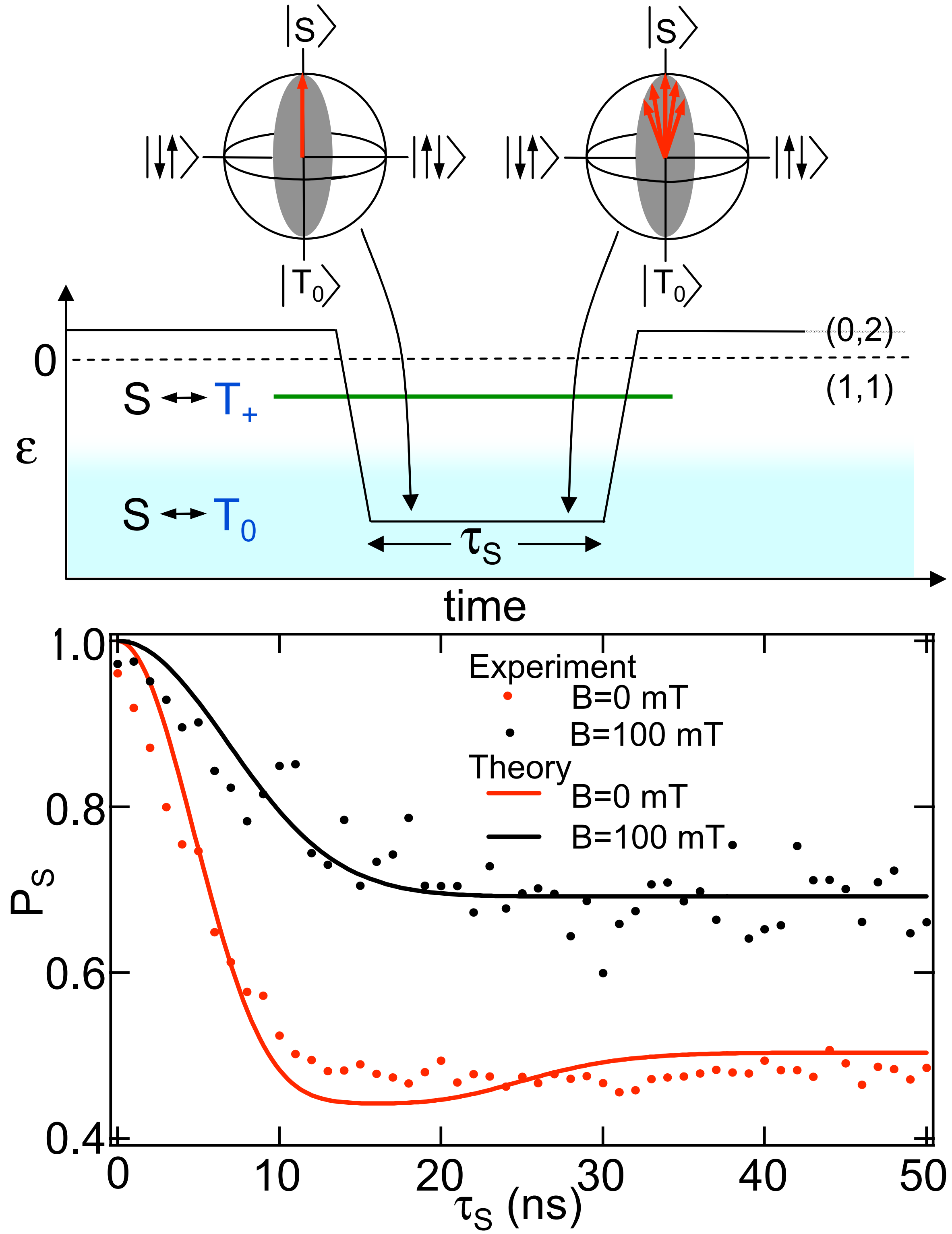
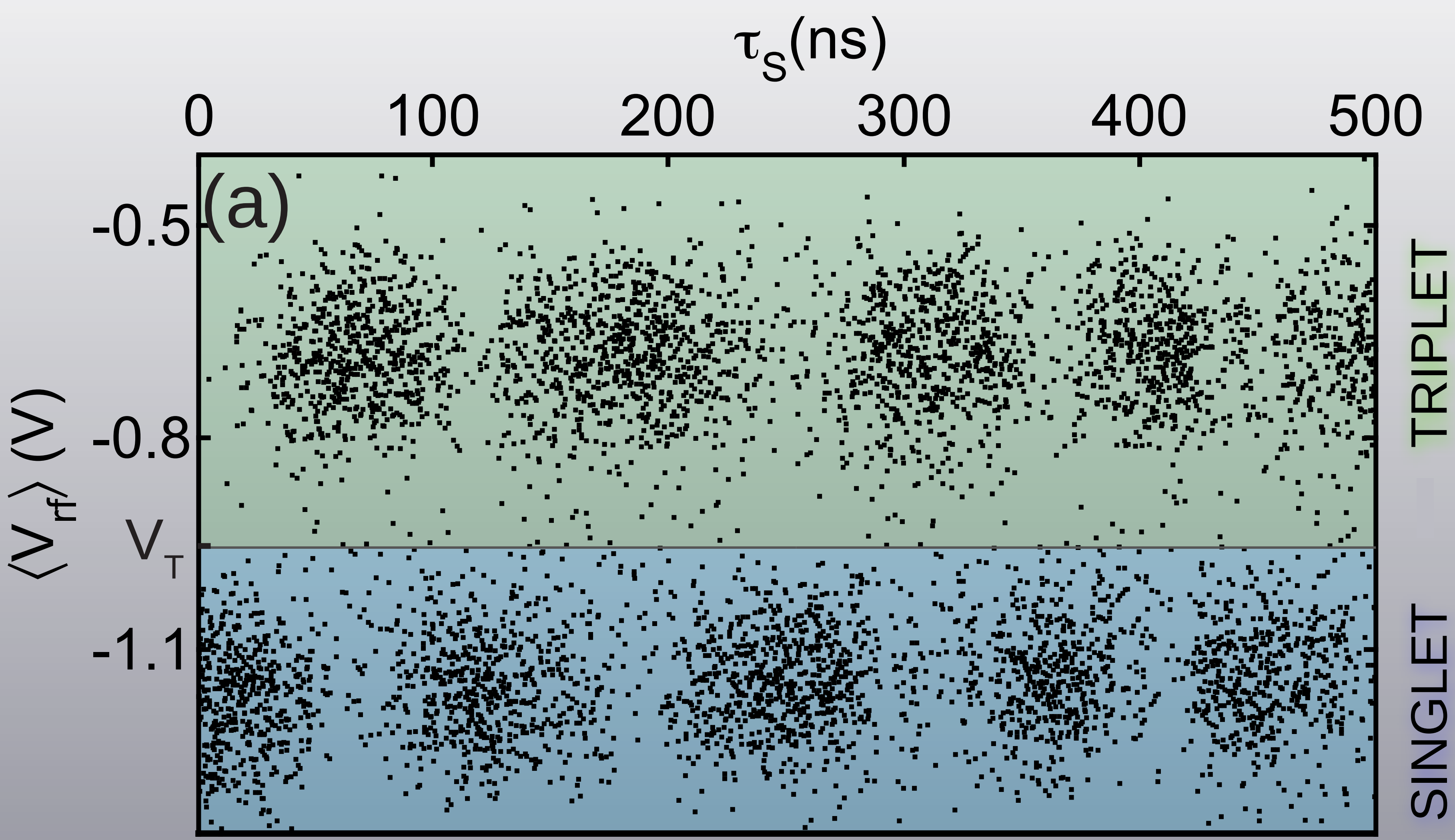
Inhomogeneous Dephasing

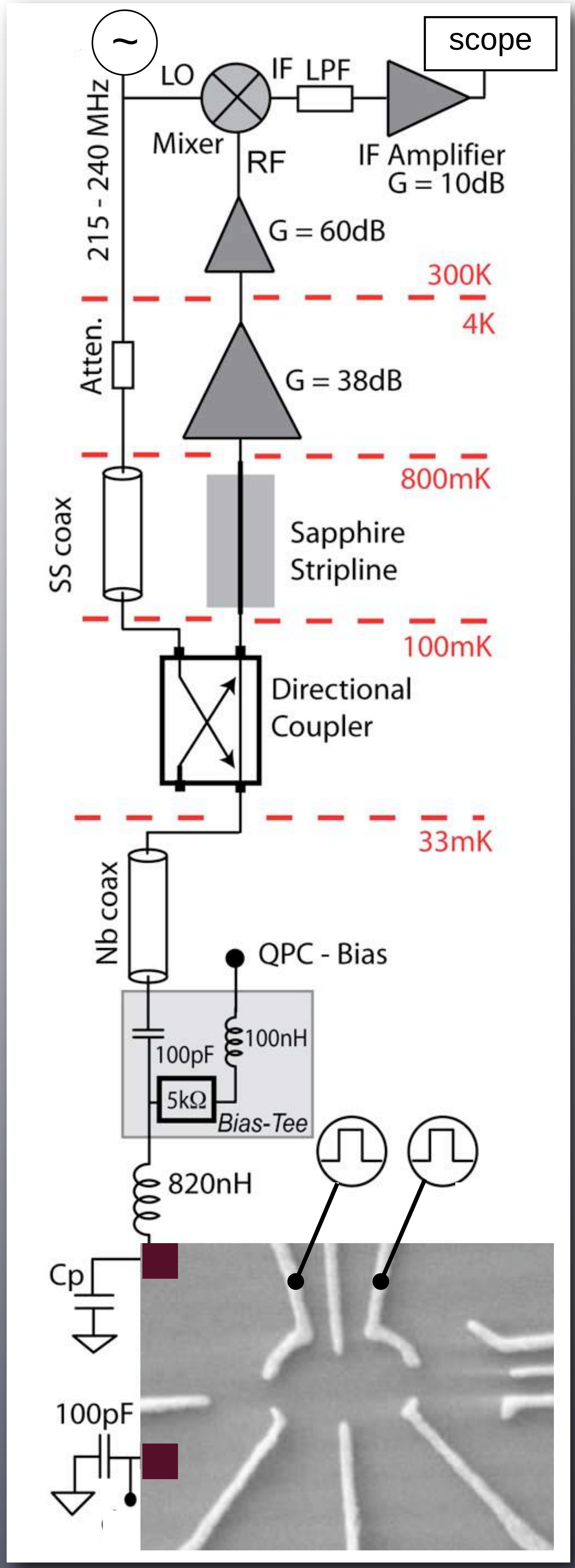
the situation in GaAs

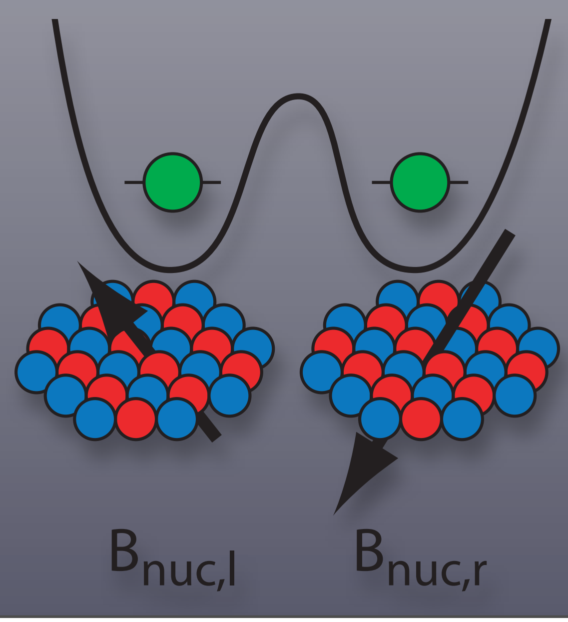


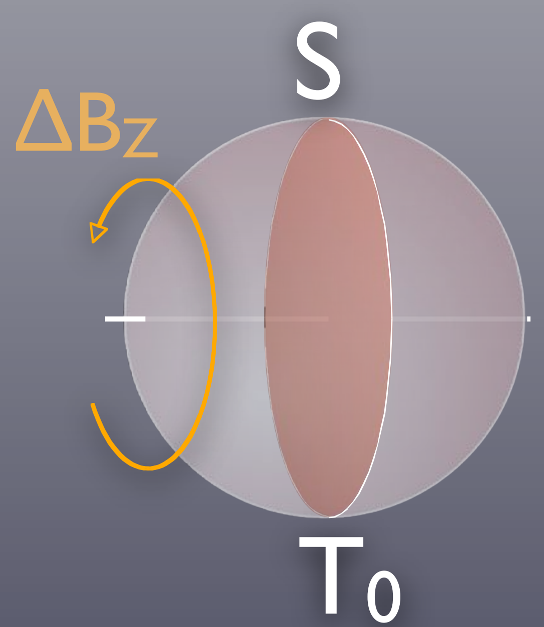


Inhomogeneous dephasing due to hyperfine fields in GaAs is revealed in single-shot measurements

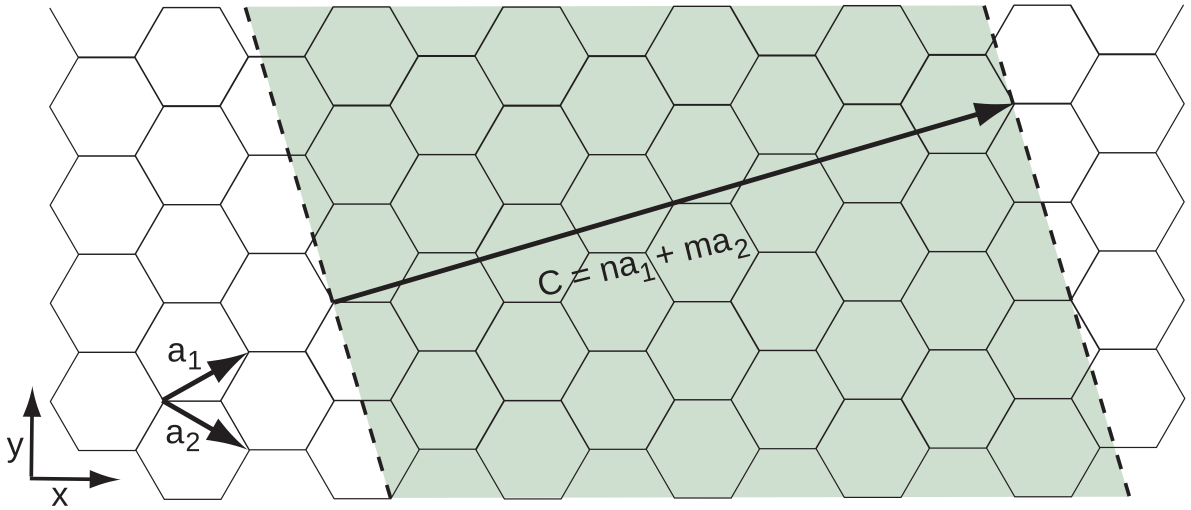


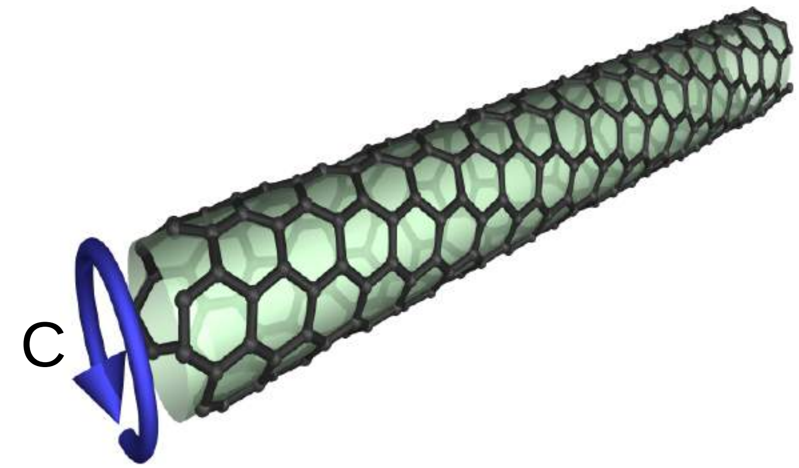


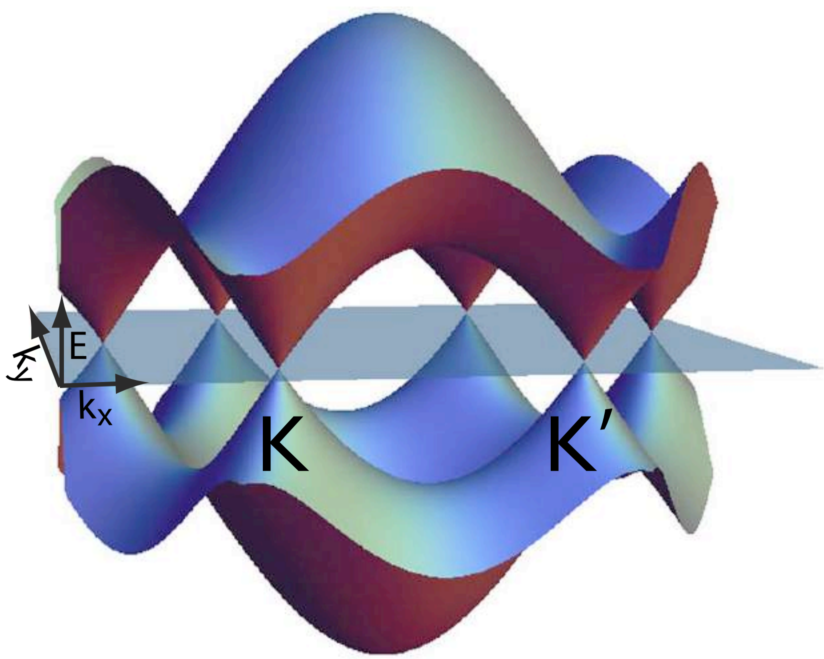




Carbon nanotubes

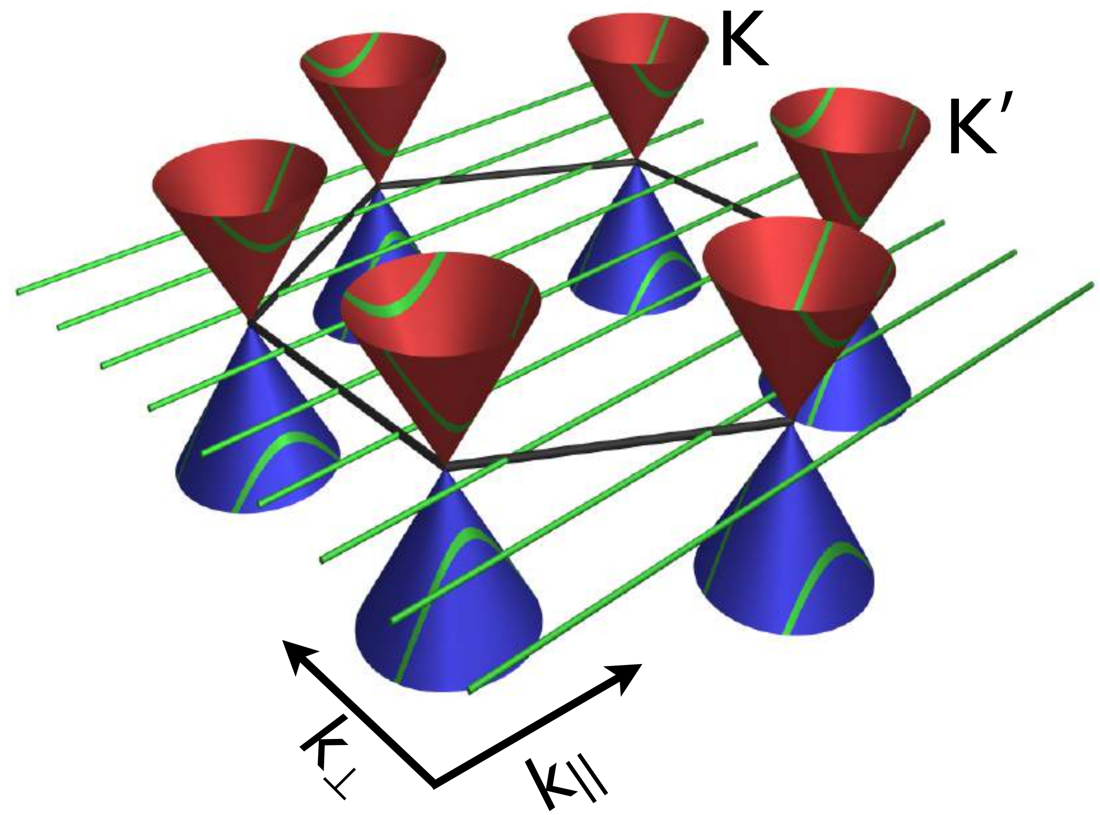




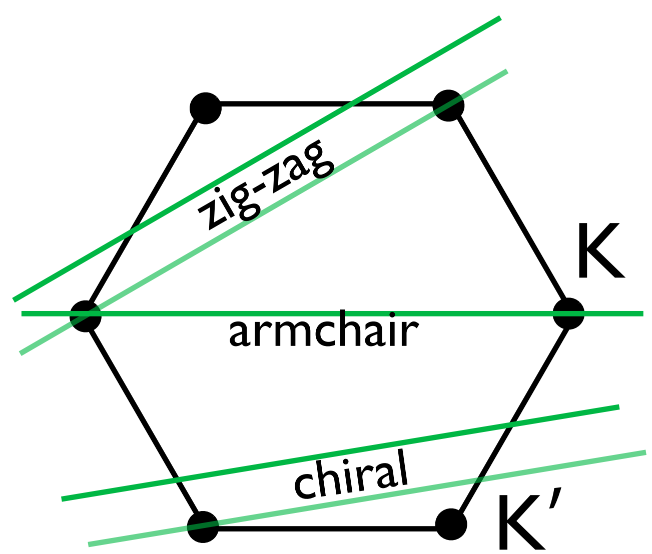


roll up

$$rk_\perp = \text{integer}$$



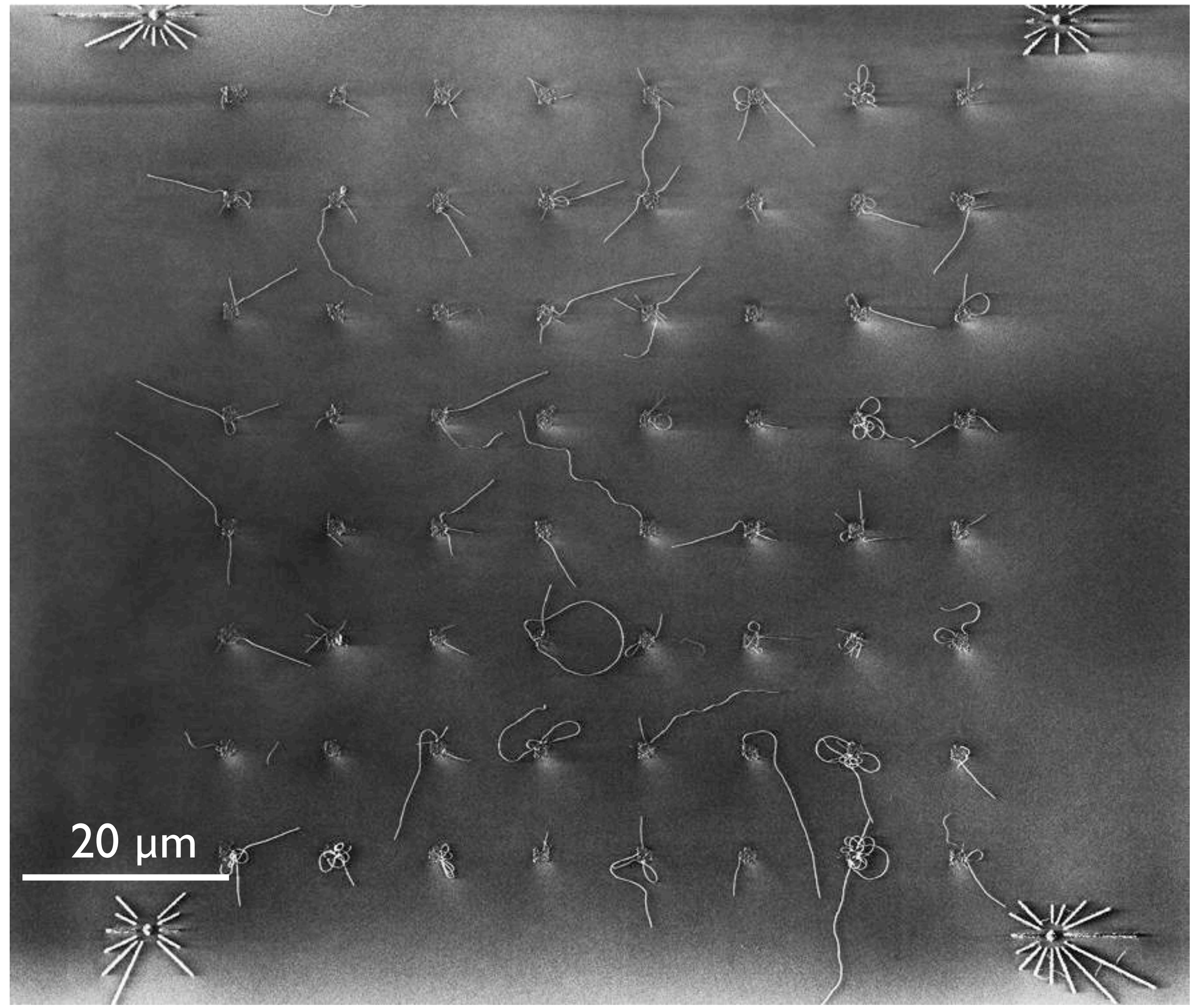
quantization around circumference gives 0 or 1.4 eV · nm/r gap



perturbations induce small ~10s meV gaps

Controlling Hyperfine Coupling using Nanotube Quantum Dots

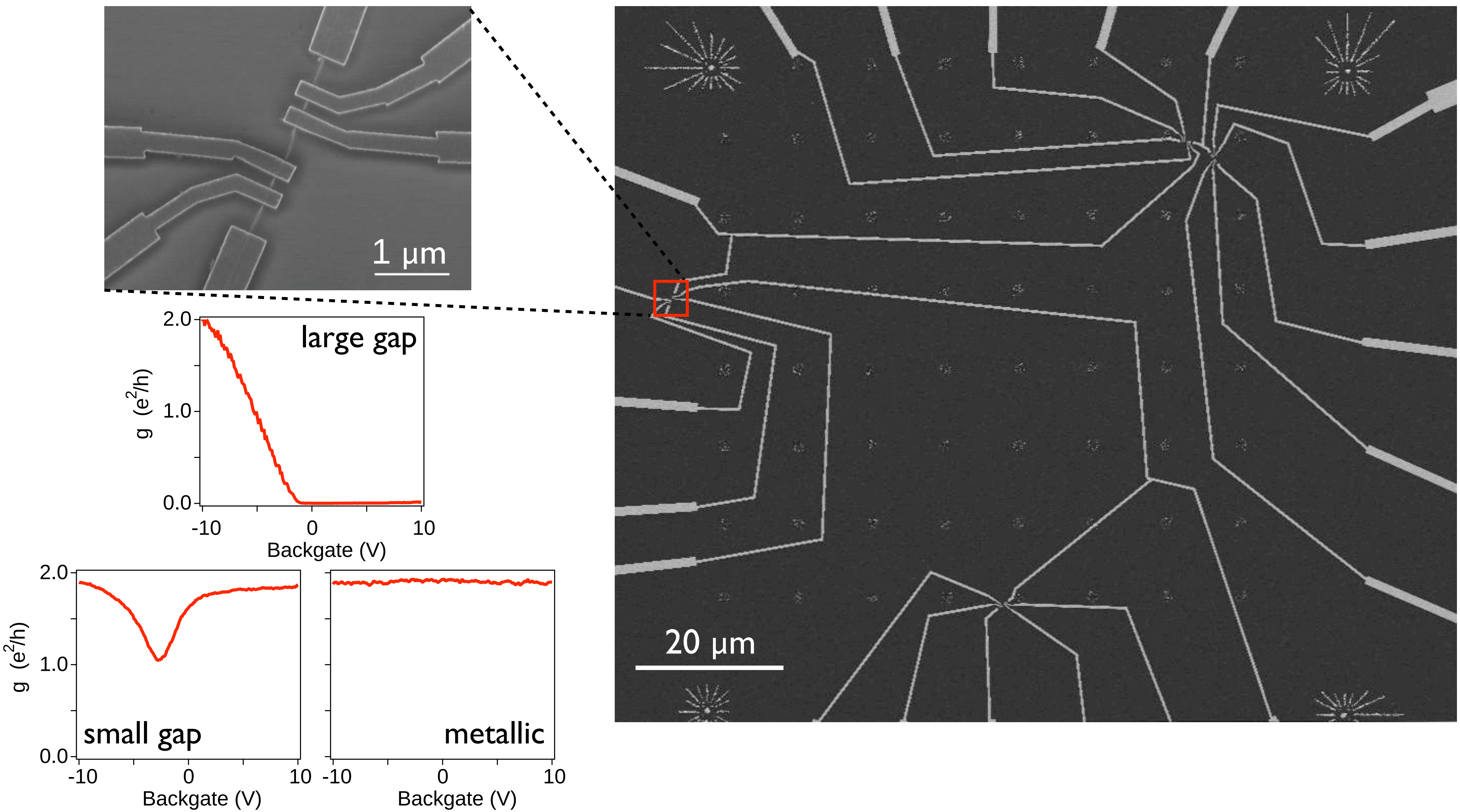
- CVD growth with 99% $^{12}CH_4$ or 99% $^{13}CH_4$



$^{13}CH_4$

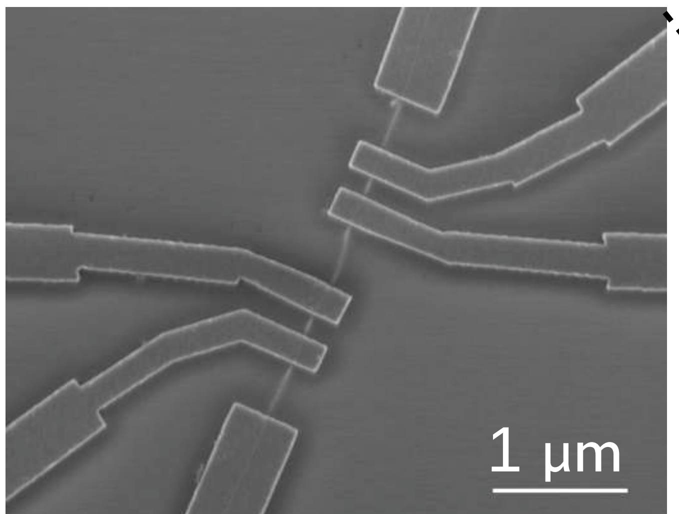
Controlling Hyperfine Coupling using Nanotube Quantum Dots

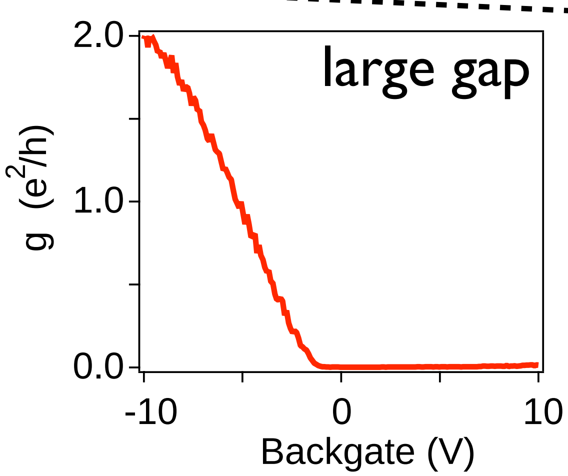
- Pd contacts

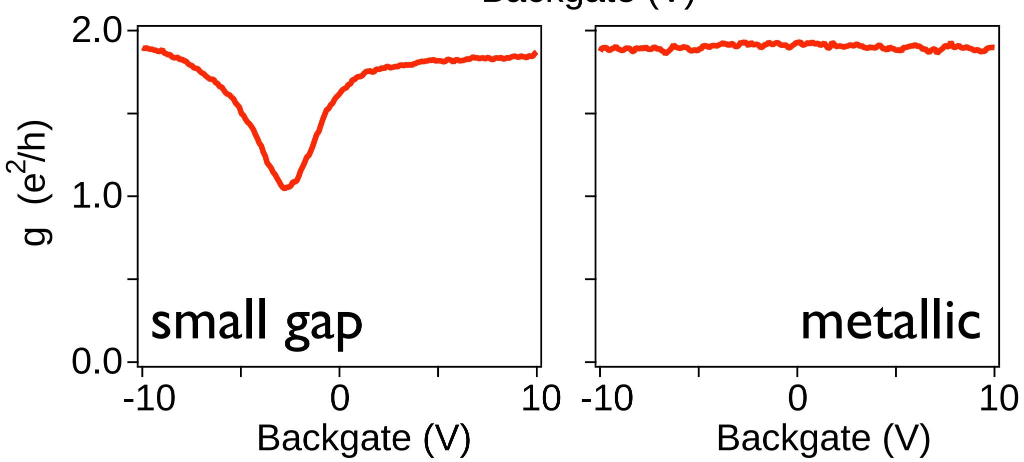


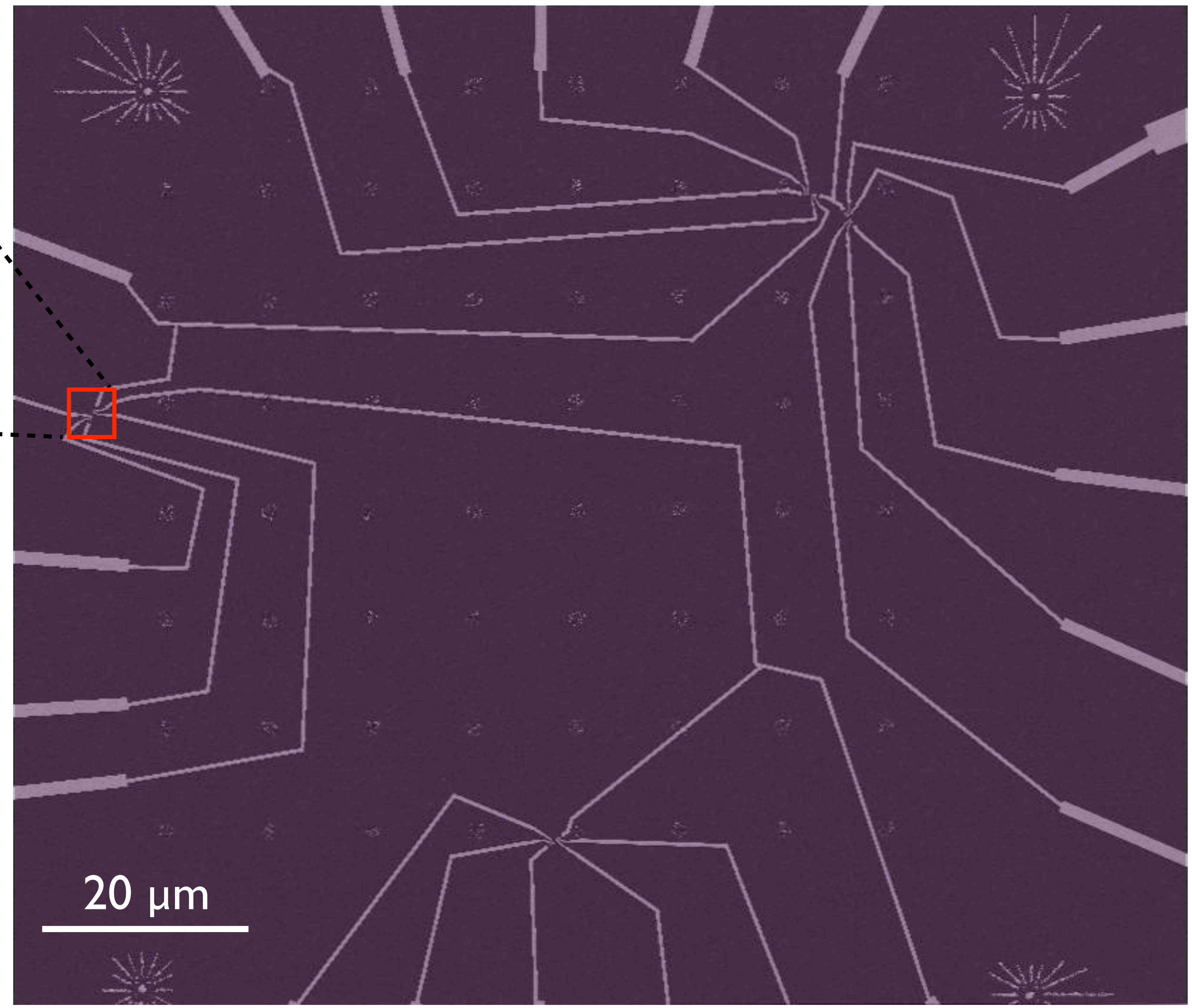
Controlling Hyperfine Coupling using Nanotube Quantum Dots

- Pd contacts
- NO_2 + Al_2O_3 ALD



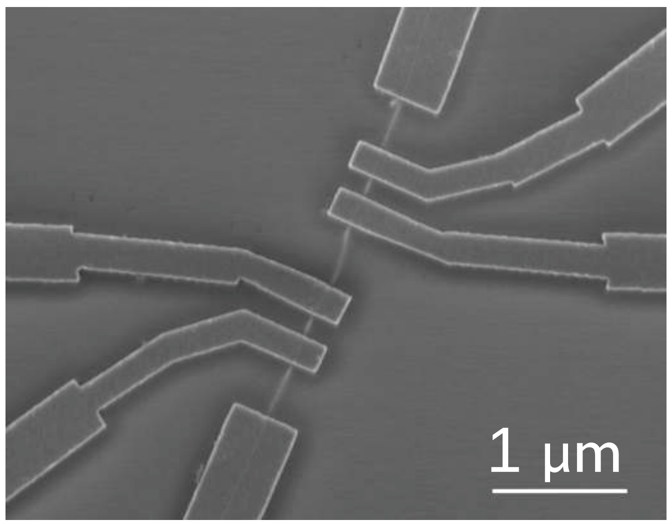


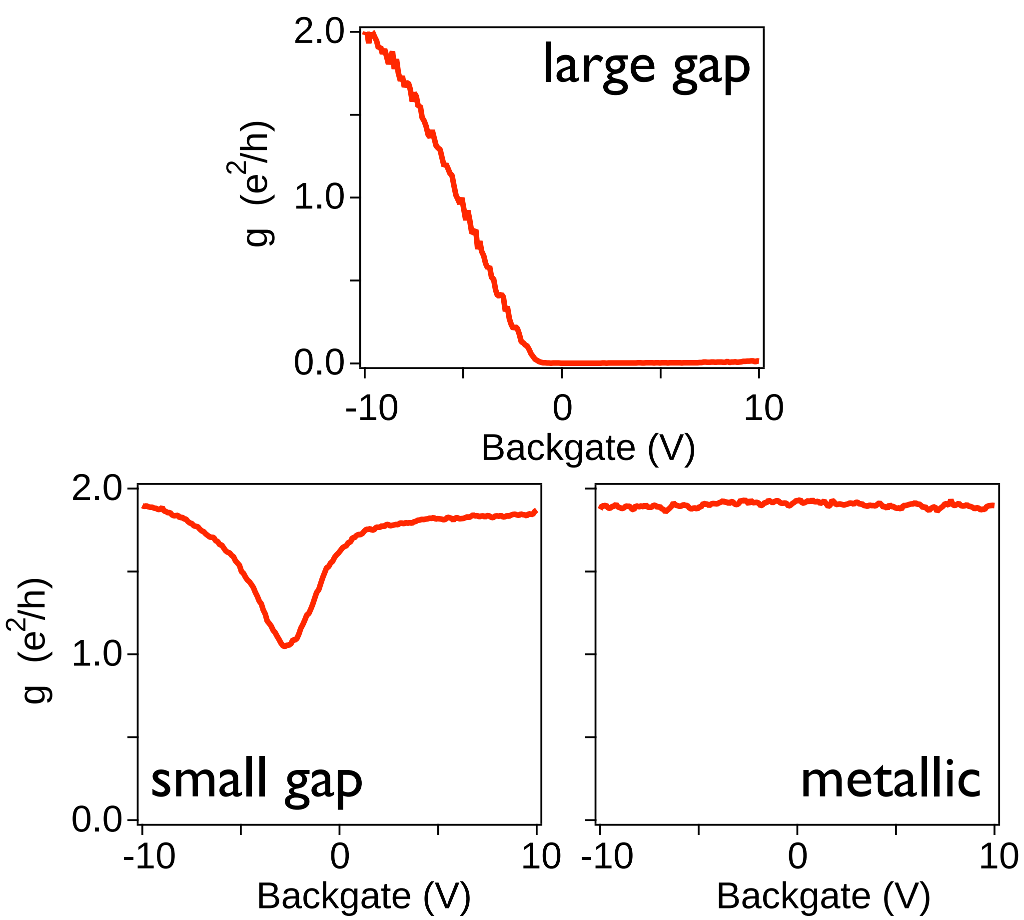


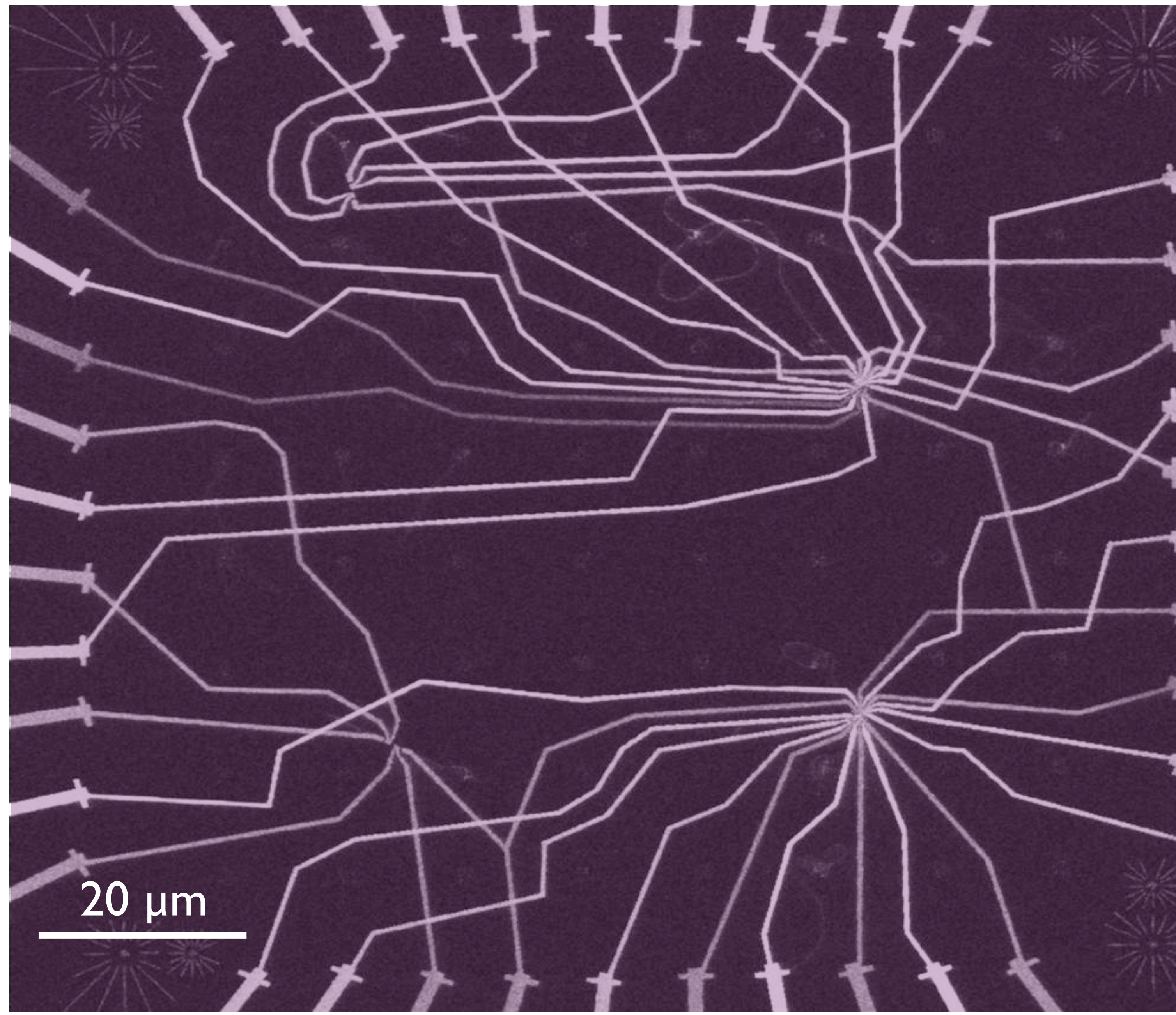


Controlling Hyperfine Coupling using Nanotube Quantum Dots

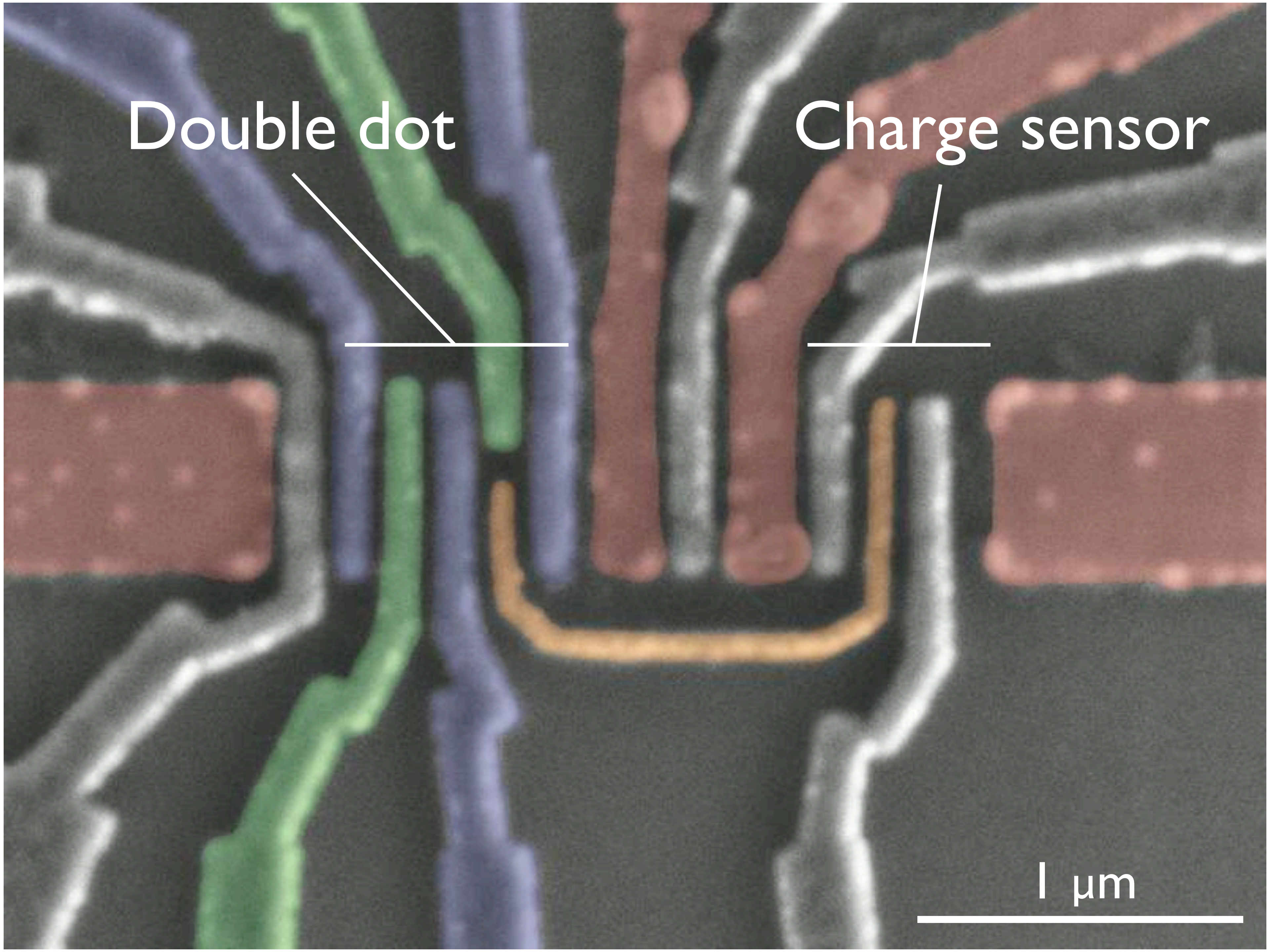
- Pd contacts
- Al_2O_3 + NO_2 ALD
- Al top gates







Devices



- CVD growth with $^{12}CH_4$ or $^{13}CH_4$
- Fe catalyst
- Pd contacts
- Al_2O_3 + NO_2 ALD
- Al top gates

Related work

DQDs: Biercuk *et al.* Nano Lett. (2005) Graeber *et al.* PRB (2006)
Sapmaz *et al.*, Nano Lett. (2006) Jorgensen *et al.* Nat. Phys. (2008)

Single dot charge sensing: Biercuk *et al.* PRB (2006)

$^{13}CH_4$: Liu and Fan, JACS (2001)

NO_2: Farmer and Gordon, Nano Lett. (2006)
Williams *et al.*, Science (2007)

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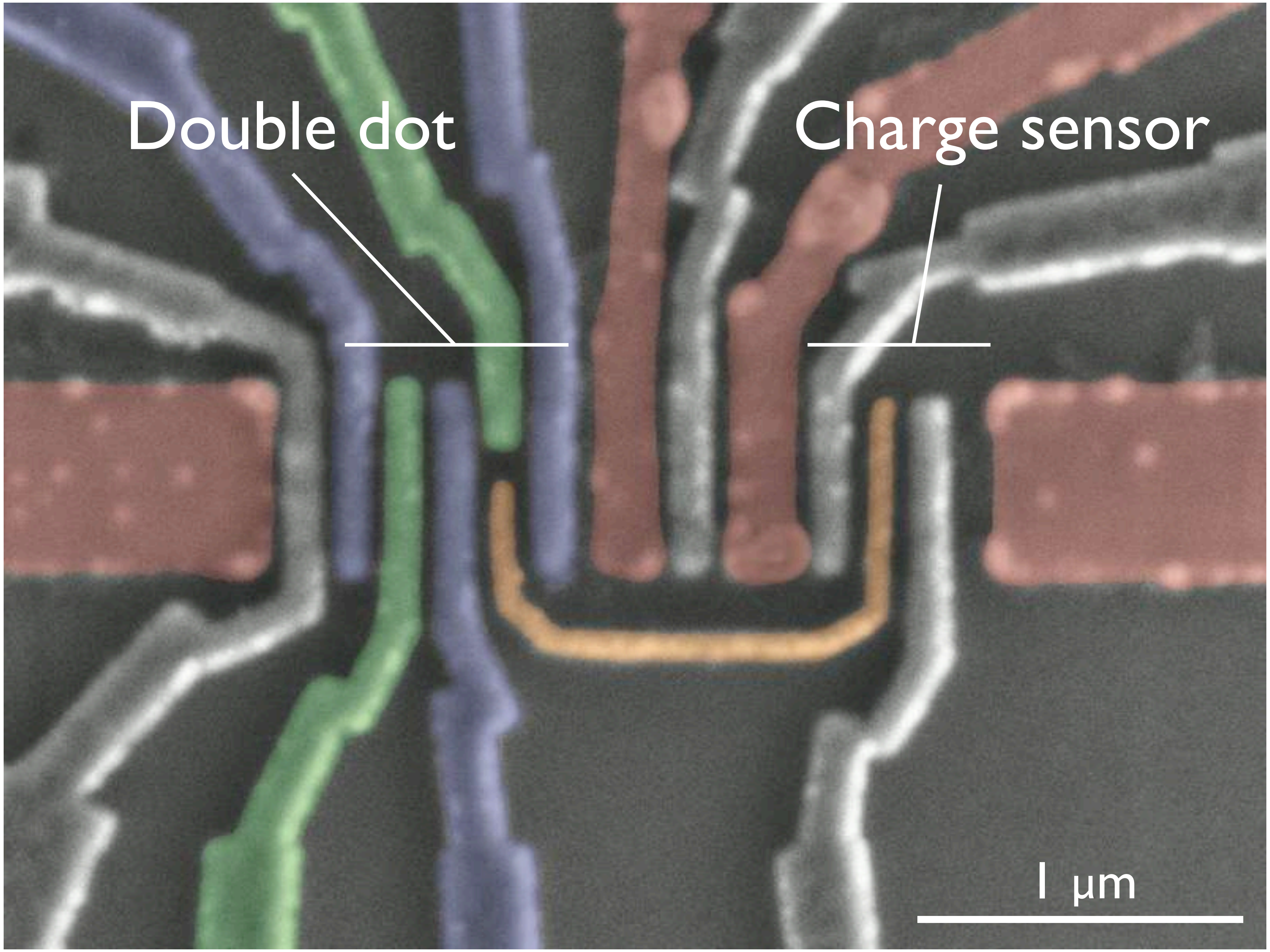

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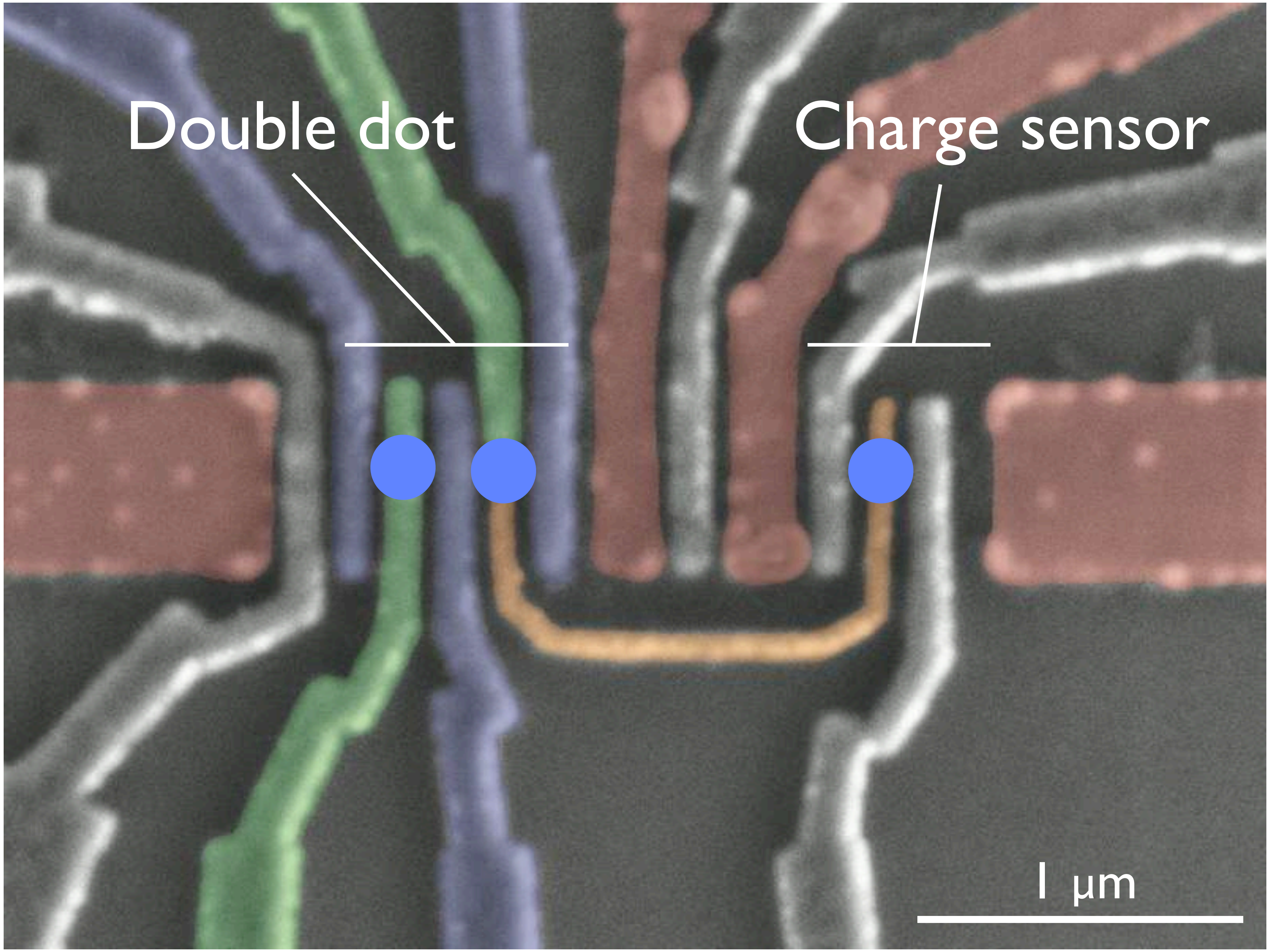

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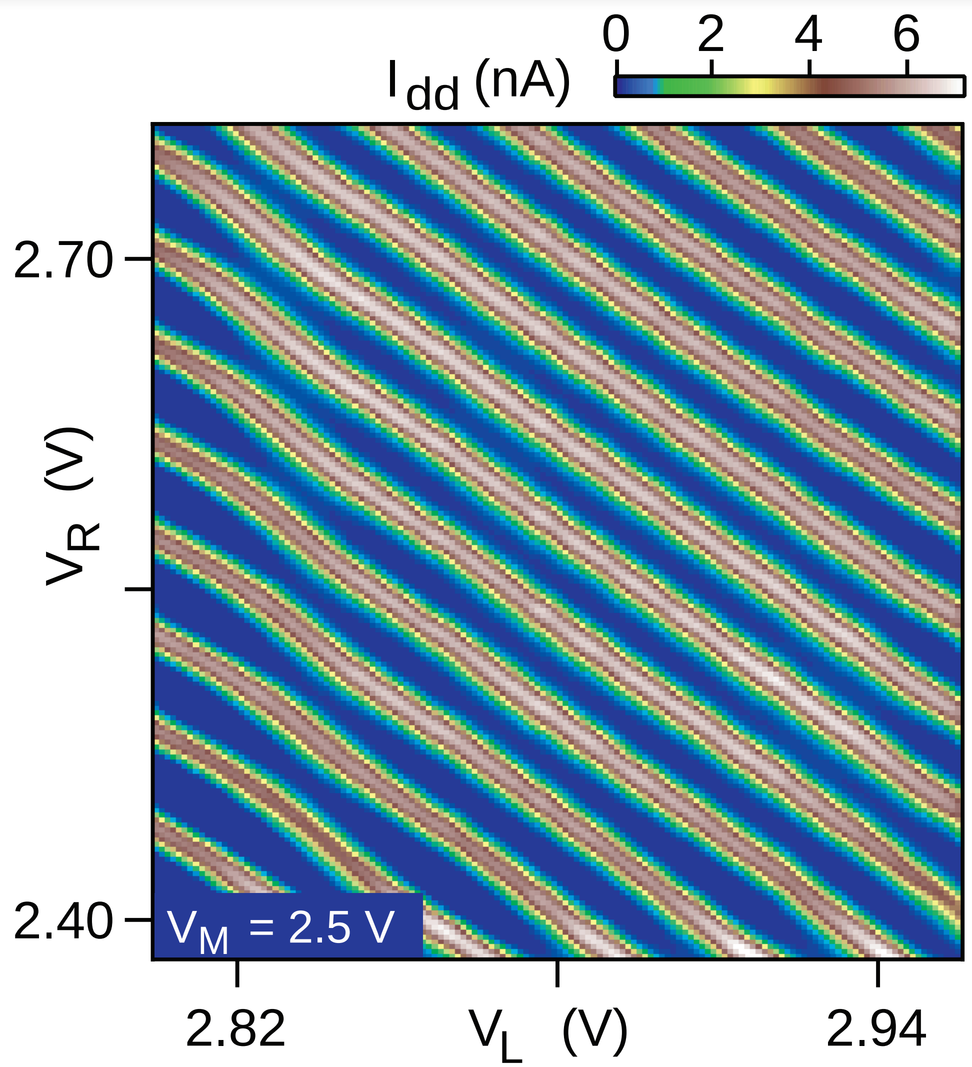
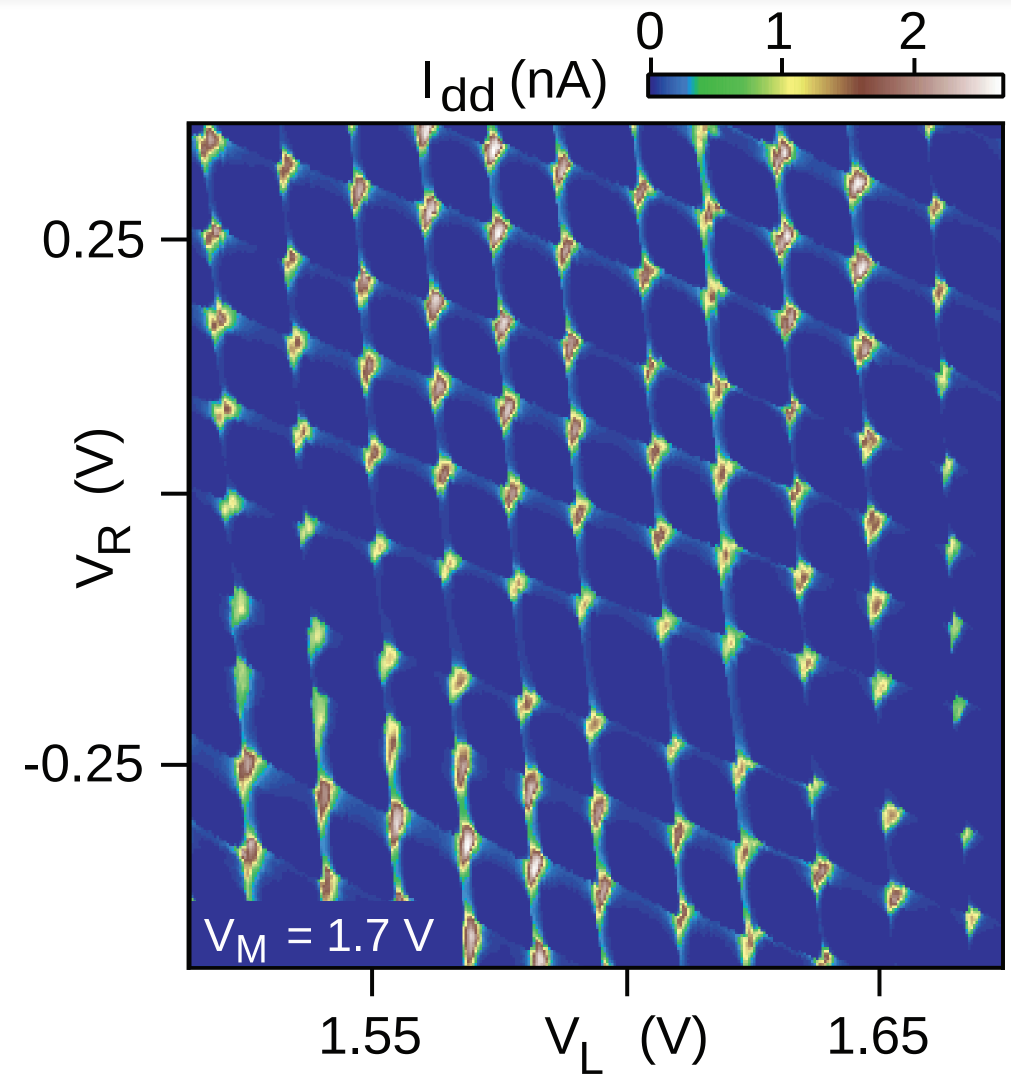
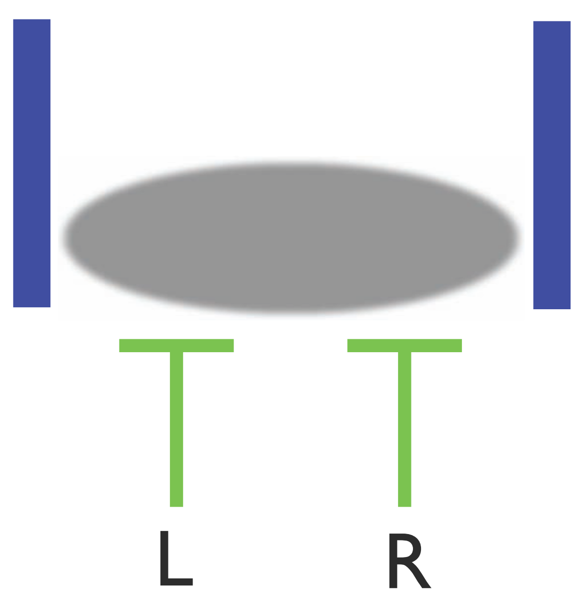
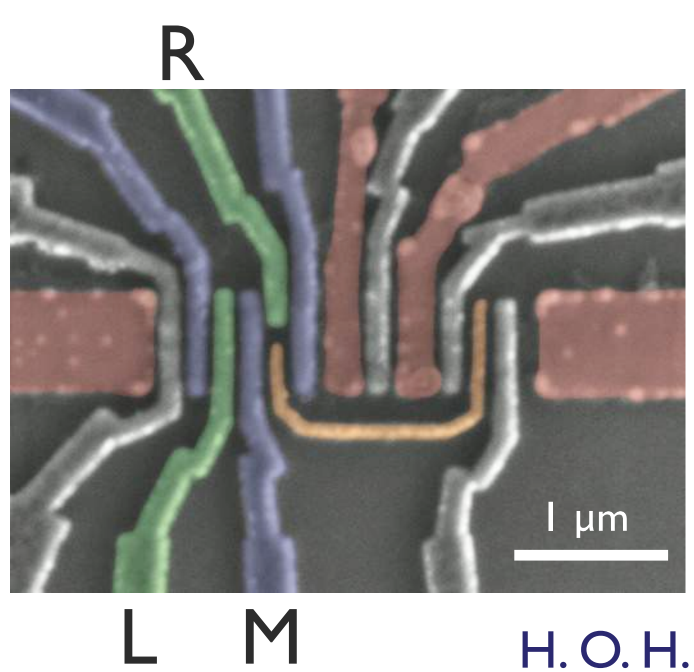
NO_2: Farmer and Gordon, Nano Lett. (2006)
Williams *et al.*, Science (2007)

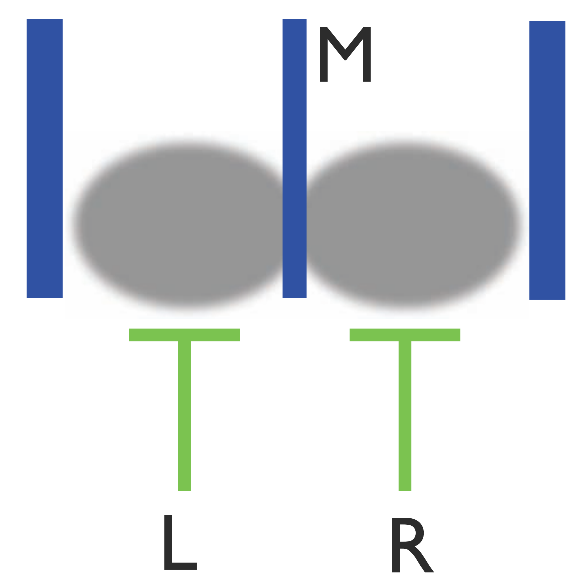
Tunable double dot





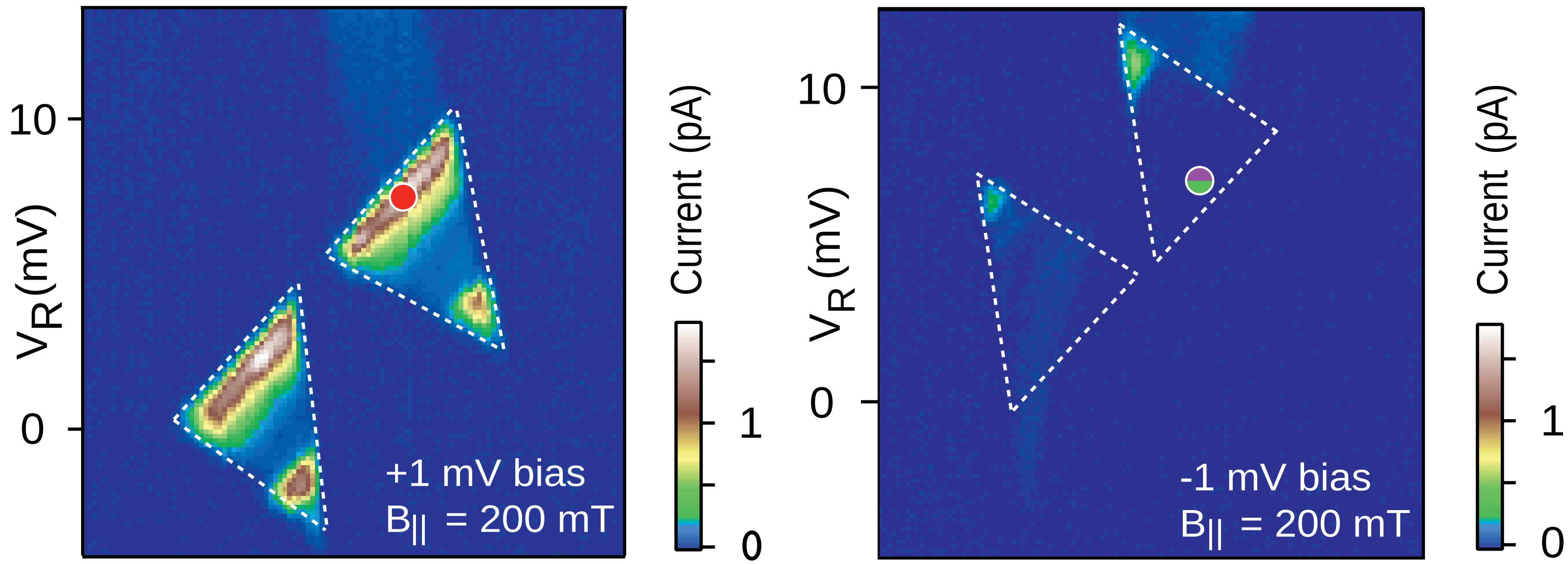


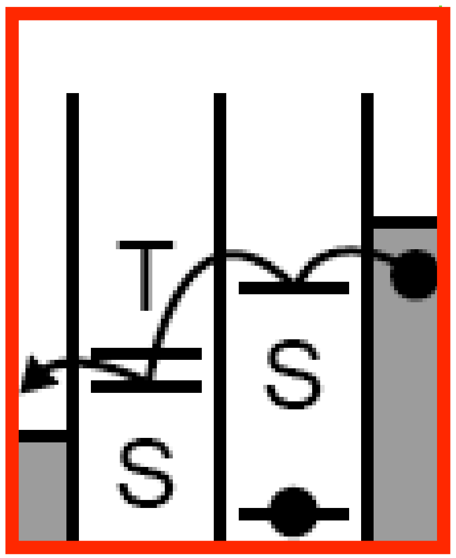


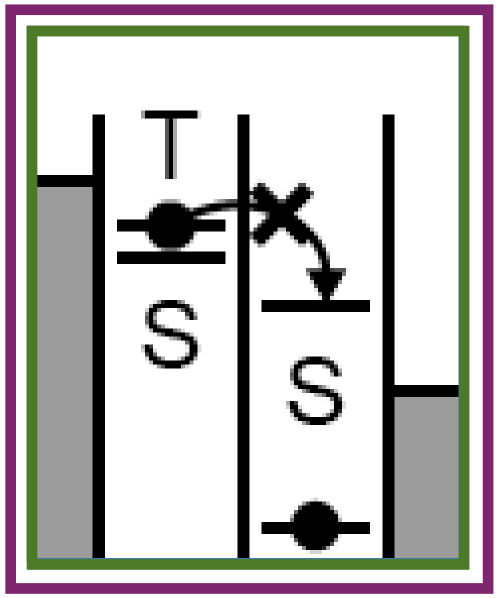


H. O. H. Churchill, et al. Nature Physics **5**, 321(2009).

^{13}C spin blockade







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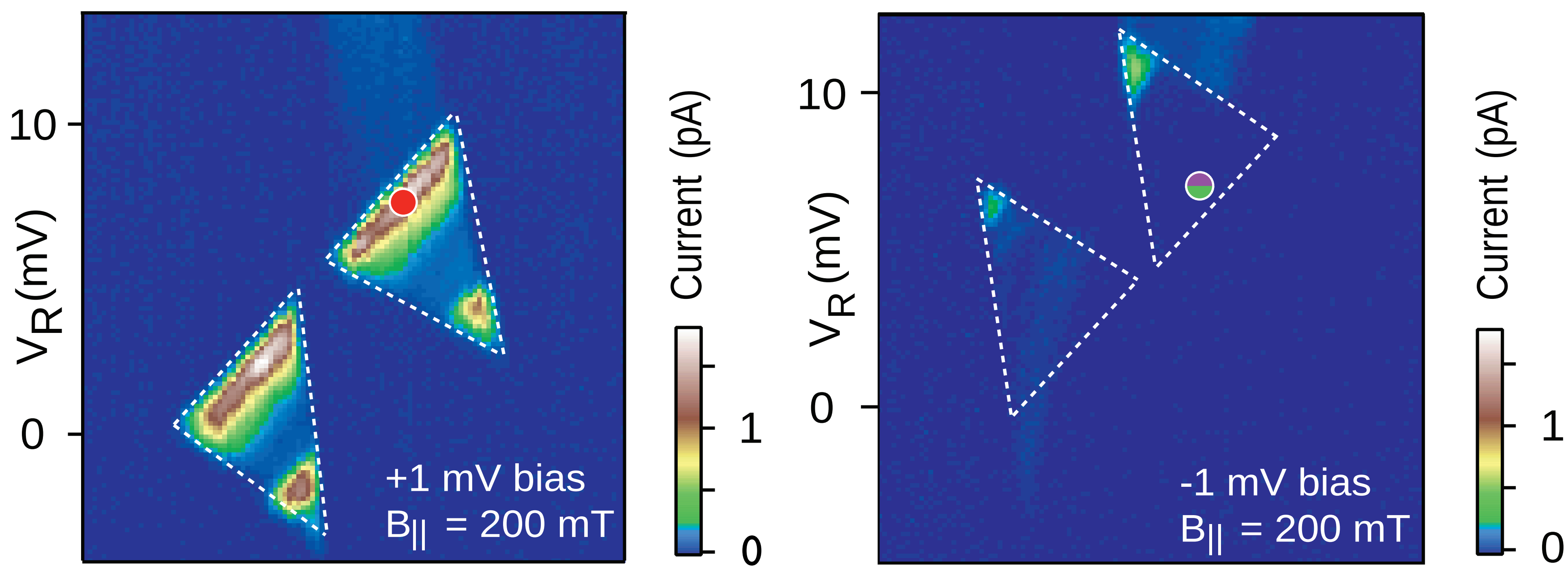
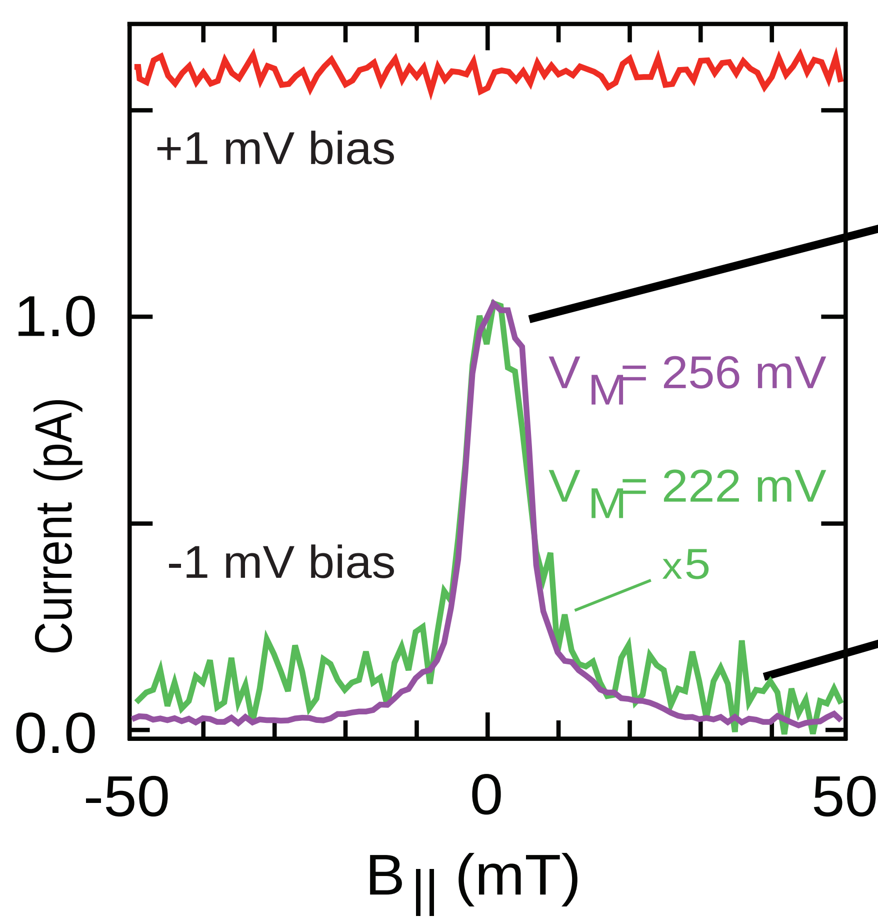
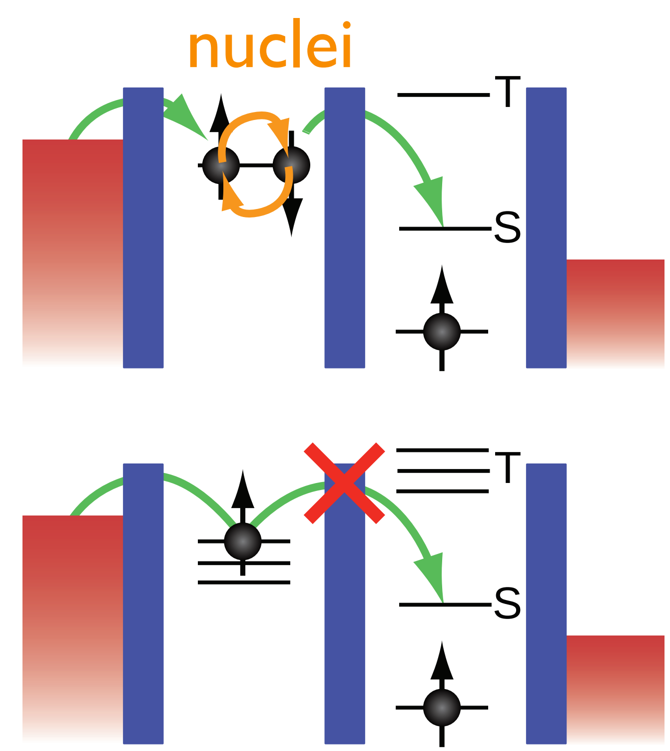
^{13}C spin blockade

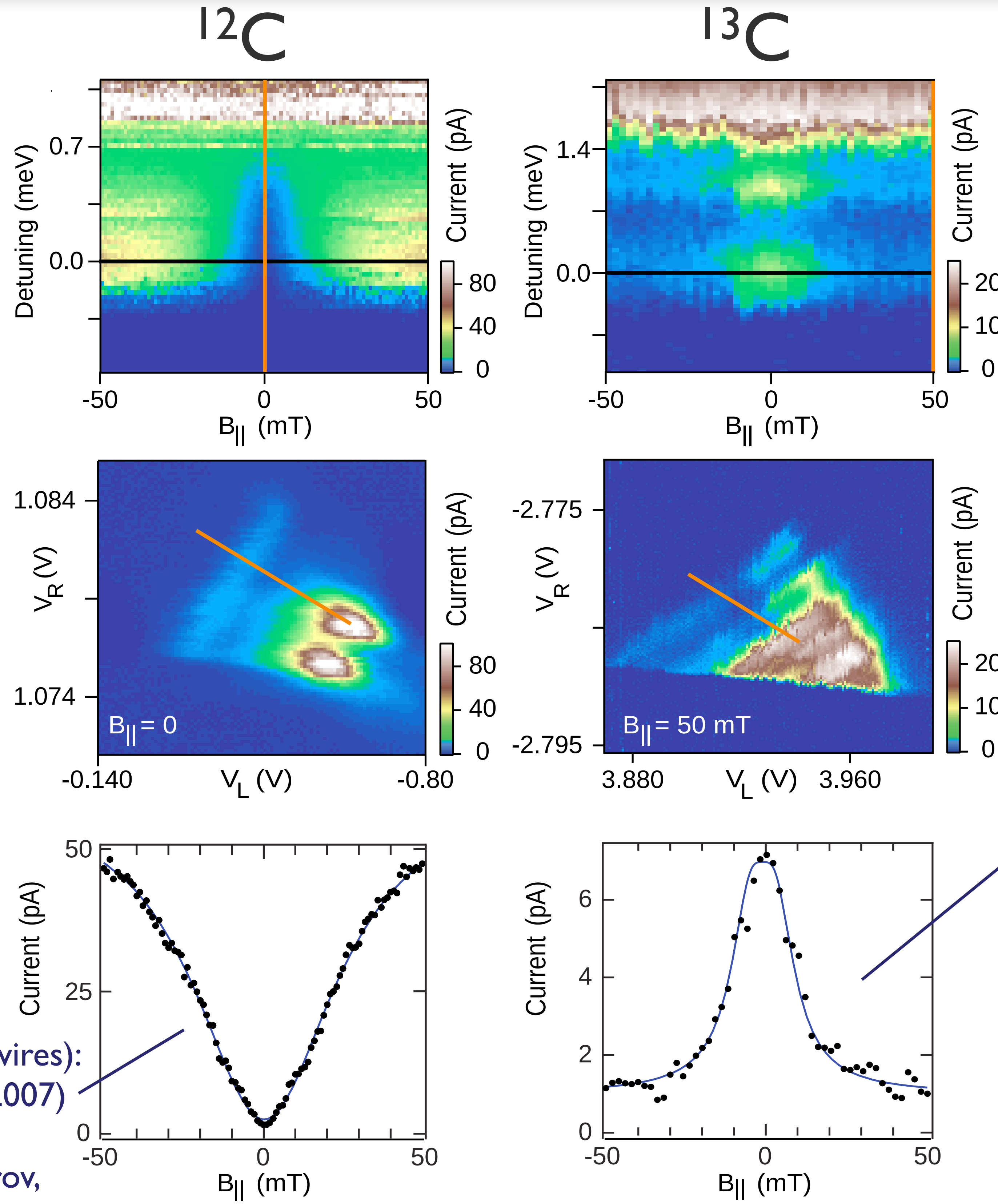


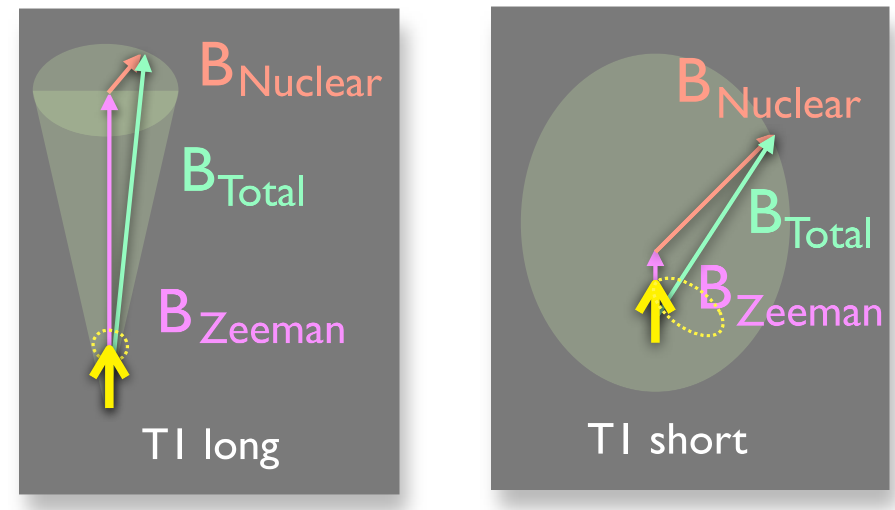




H. O. H. Churchill, et al. Nature Physics **5**, 321(2009).

Magnetic field dependence of spin relaxation





See Also
Expt:
Koppens, Folk, et al. (GaAs)
Science **305**, 1346 (2005).
Theory:
Jouravlev and Nazarov
PRL **96,** 176804 (2006)

See Also
Expt:
Ensslin group (InAs wires):
PRL **99,** 036801 (2007)
Theory:
Danon and Nazarov,
arXiv:0905.181 (2009)

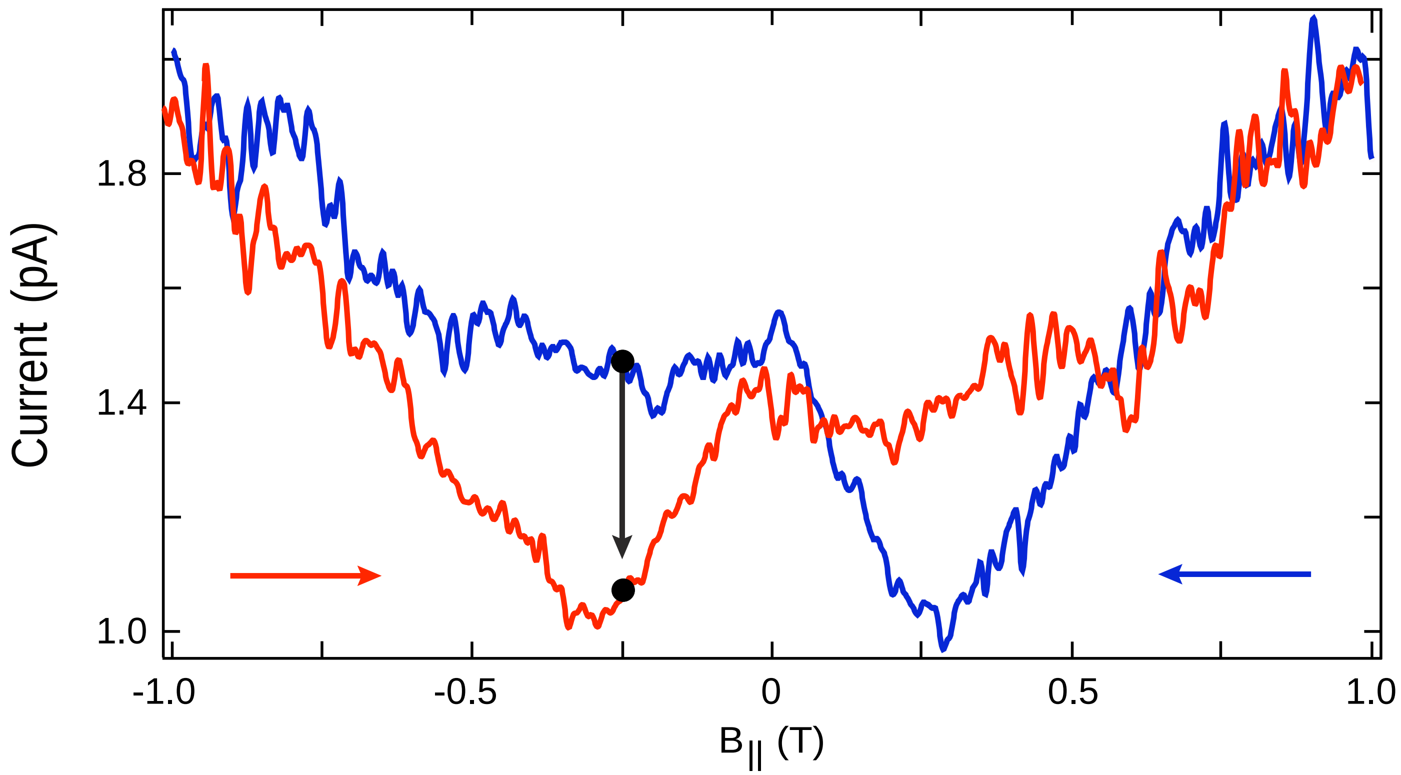
$$g\mu_B B_{\rm nuc} = A/\sqrt{N}$$

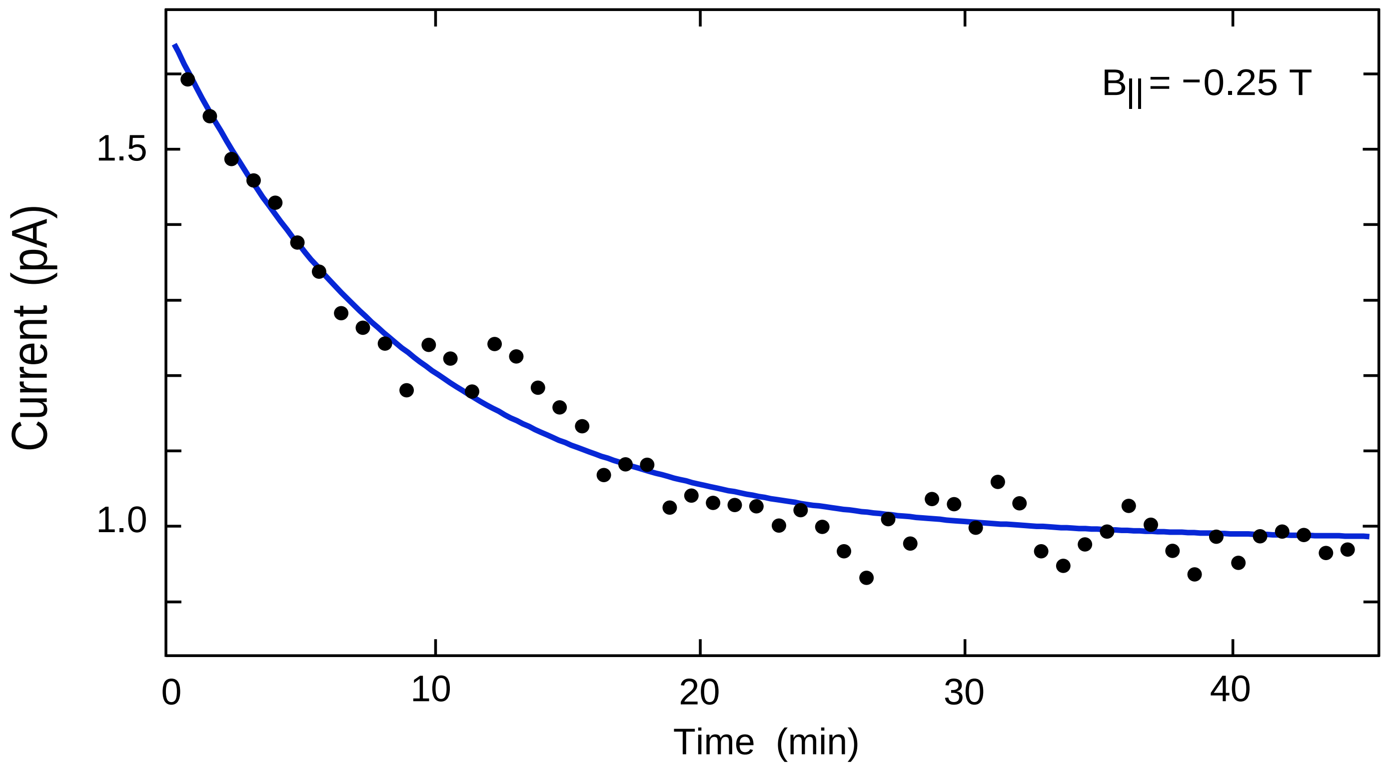
$$B_{\rm nuc} \;=\; 6.1 \;\; {\rm mT}$$

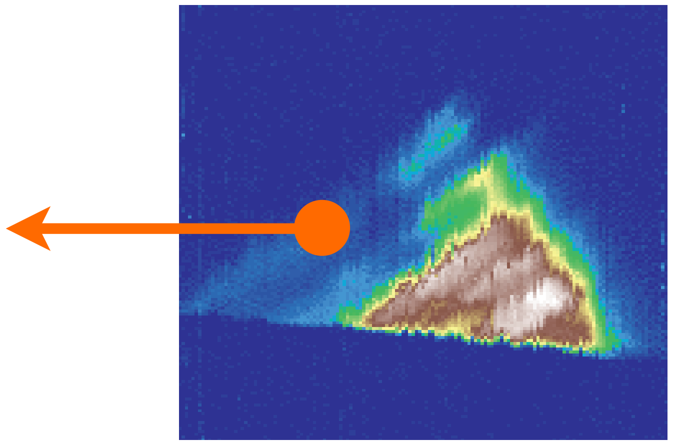
$$\rightarrow A \sim 100 \;\mu{\rm eV}$$

H. O. H. Churchill, et al. Nature Physics **5**, 321(2009).

Hysteresis in ^{13}C leakage current



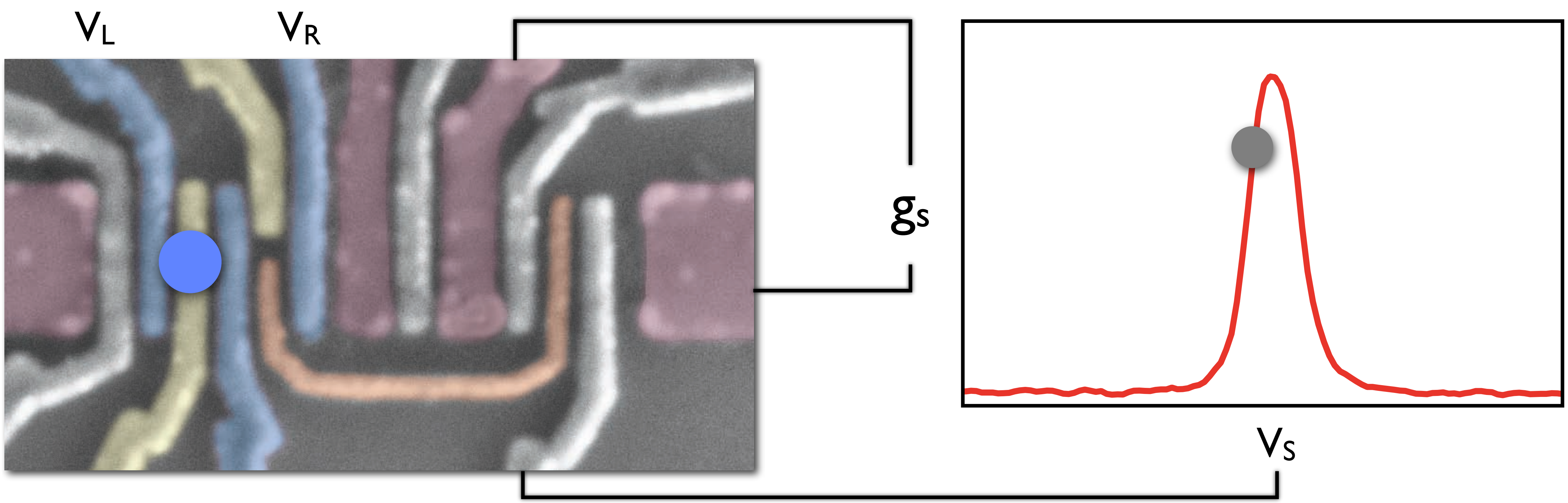




sets independent lower bound on A ~ 50 μeV

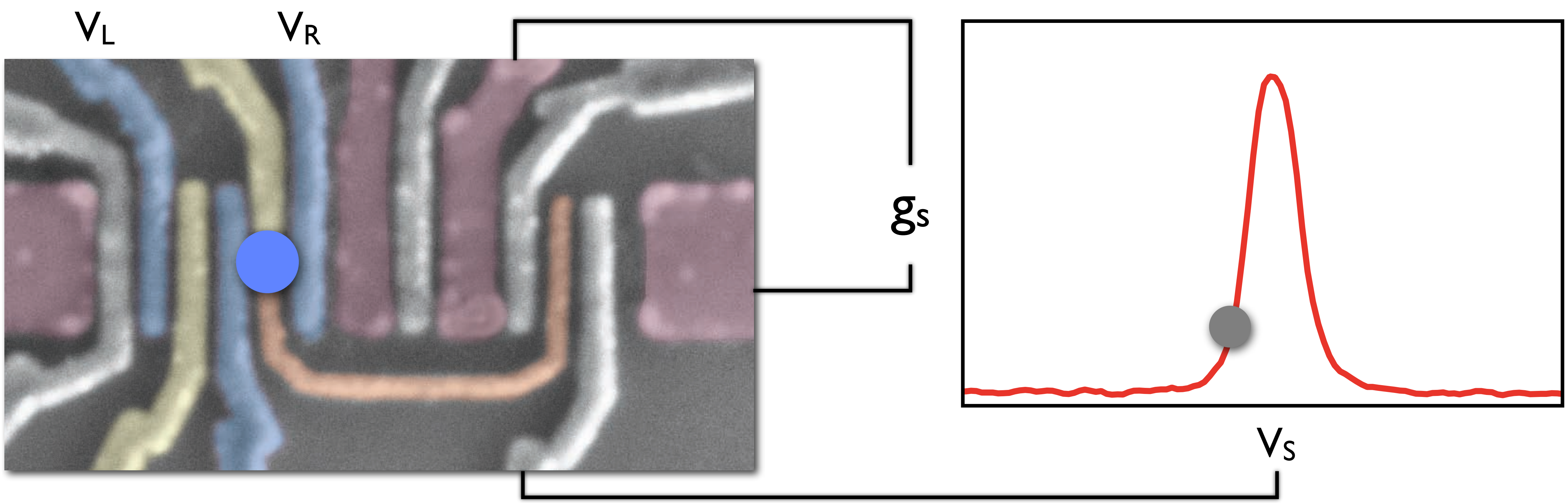
H. O. H. Churchill, et al. Nature Physics **5**, 321(2009).

Charge sensing



double dot charges
'gate' sensor dot

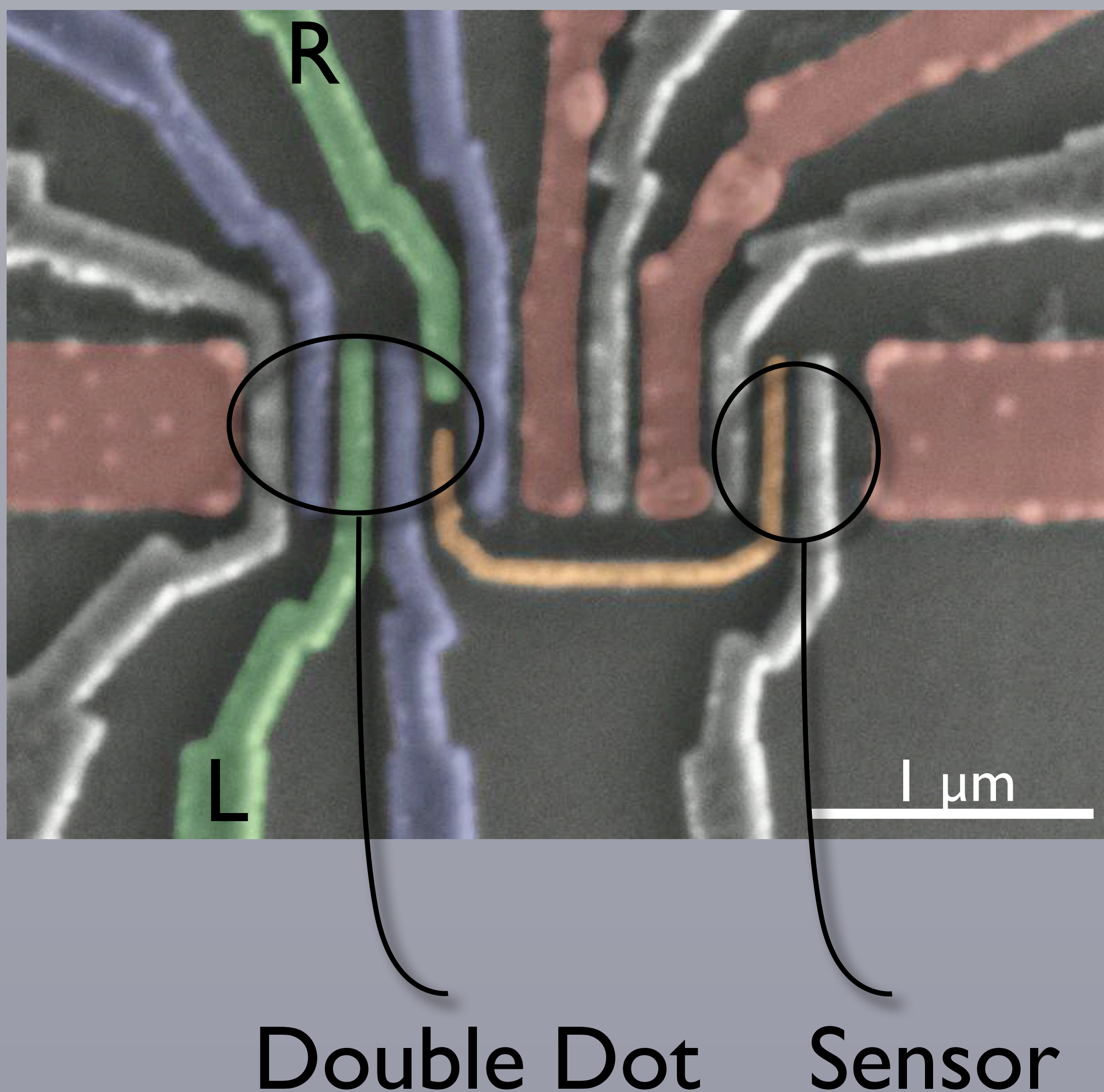
Charge sensing



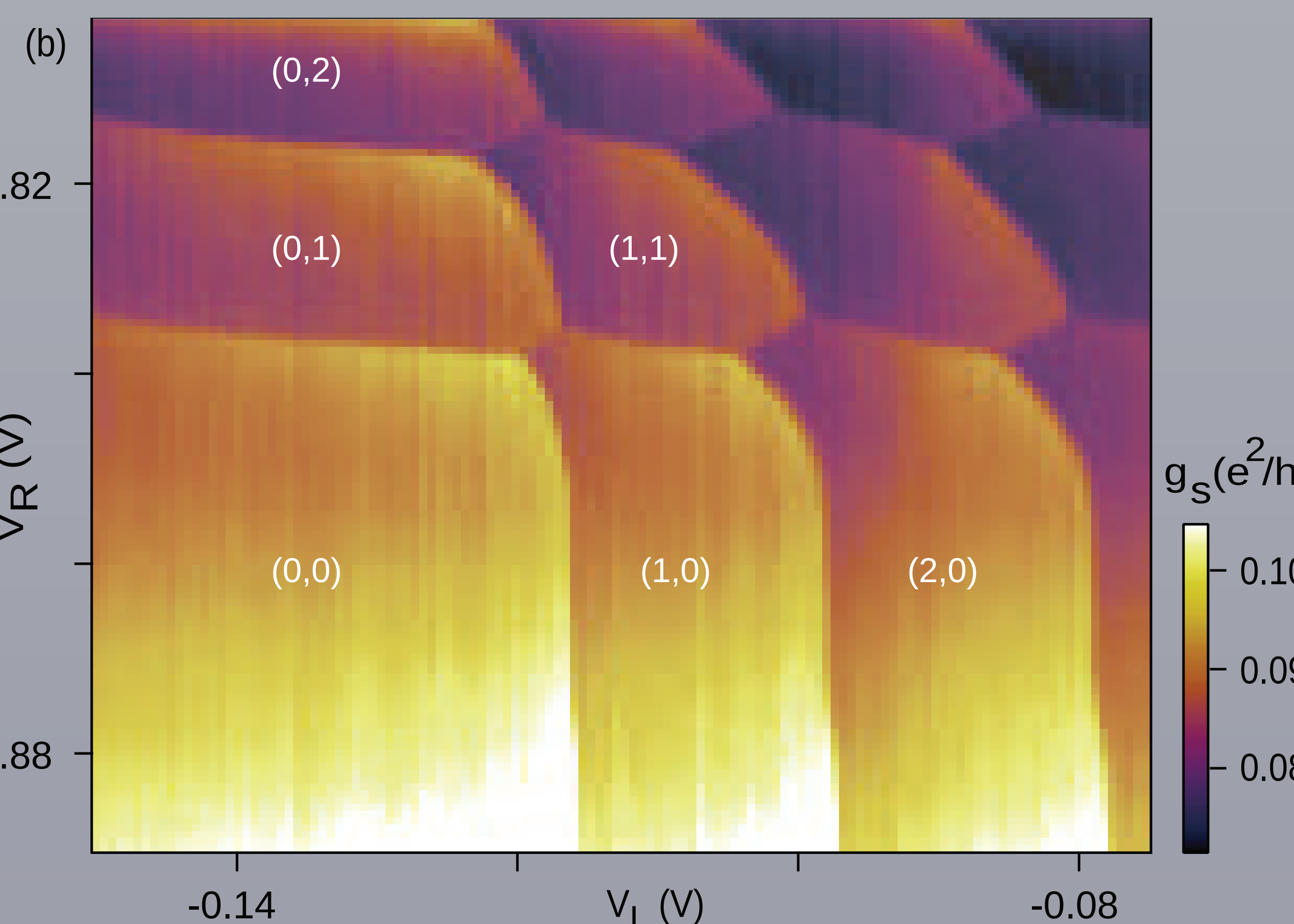
double dot charges
'gate' sensor dot

^{13}C Nanotube Double Dot with Integrated Charge Sensor

Few-Electron Regime

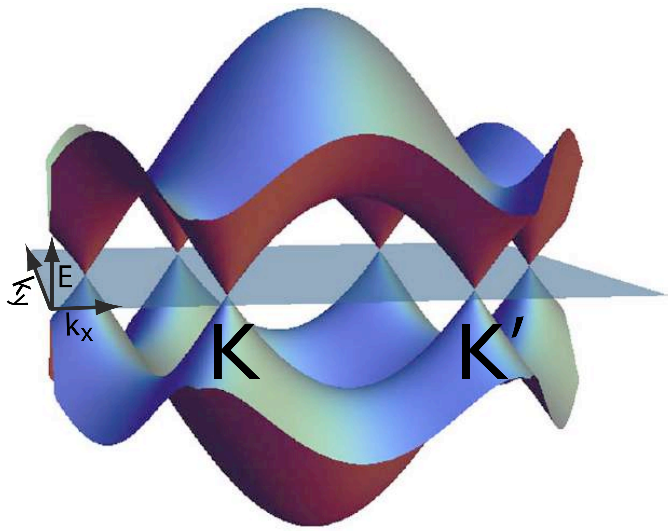


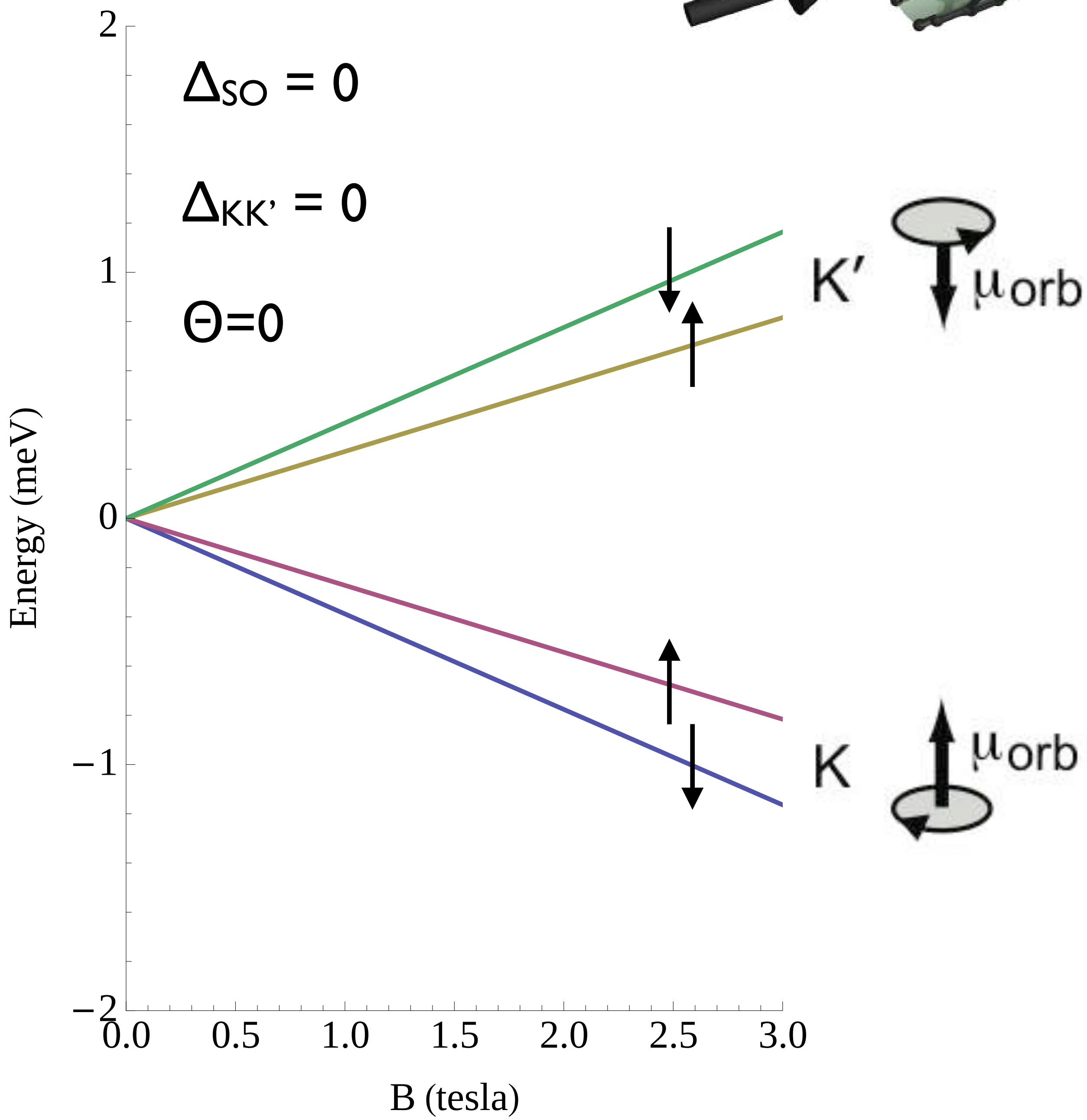
SENSOR SIGNAL

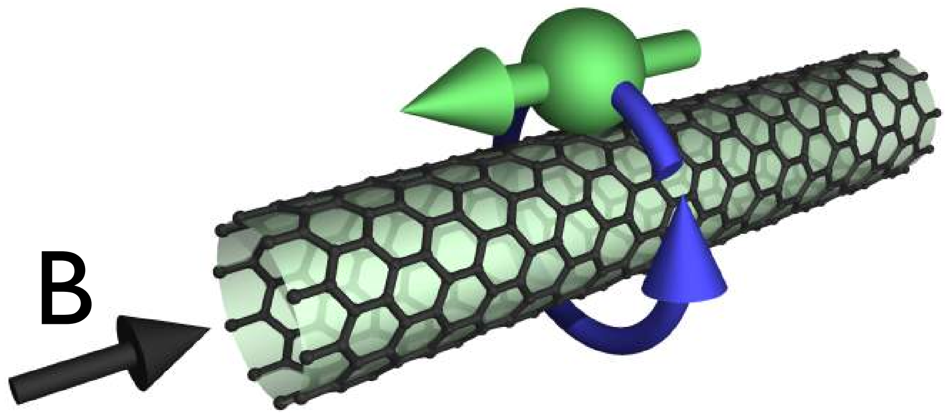


H. O. H. Churchill, et al. Phys. Rev. Lett. **102** 1066802 (2009).

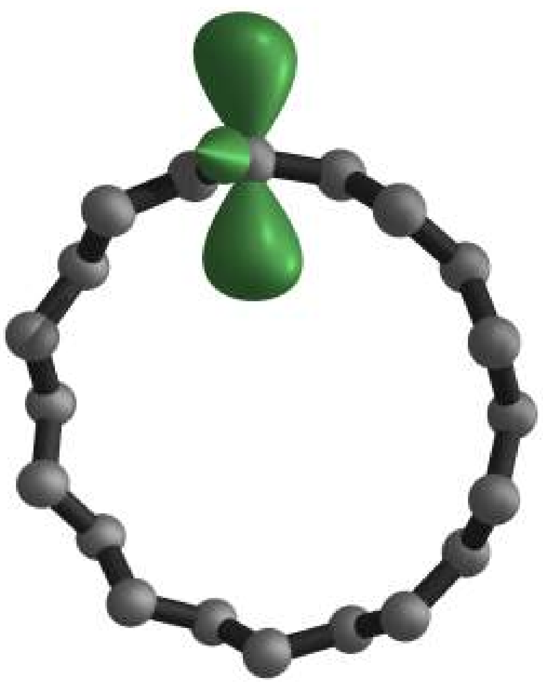
Levels in a single dot

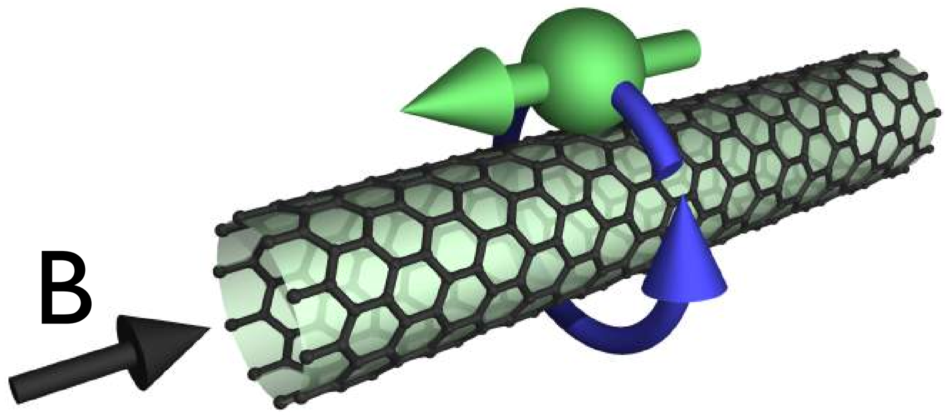


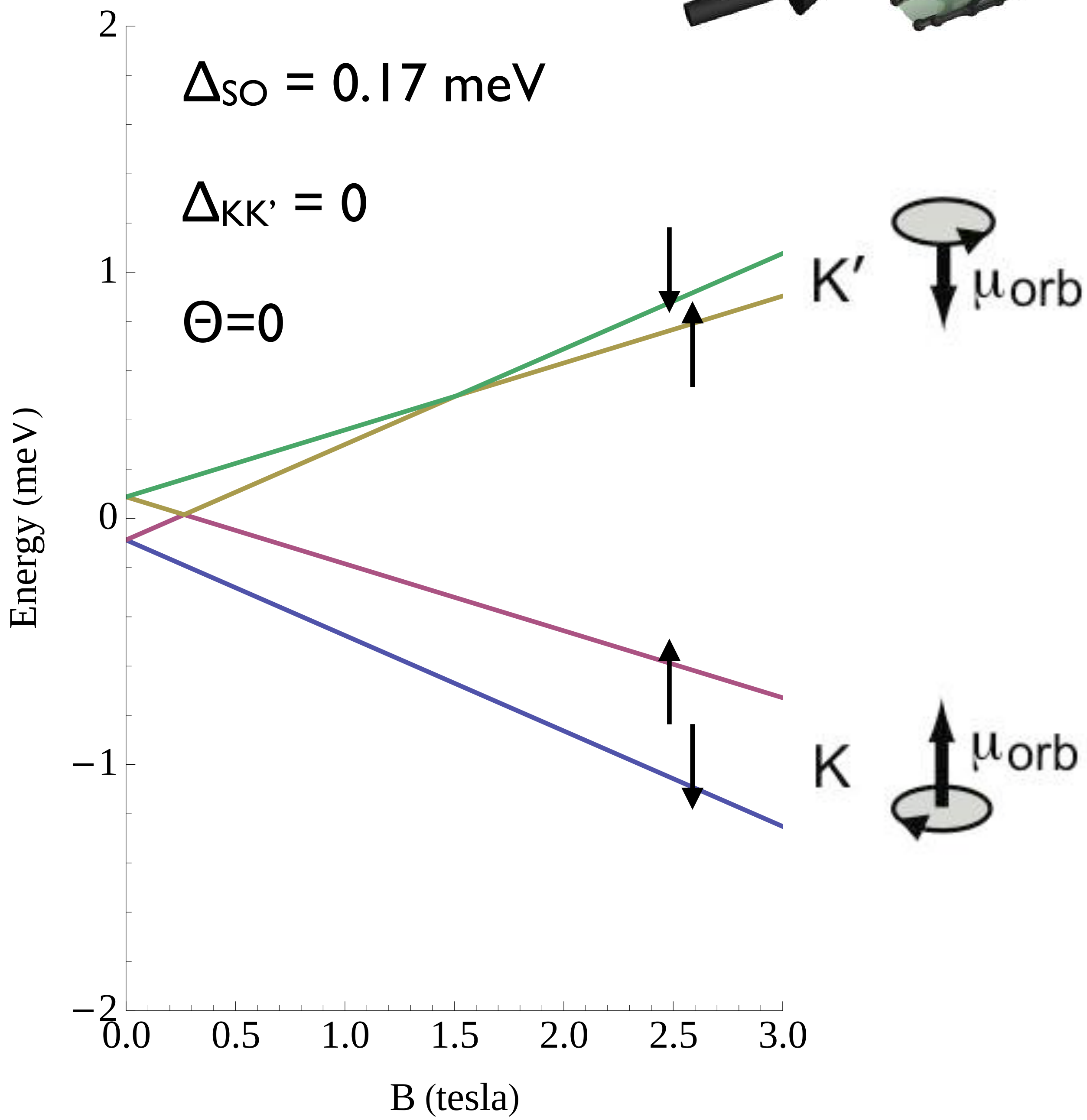




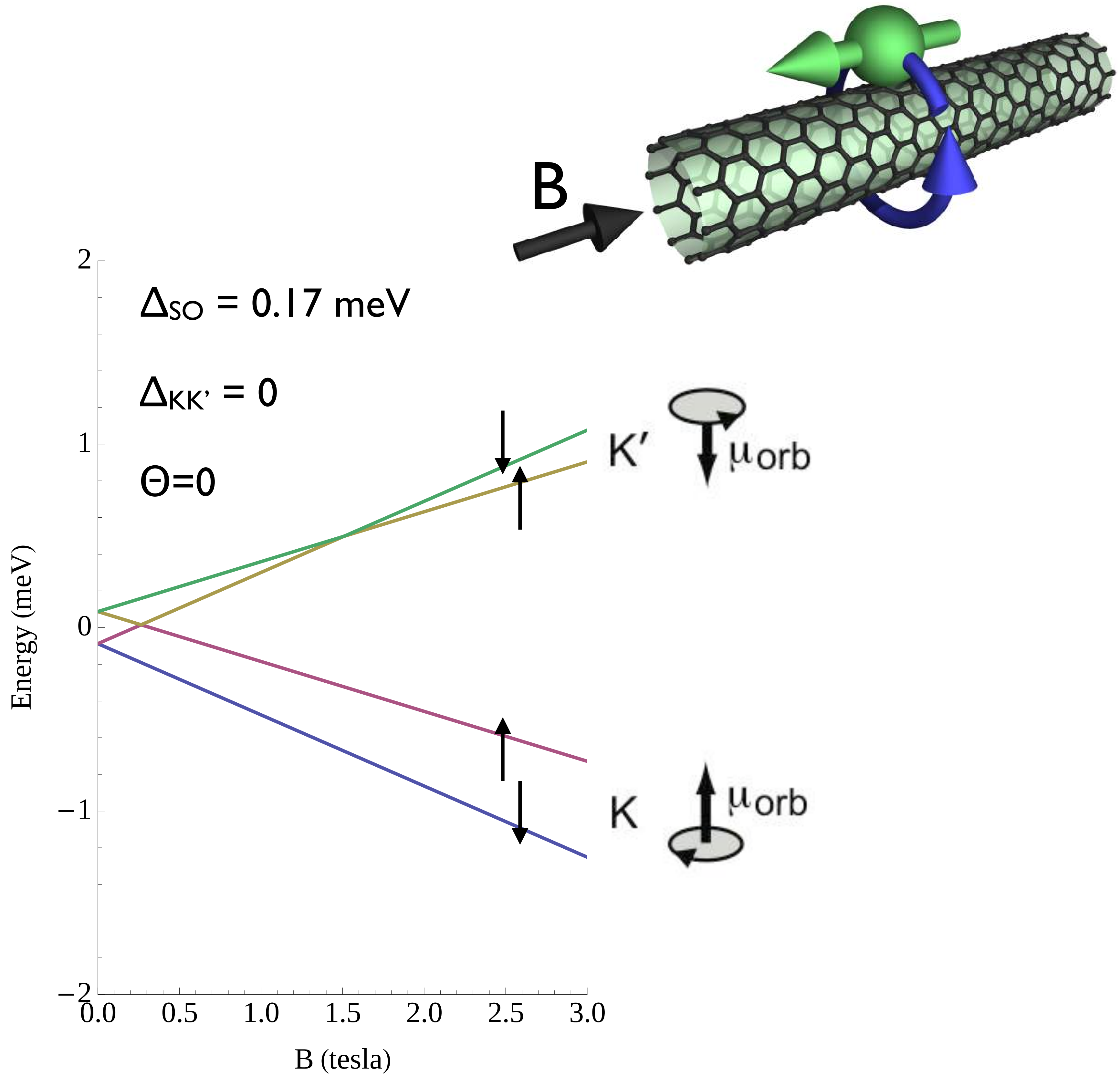
Levels in a single dot, including spin-orbit coupling



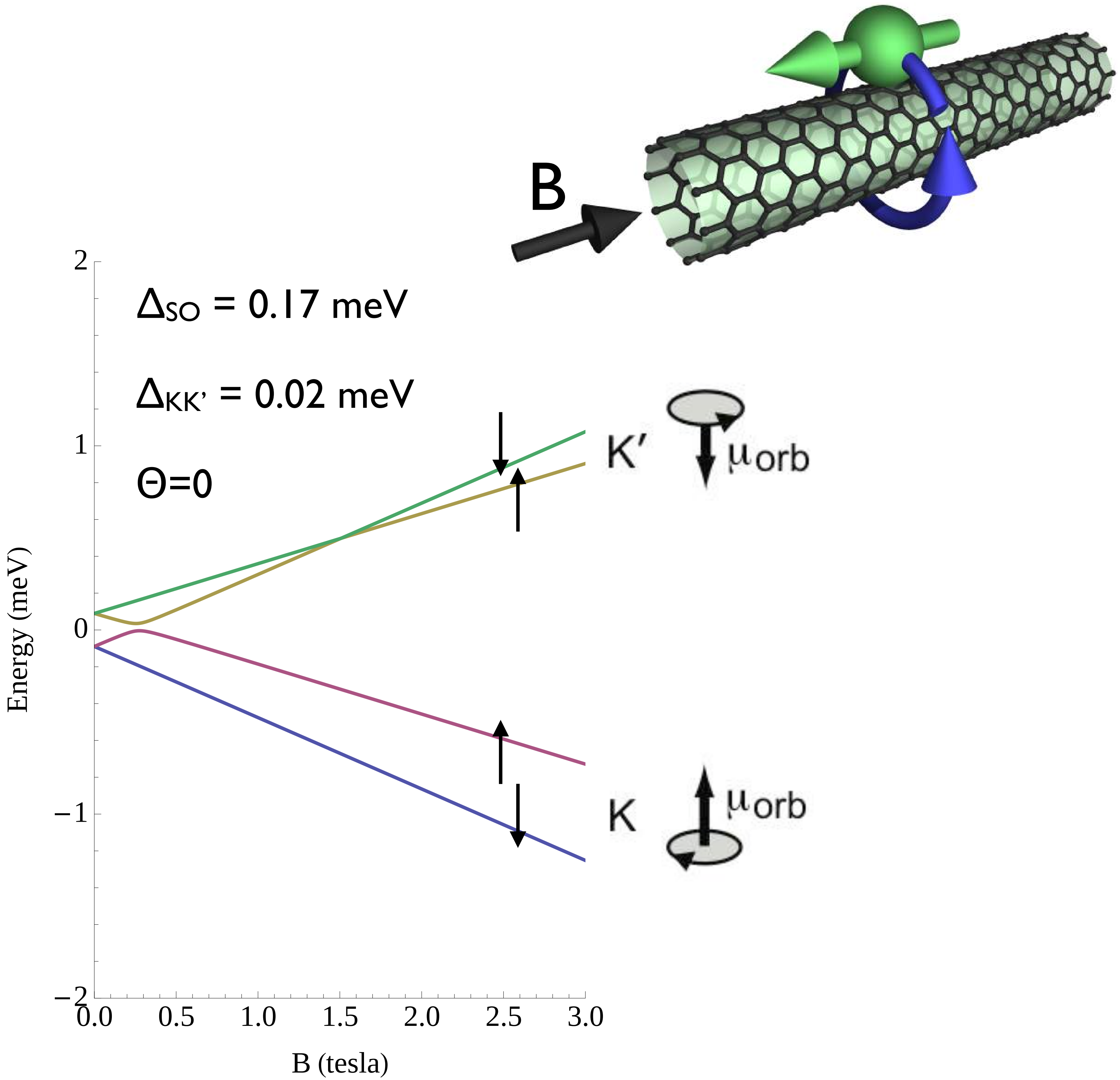




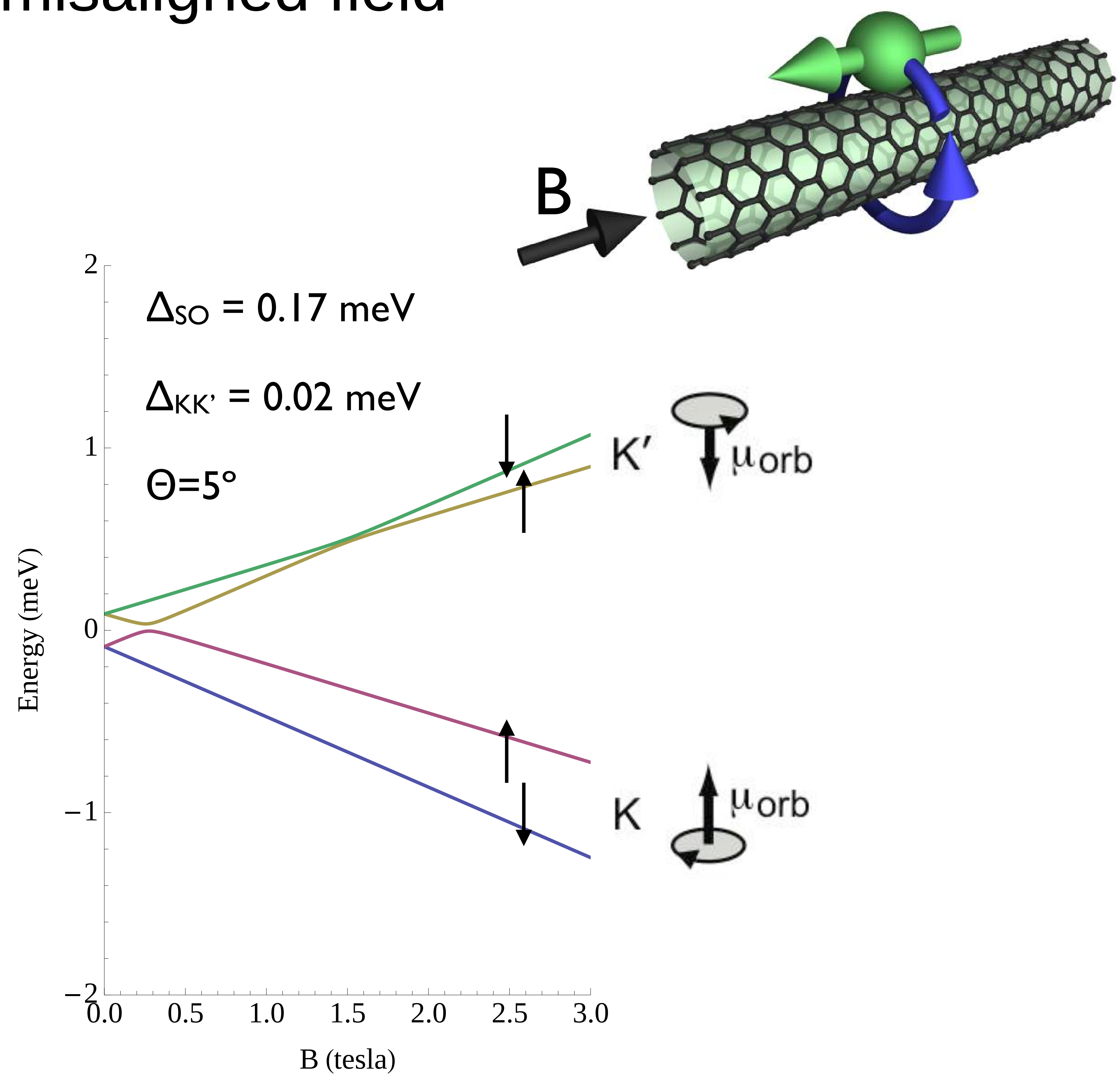
Levels in a single dot, including spin-orbit coupling



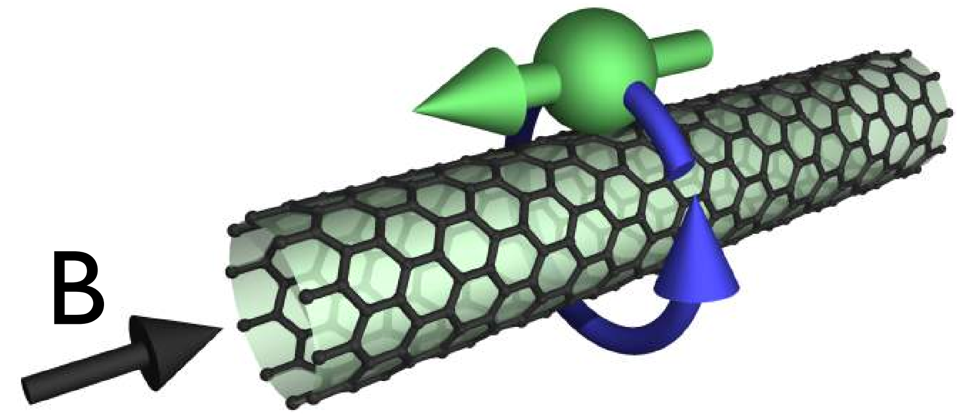
Levels in a single dot, including spin-orbit coupling and valley mixing

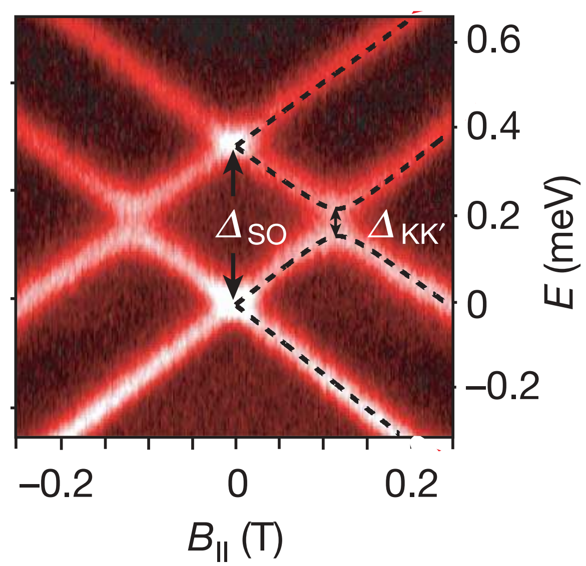


Levels in a single dot, including spin-orbit coupling, valley mixing, and misaligned field

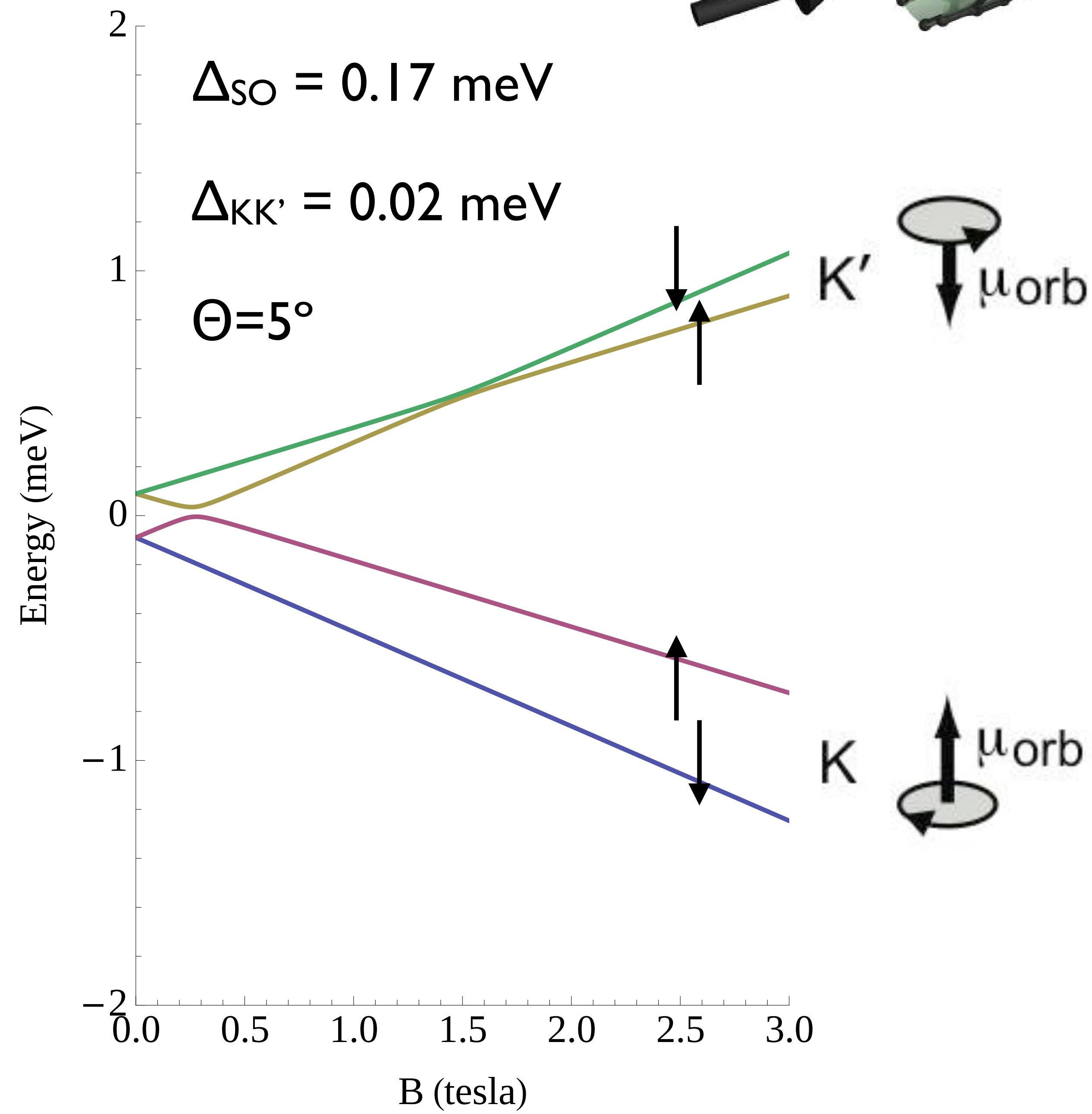


Levels in a single dot, including spin-orbit coupling, valley mixing, and misaligned field



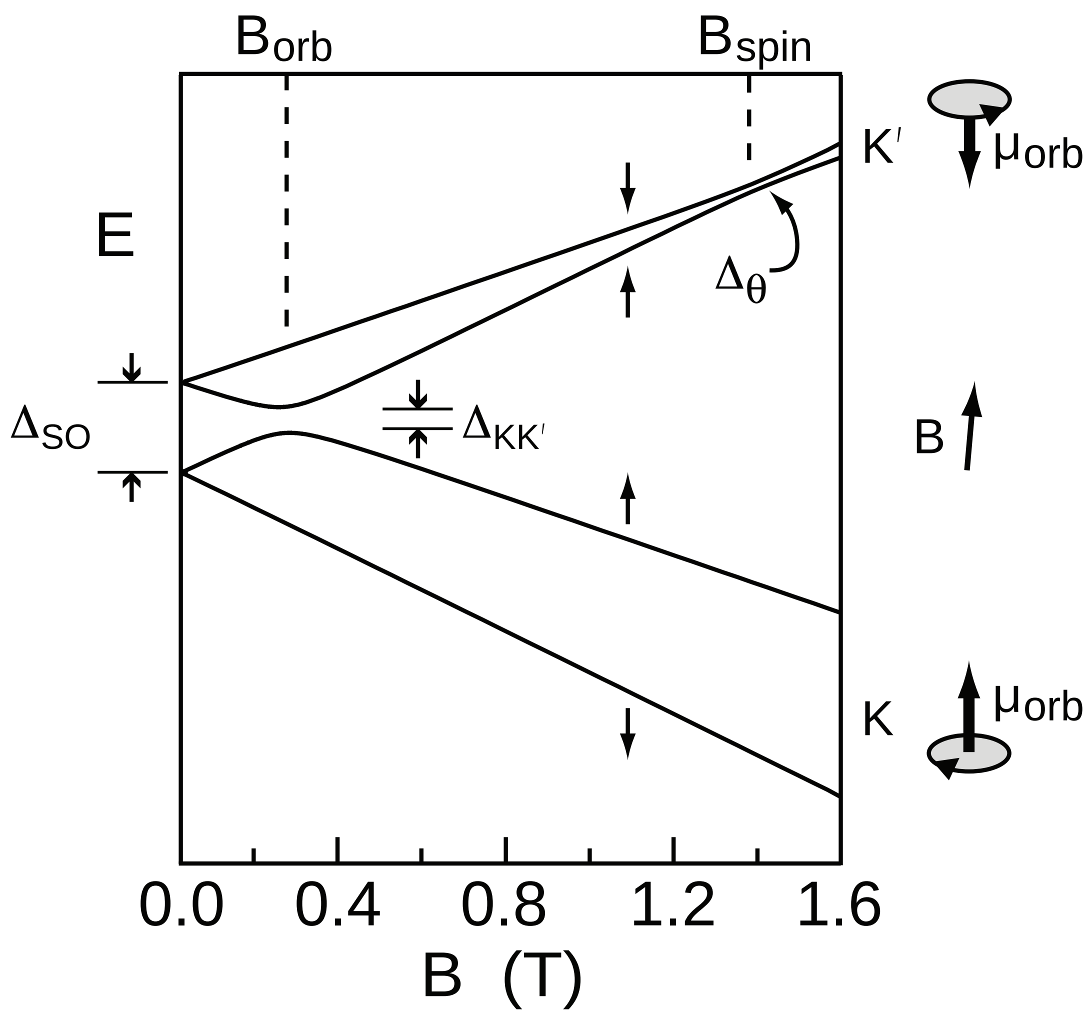


See Also
Kuemmeth, Ilani *et al.*
Nature **452,** 448 (2008)

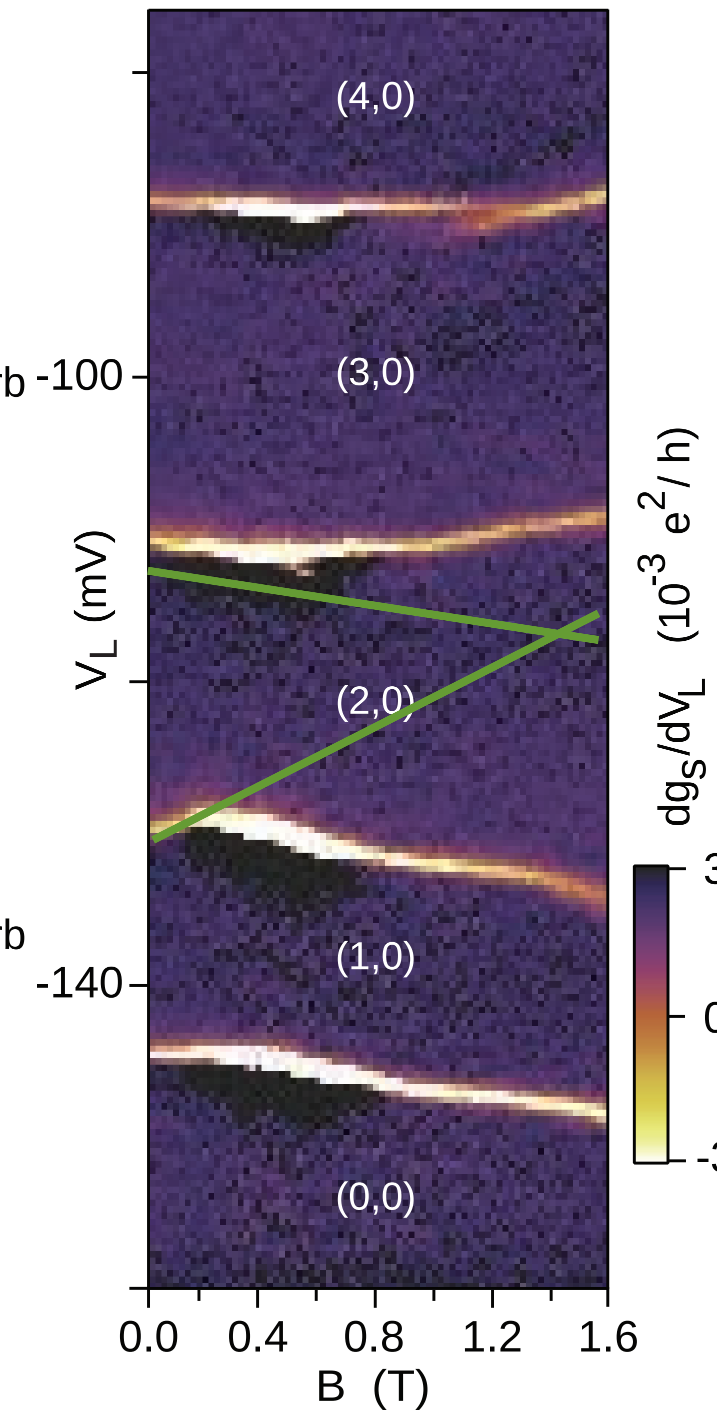


Levels in a single dot

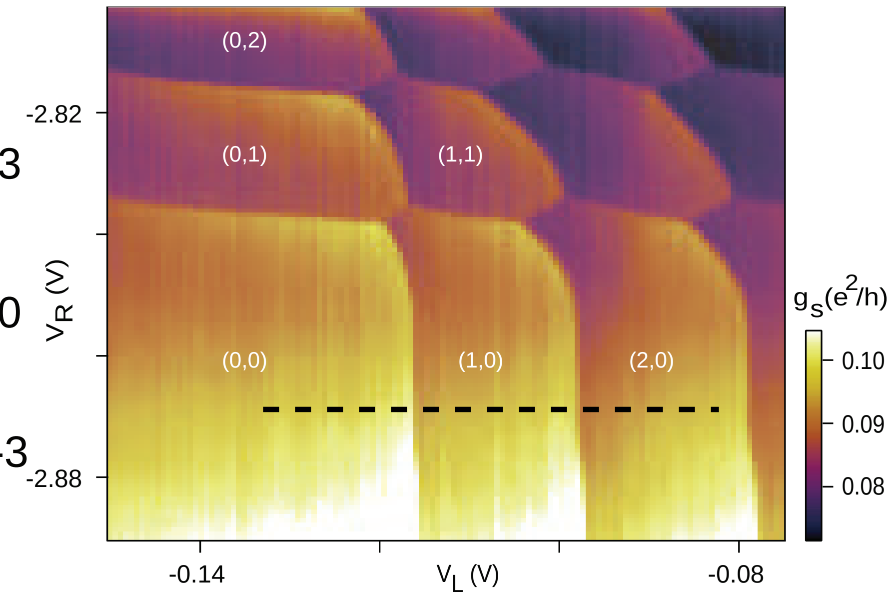
single-particle levels



addition spectrum



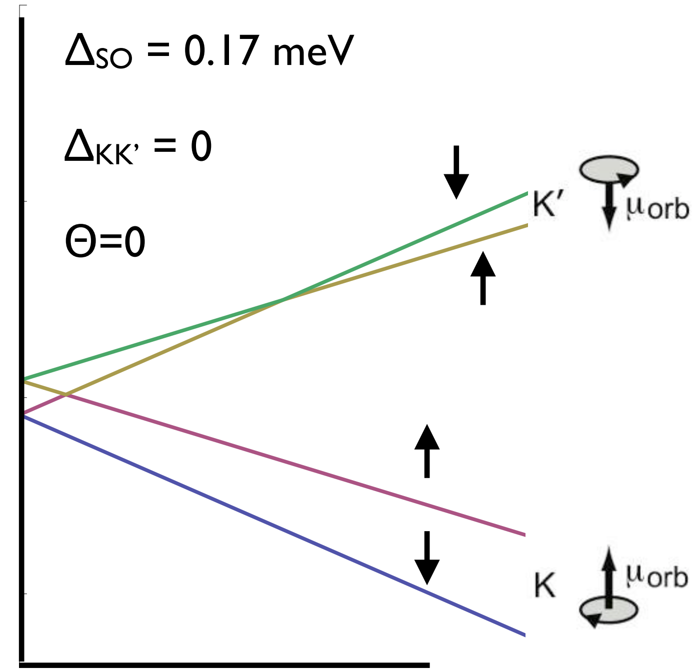
slopes differ by $2\mu_B$



H. O. H. Churchill, et al. Phys. Rev. Lett. **102** 1066802 (2009).

(1,1) and (0,2) nanotube double dot states

one-electron states

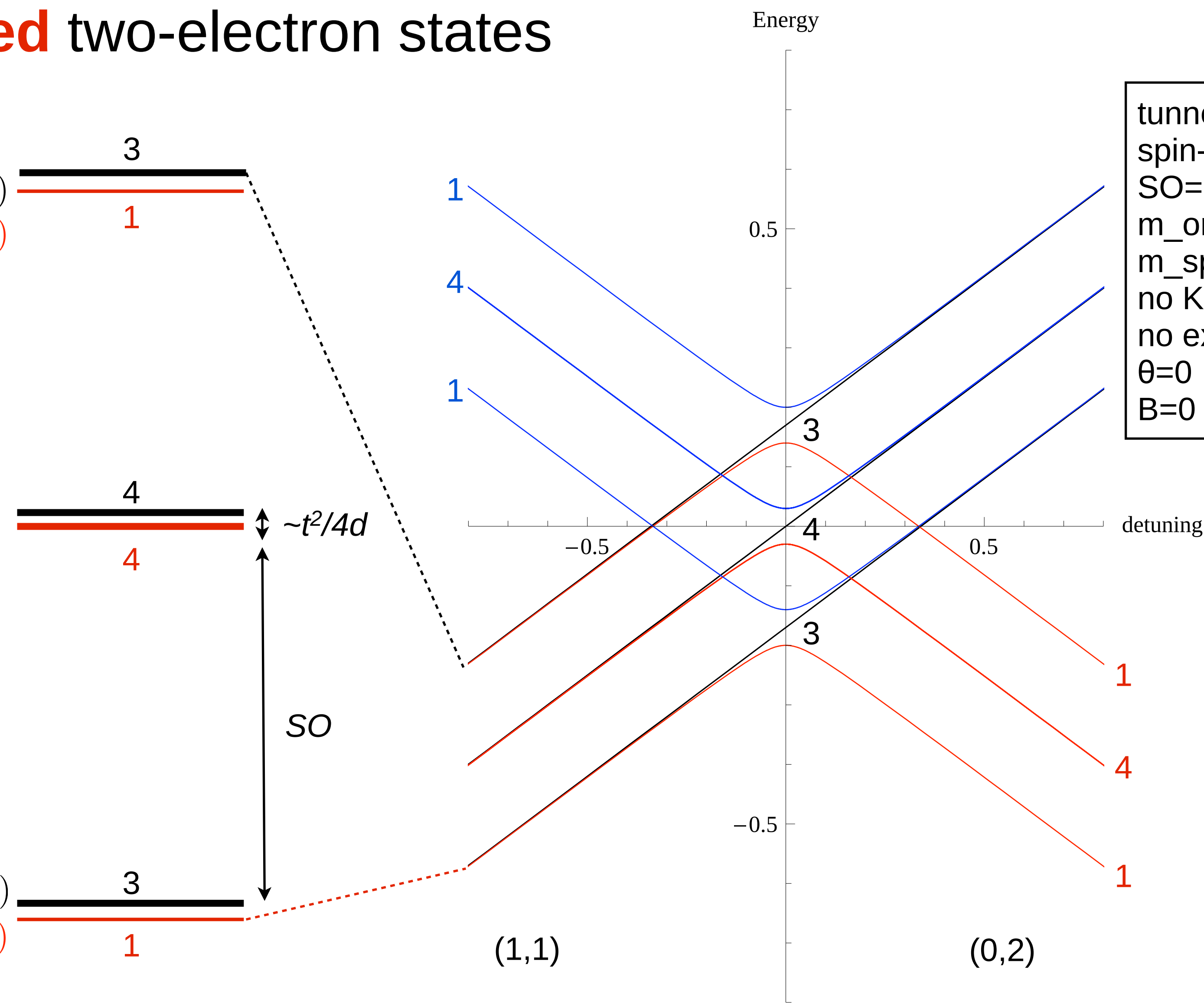


10 blocked and **6 unblocked** two-electron states

$(|R\rangle|L\rangle - |L\rangle|R\rangle) \otimes |K\rangle|K\rangle \otimes \mathbf{T}_+$
$(|R\rangle|L\rangle - |L\rangle|R\rangle) \otimes |K'\rangle|K'\rangle \otimes \mathbf{T}_-$
$(|R\rangle|L\rangle - |L\rangle|R\rangle) \otimes (|K'\downarrow\rangle|K\uparrow\rangle + |K\uparrow\rangle|K'\downarrow\rangle)$
$(|R\rangle|L\rangle + |L\rangle|R\rangle) \otimes (|K'\downarrow\rangle|K\uparrow\rangle - |K\uparrow\rangle|K'\downarrow\rangle)$

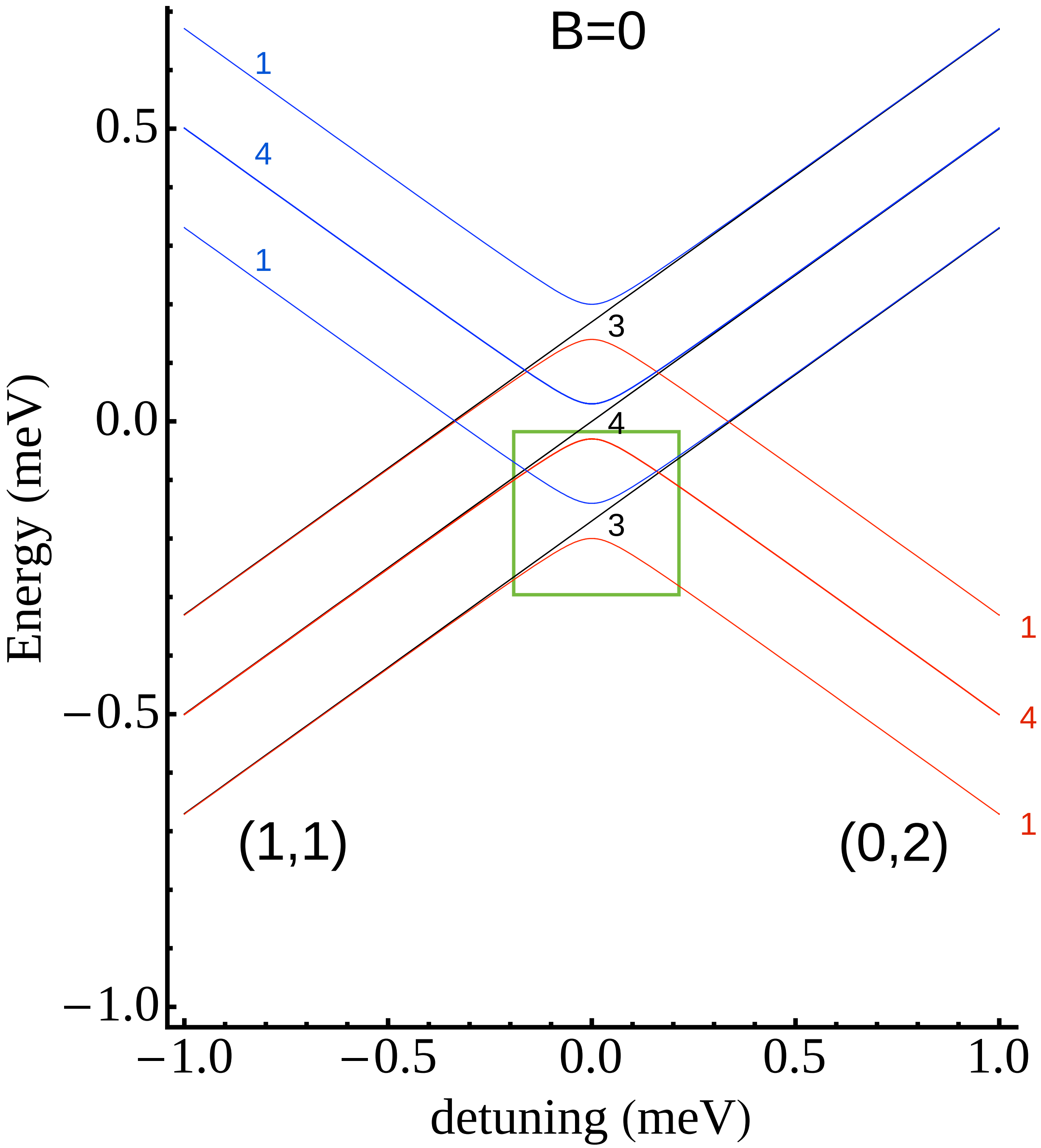
$(|R\rangle|L\rangle - |L\rangle|R\rangle) \otimes |K\rangle|K\rangle \otimes \mathbf{T}_0$
$(|R\rangle|L\rangle - |L\rangle|R\rangle) \otimes |K'\rangle|K'\rangle \otimes \mathbf{T}_0$
$(|R\rangle|L\rangle - |L\rangle|R\rangle) \otimes (|K'\rangle|K\rangle + |K\rangle|K'\rangle) \otimes \mathbf{T}_-$
$(|R\rangle|L\rangle - |L\rangle|R\rangle) \otimes (|K'\rangle|K\rangle + |K\rangle|K'\rangle) \otimes \mathbf{T}_+$
$(|R\rangle|L\rangle + |L\rangle|R\rangle) \otimes |K'\rangle|K'\rangle \otimes \mathbf{S}$
$(|R\rangle|L\rangle + |L\rangle|R\rangle) \otimes |K\rangle|K\rangle \otimes \mathbf{S}$
$(|R\rangle|L\rangle + |L\rangle|R\rangle) \otimes (|K'\rangle|K\rangle - |K\rangle|K'\rangle) \otimes \mathbf{T}_+$
$(|R\rangle|L\rangle + |L\rangle|R\rangle) \otimes (|K'\rangle|K\rangle - |K\rangle|K'\rangle) \otimes \mathbf{T}_-$

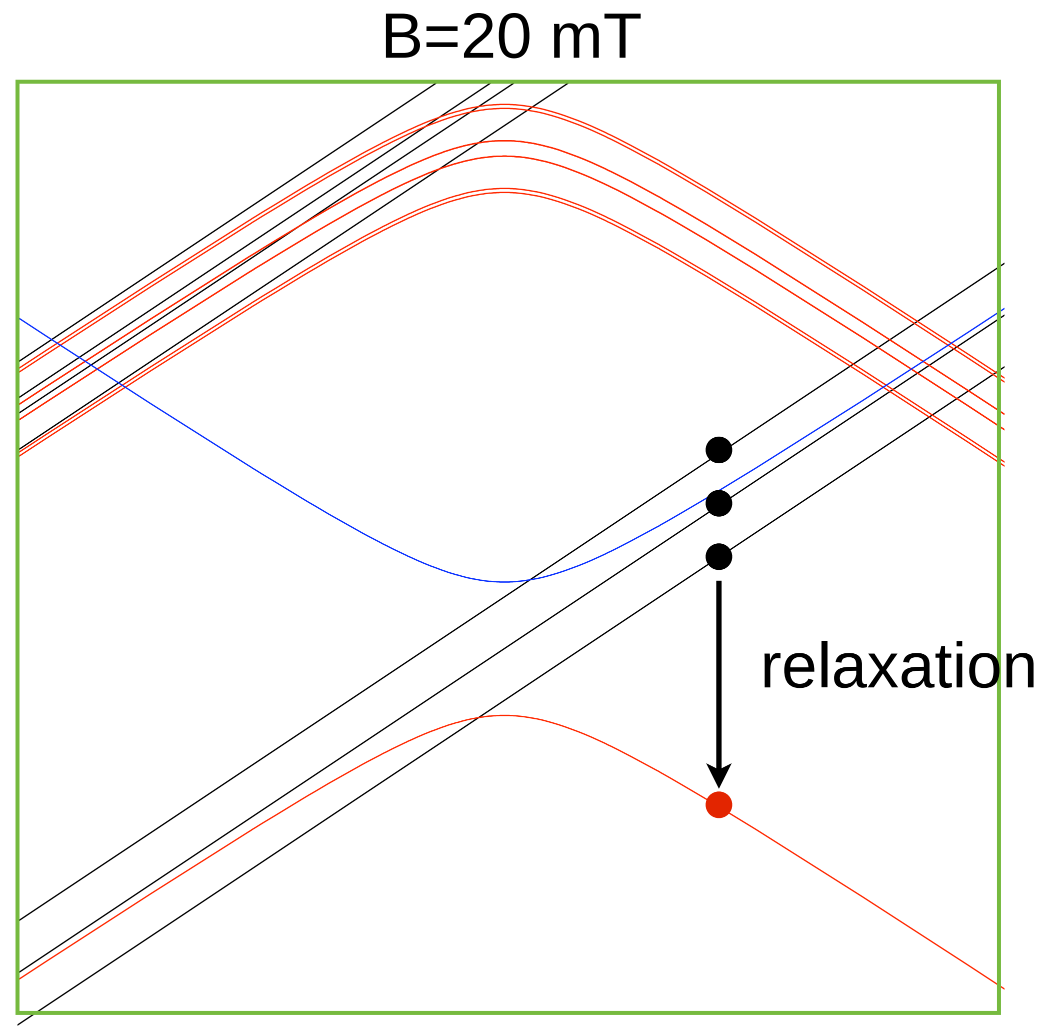
$(|R\rangle|L\rangle - |L\rangle|R\rangle) \otimes |K\rangle|K\rangle \otimes \mathbf{T}_-$
$(|R\rangle|L\rangle - |L\rangle|R\rangle) \otimes |K'\rangle|K'\rangle \otimes \mathbf{T}_+$
$(|R\rangle|L\rangle - |L\rangle|R\rangle) \otimes (|K'\uparrow\rangle|K\downarrow\rangle + |K\downarrow\rangle|K'\uparrow\rangle)$
$(|R\rangle|L\rangle + |L\rangle|R\rangle) \otimes (|K'\uparrow\rangle|K\downarrow\rangle - |K\downarrow\rangle|K'\uparrow\rangle)$



tunneling t=0.03 meV
spin-orbit
SO=0.17meV
m_orb=0.33 meV/T
m_spin=0.058 meV/T
no KK' scattering
no exchange
θ=0
B=0

Pauli blockade in carbon nanotube double dot despite spin-orbit coupling



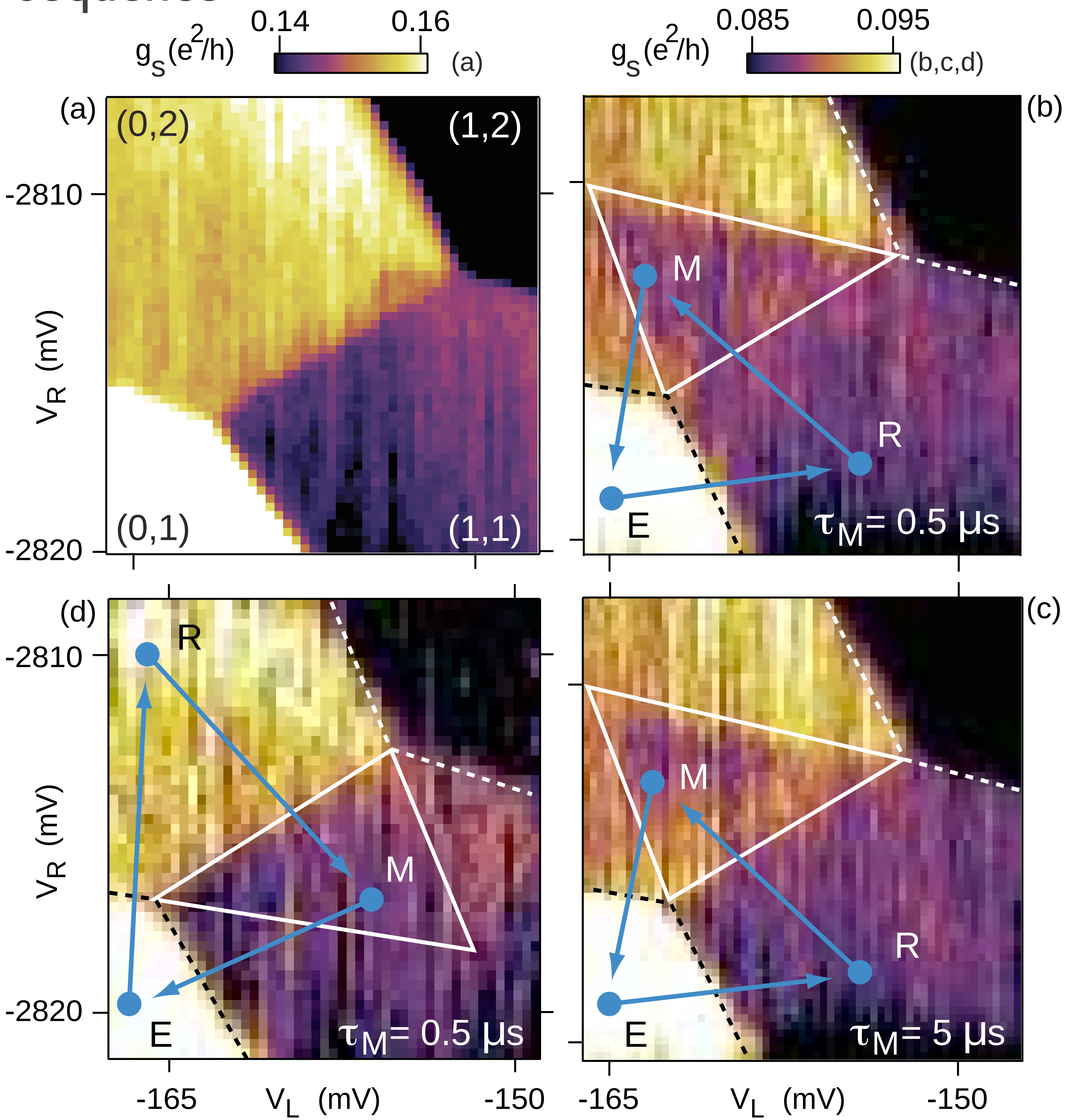


- $(|R\rangle|L\rangle - |L\rangle|R\rangle) \otimes |K'\rangle|K'\rangle \otimes \mathbf{T}_+$
- $(|R\rangle|L\rangle - |L\rangle|R\rangle) \otimes (|K'\uparrow\rangle|K\downarrow\rangle + |K\downarrow\rangle|K'\uparrow\rangle)$
- $(|R\rangle|L\rangle - |L\rangle|R\rangle) \otimes |K\rangle|K\rangle \otimes \mathbf{T}_-$

- $(|R\rangle|L\rangle + |L\rangle|R\rangle) \otimes (|K'\uparrow\rangle|K\downarrow\rangle - |K\downarrow\rangle|K'\uparrow\rangle)$

lowest two-particle states have different spin & valley symmetries

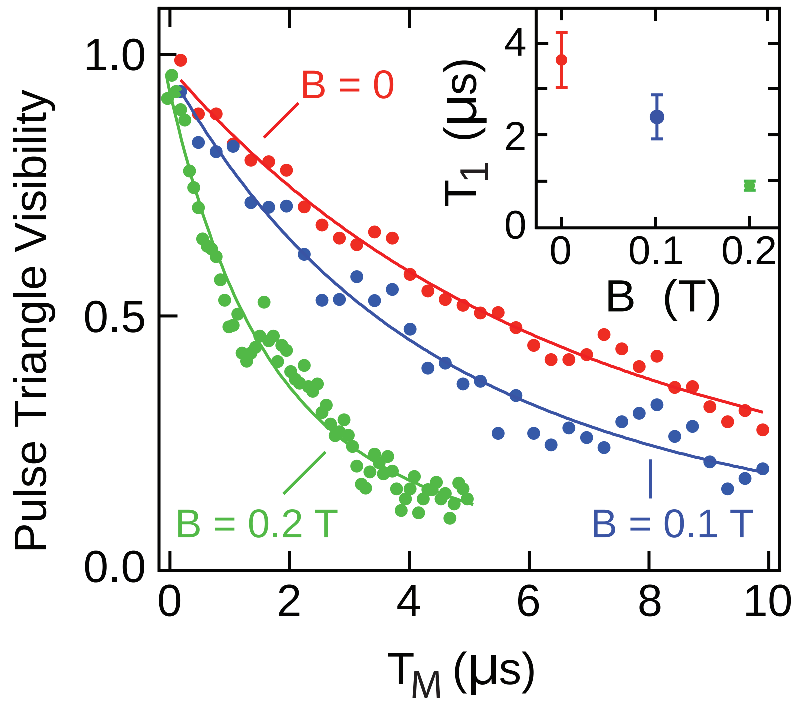
T1 sequence

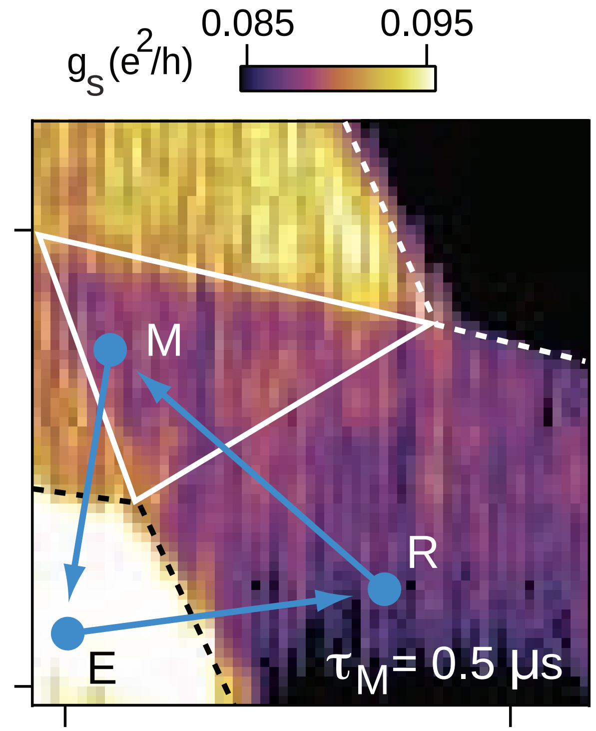


$g_S(e^2/h)$
0.14
0.16
(a)
$g_S(e^2/h)$
0.085
0.095
(b,c,d)
(a)
(0,2)
(1,2)
(0,1)
(1,1)
-2810
-2820
V_R (mV)
(b)
M
R
E
τ_M= 0.5 μs
(d)
R
M
E
τ_M= 0.5 μs
(c)
M
R
E
τ_M= 5 μs
-165
V_L (mV)
-150

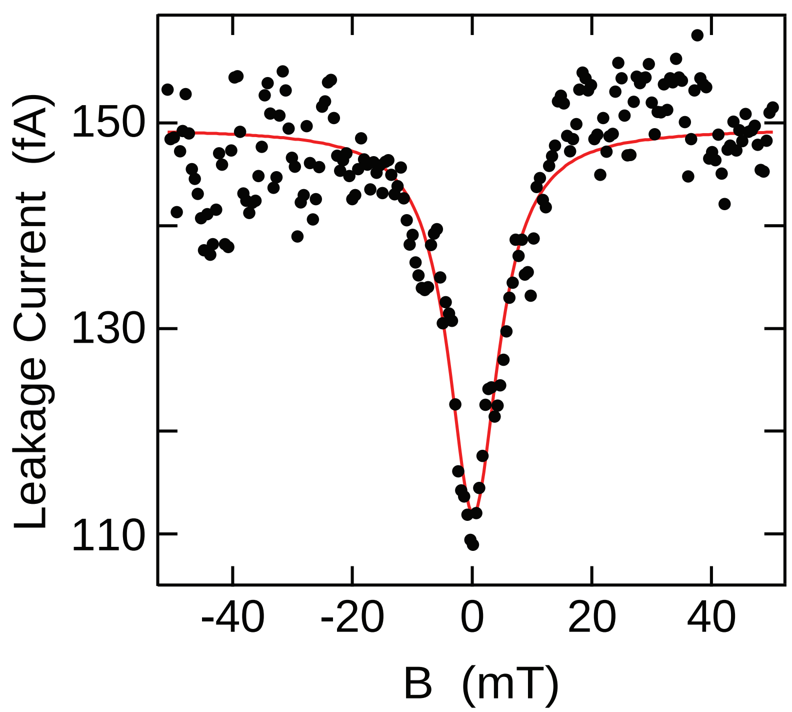
B-dependence of relaxation rate

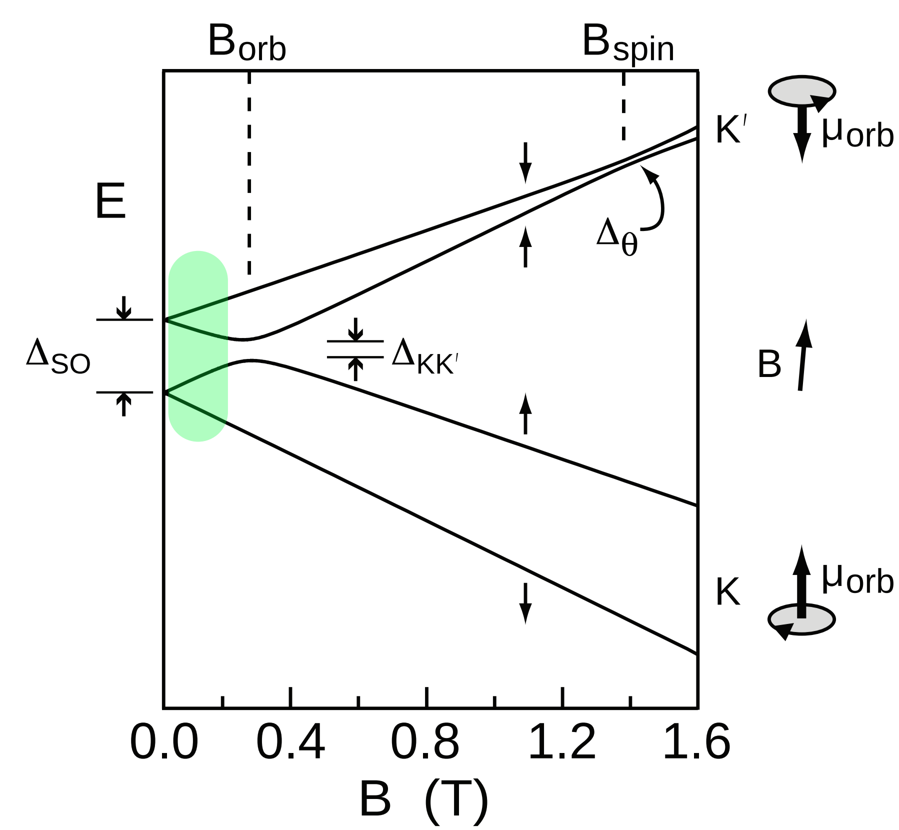
Charge sensing



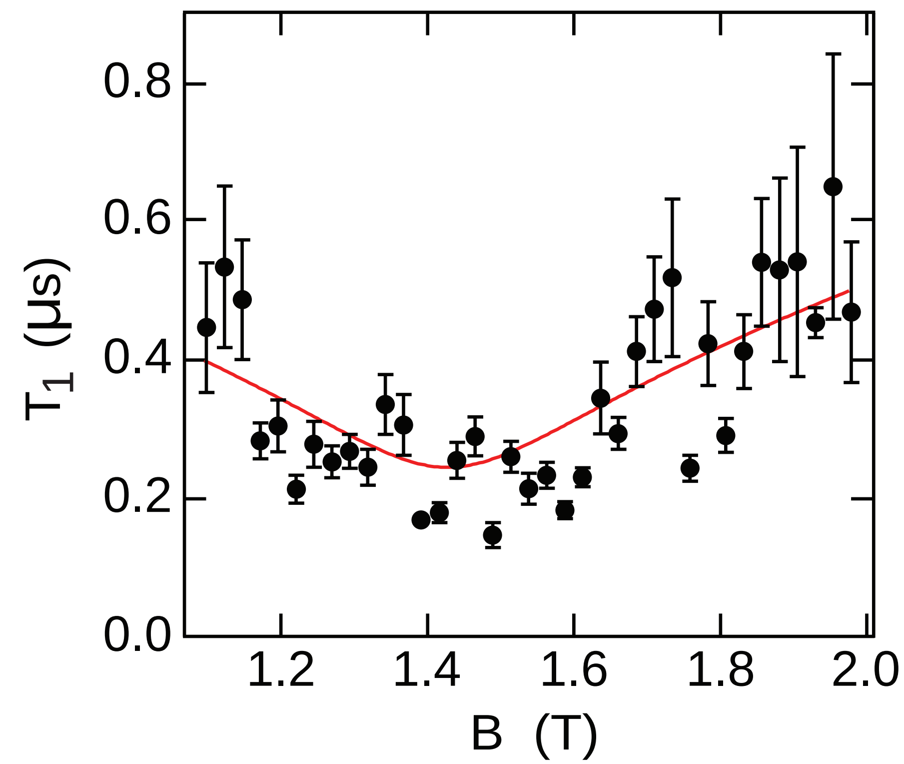


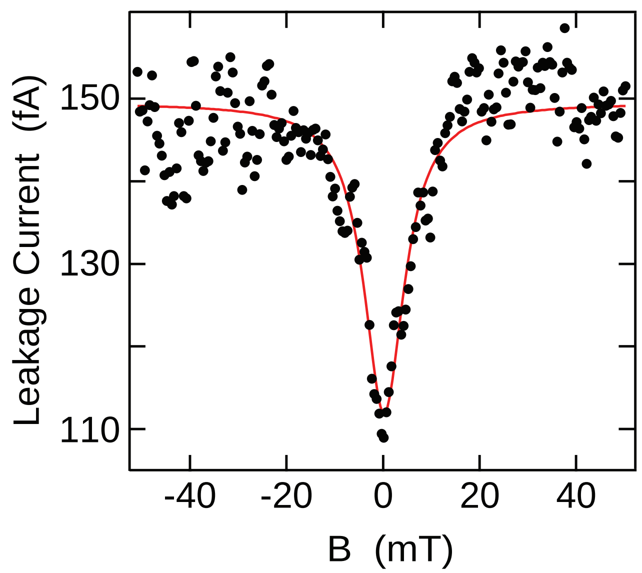
Transport

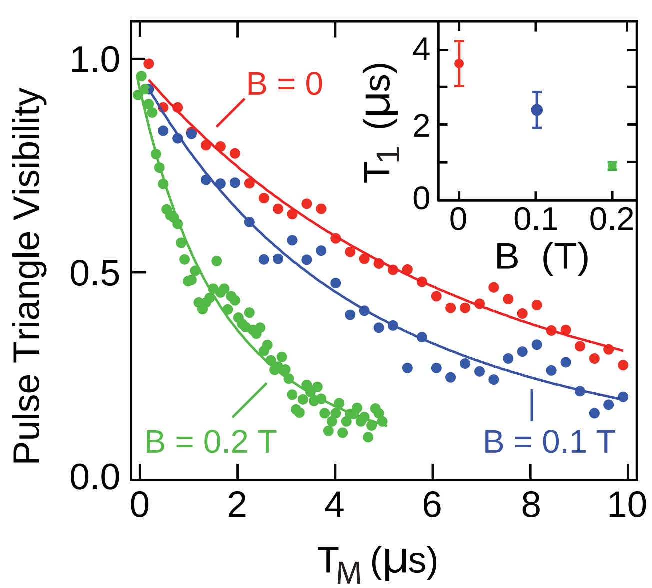


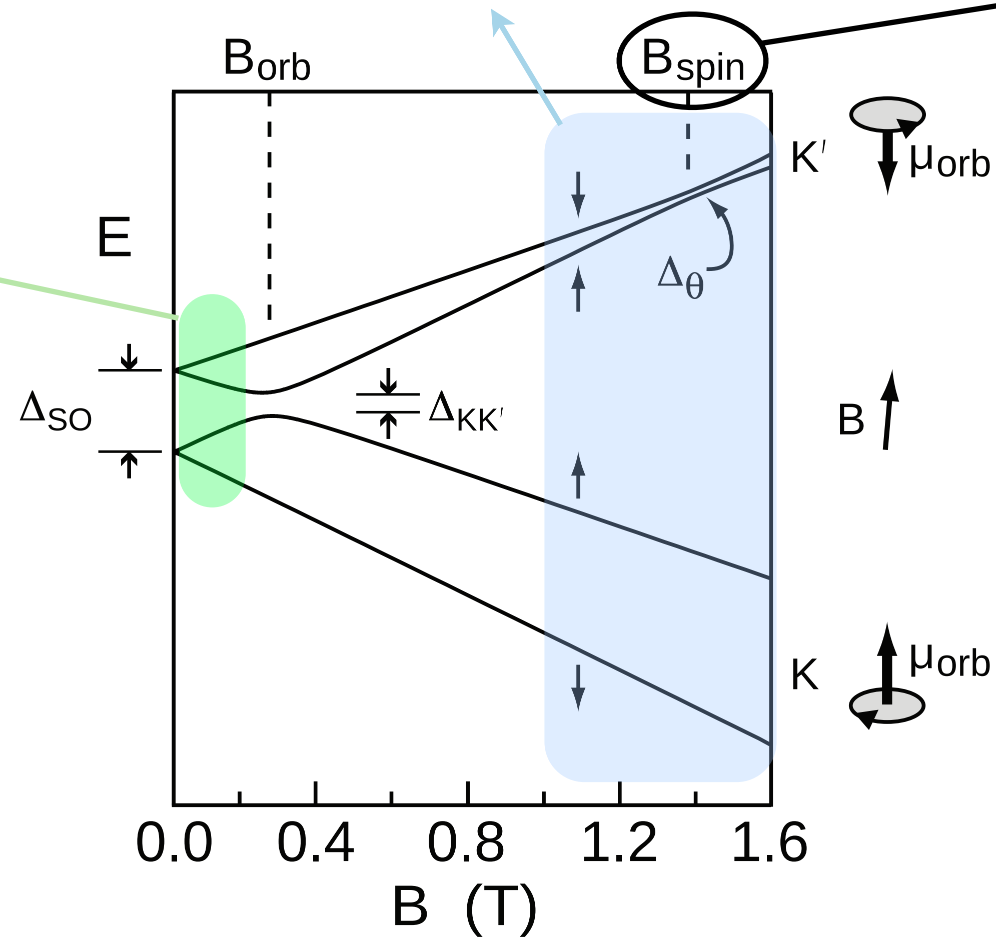


B-dependence of relaxation rate





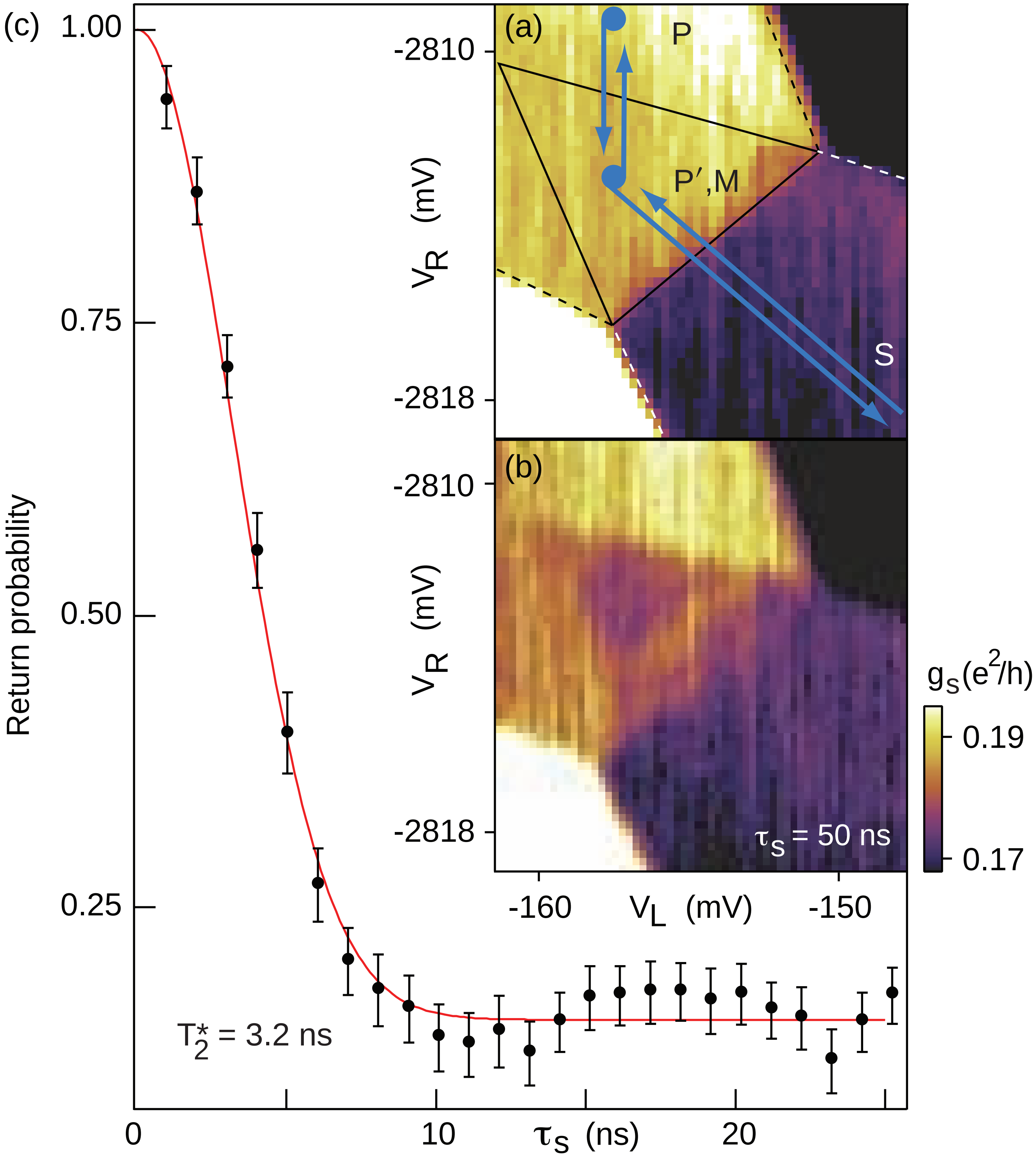


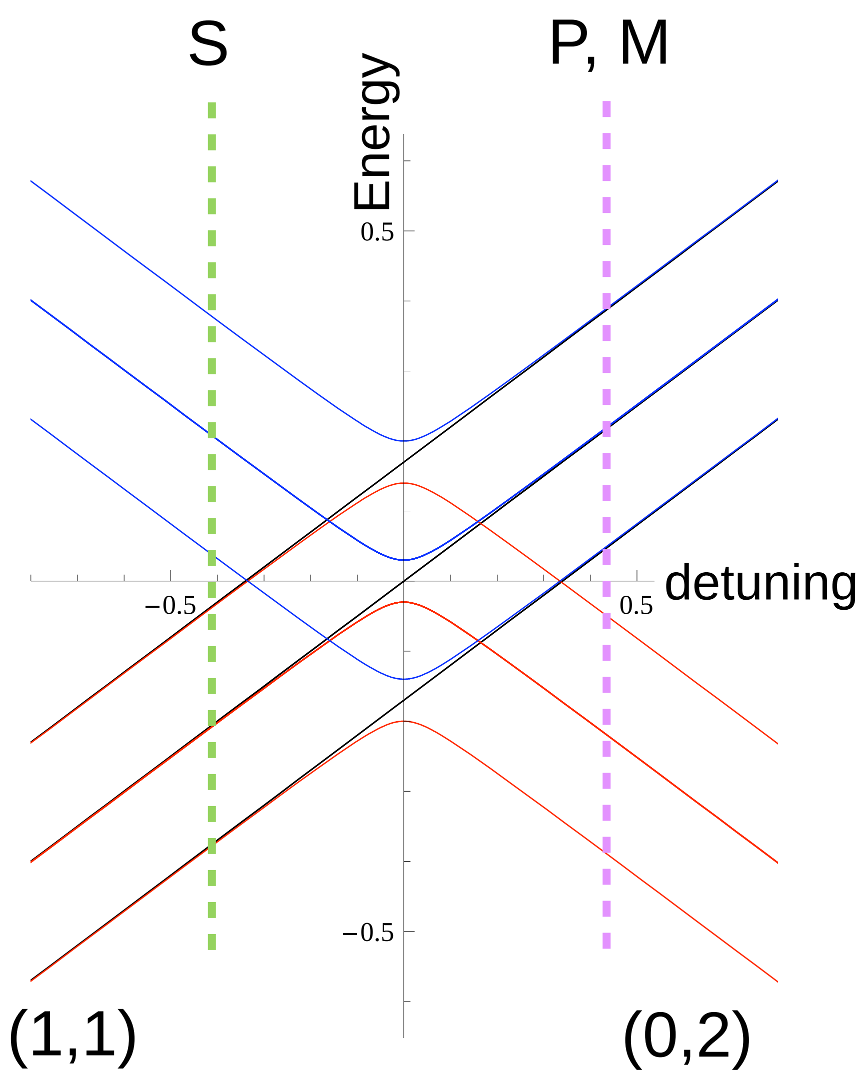


$$T_1 \propto \sqrt{\text{splitting}}$$

Bulaev *et al.* PRB **77,** 235301 (2008)

Inhomogeneous Dephasing

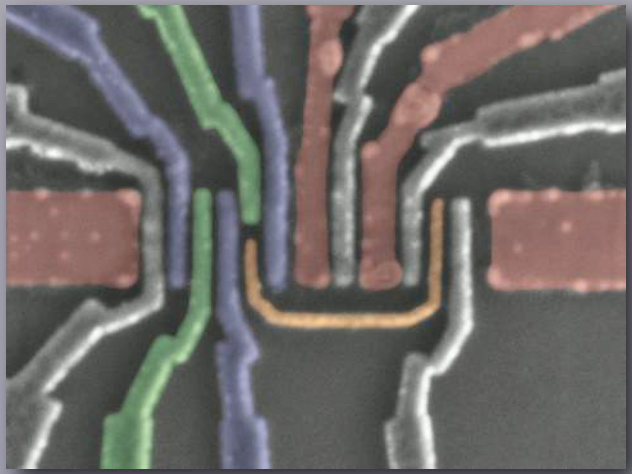


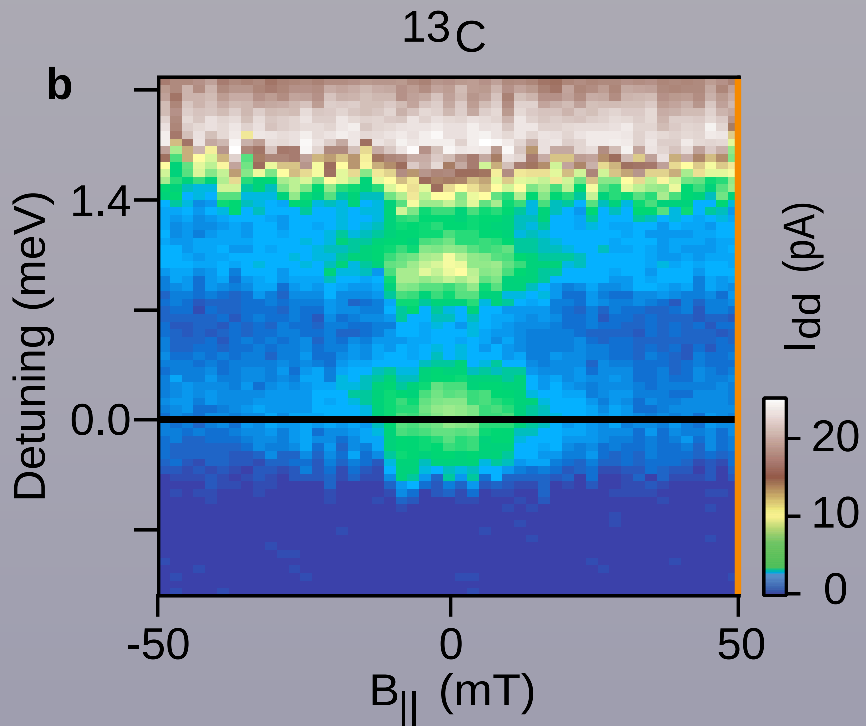


$$T_2^* = \hbar / g\mu_B \delta B_{\rm nuc}^{||} = 3.2 \text{ ns}$$

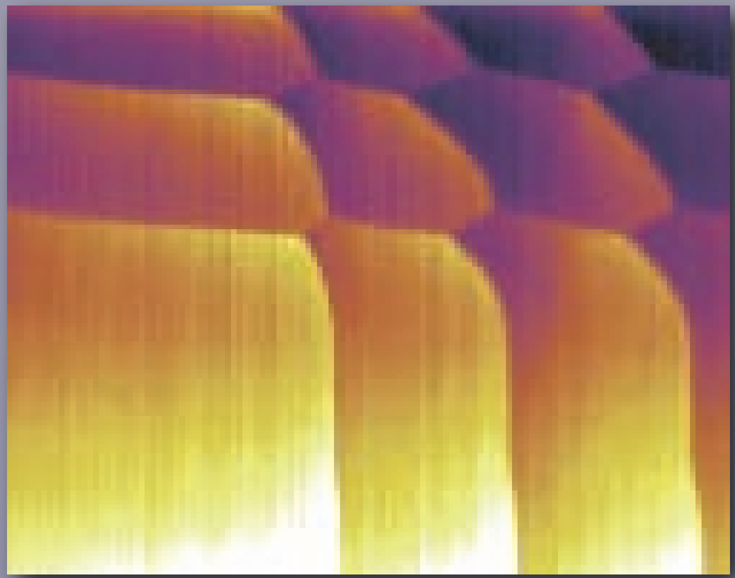
$$\longrightarrow \delta B_{\rm nuc}^{||} = 1.8 \text{ mT} \approx B_{\rm nuc}/2$$

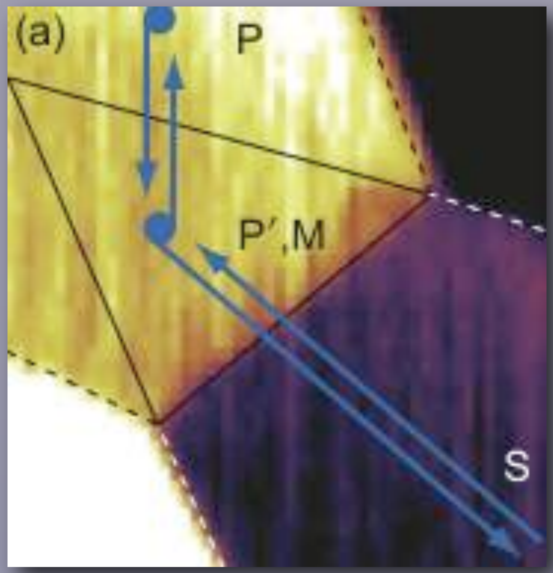
Summary





nanotubes can form gate-controlled dots with controlled hyperfine coupling





few-electron regime accessible using charge sensing readout

Both many-electron Pauli Blockade and two-electron T2* measurements indicate large hyperfine coupling in nanotubes