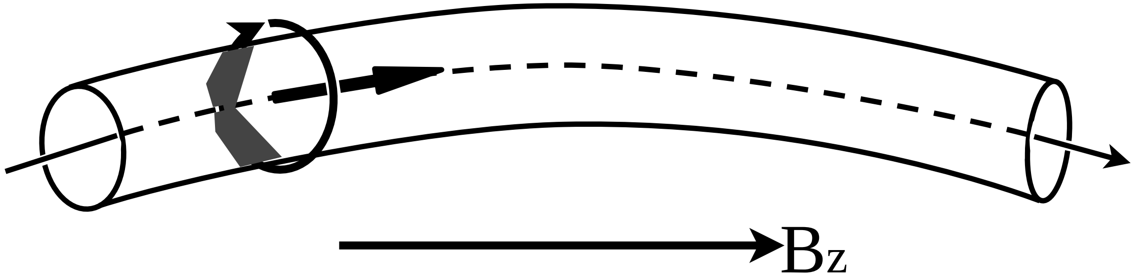
Coupling of spin and nanomechanical motion in carbon nanotubes

Mark Rudner

Niels Bohr Institute

16 July 2014



In collaboration with:

Emmanuel Rashba (*Harvard*)

Andras Palyi (*Eotvos*),Philipp Struck (*Konstanz*),Karsten Flensberg (*Copenhagen*),Guido Burkard (*Konstanz*)

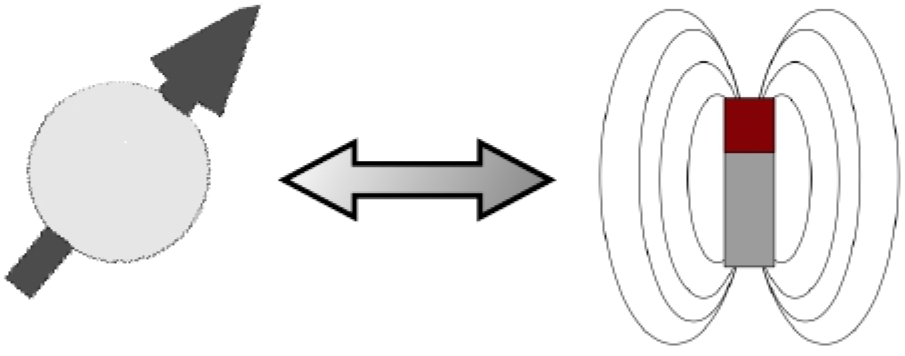
For details see:

MR and E. I. Rashba, Phys. Rev. B 81, 125426 (2010).

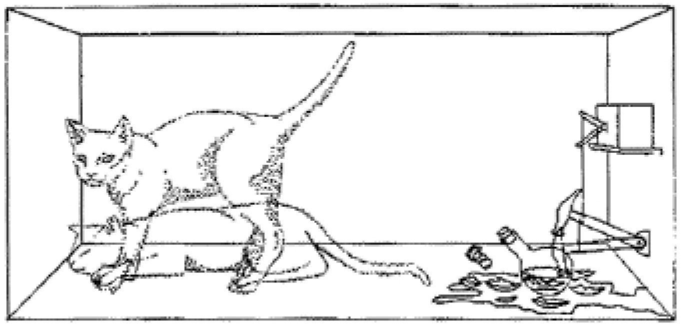
A. Palyi, P. R. Struck, MR, K. Flensberg, and G. Burkard,Phys. Rev. Lett. 108, 206811 (2012).

Understand,control,and exploit electronic properties beyond charge

Electron and nuclear spin



Quantum coherence/Entanglement



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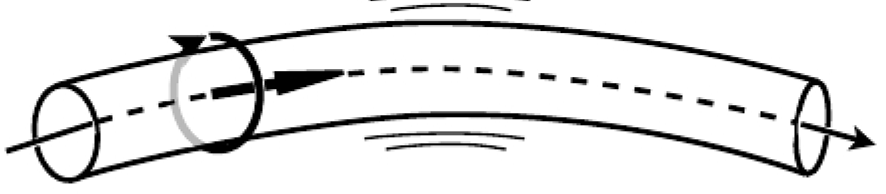
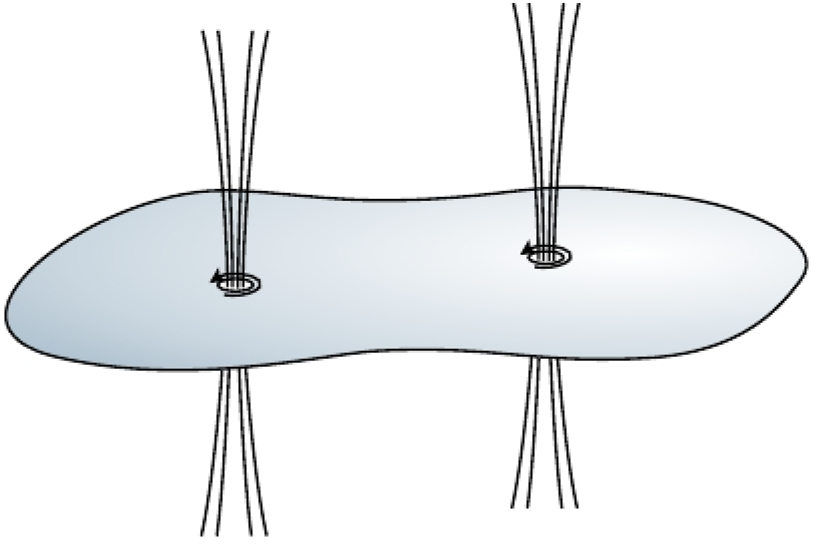
Nanomechanical motion (NEMS)



Exotic collective modes



Vibrant research community in Copenhagen

Copenhagen University

Center for Quantum Devices

The Niels Bohr International Academy

Microsoft® Research

Outline

I. Nanotube basics, spin-orbit coupling and phonons

II. Electron spin relaxation in CNT quantum dots

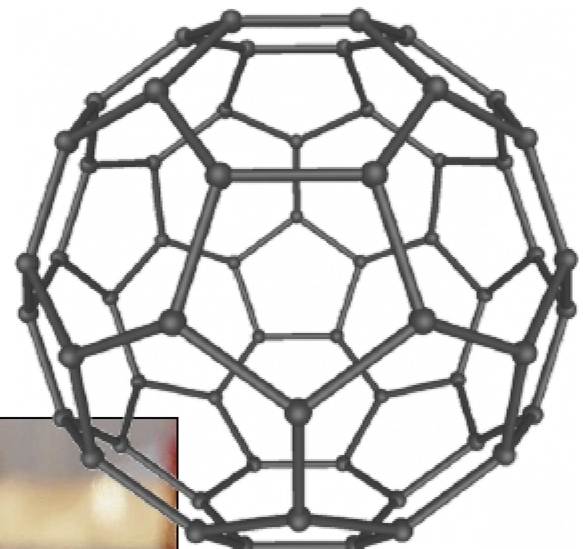
III. Coupling to phonon "cavity" mode in suspended CNT

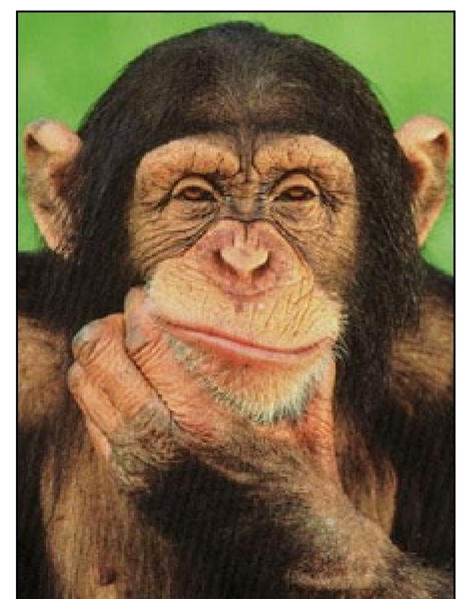
Experimental Inspiration:

H. O. H. Churchill, et al., Phys. Rev. Lett. 102, 166802 (2009).

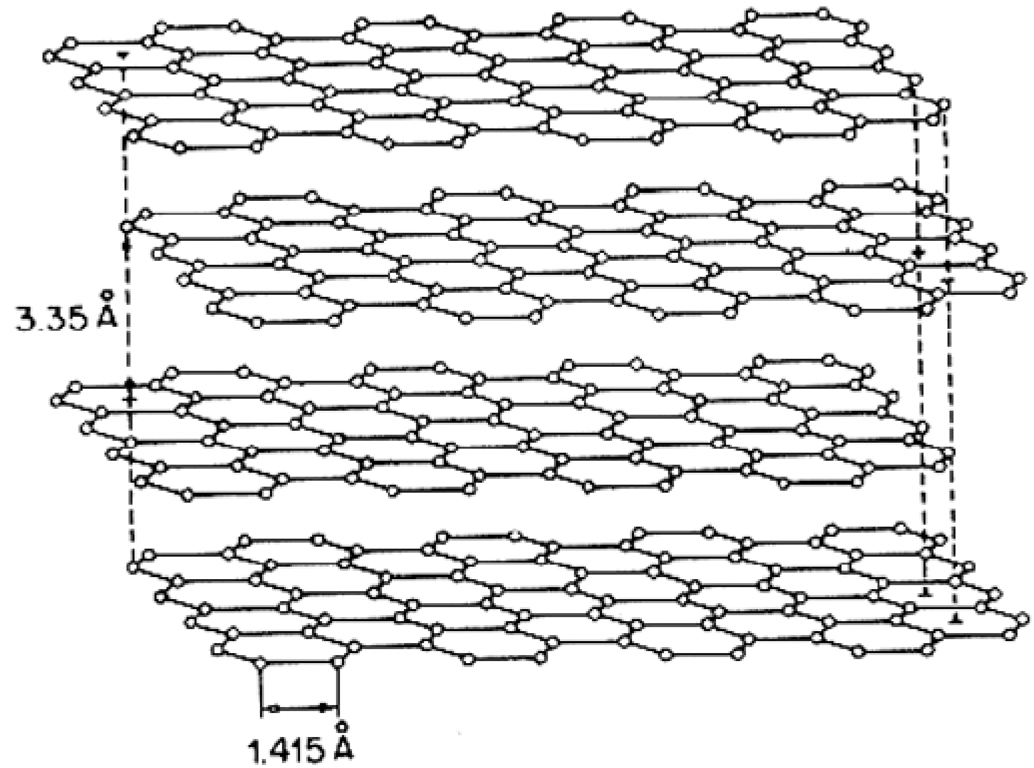
G. A. Steele, et al., Science 325, 1103 (2009).

In nature,carbon comes in many forms



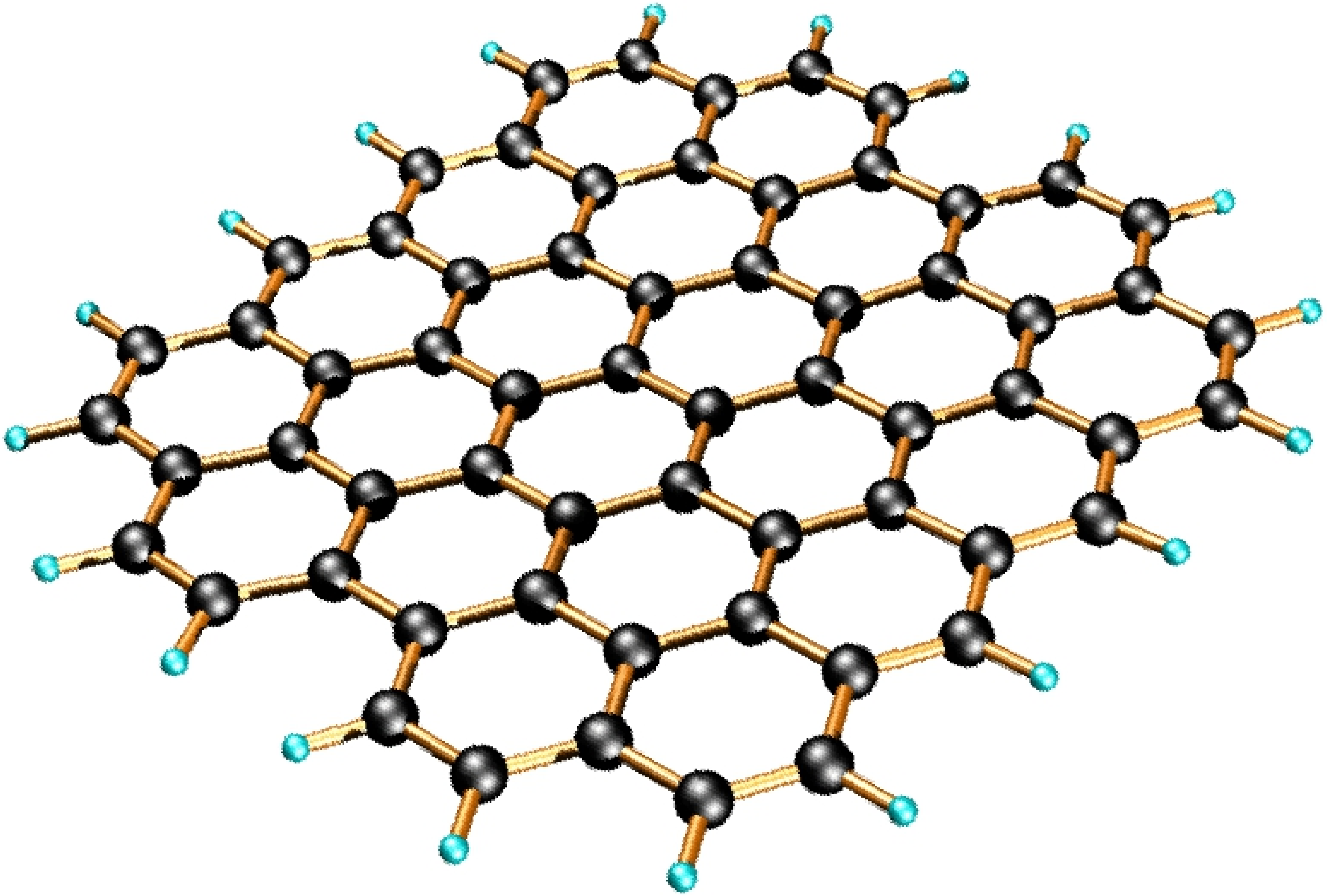


Graphite:stacked 2D sheets of carbon

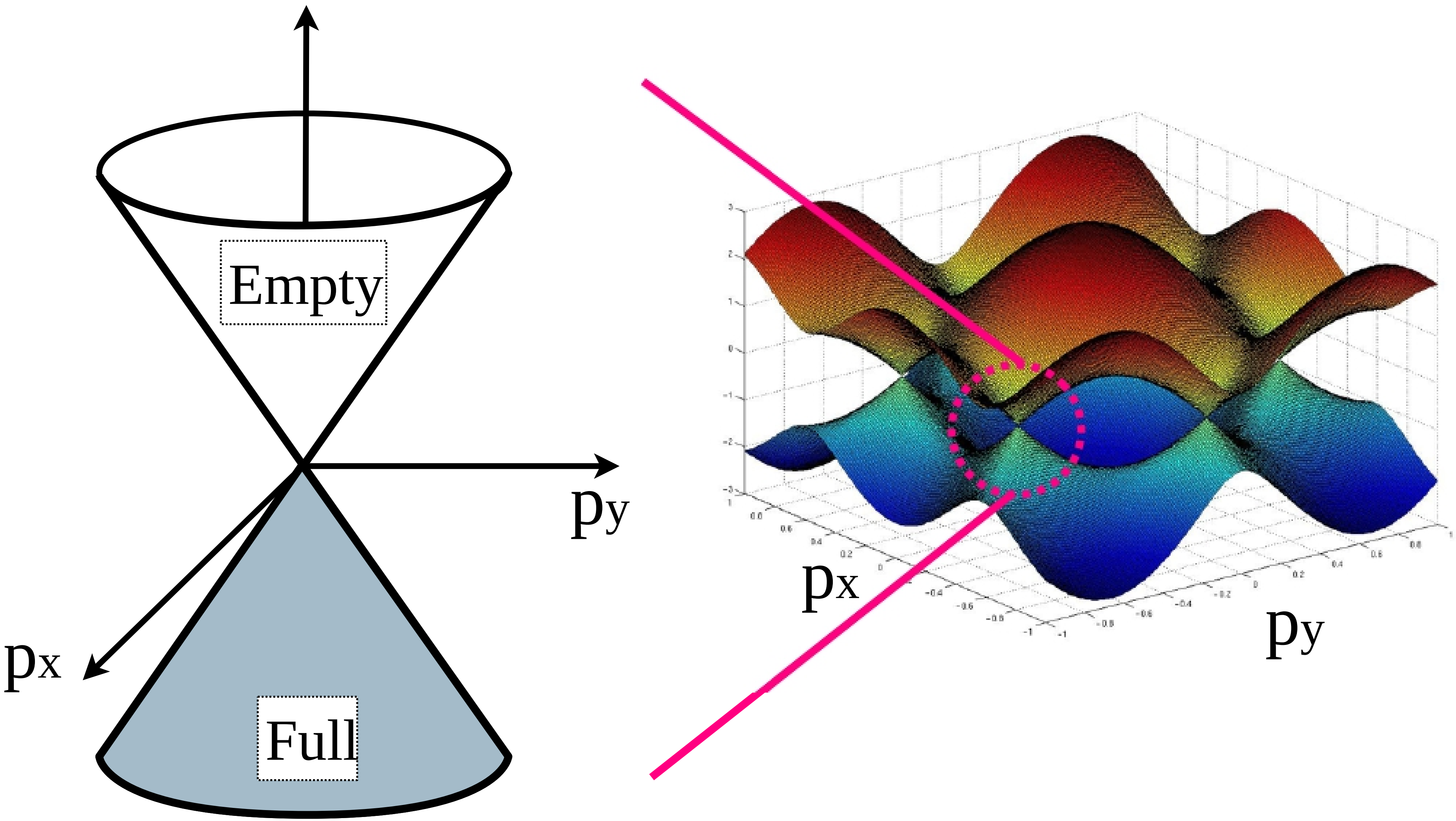


* Strong in-plane bonds,weak interaction between planes

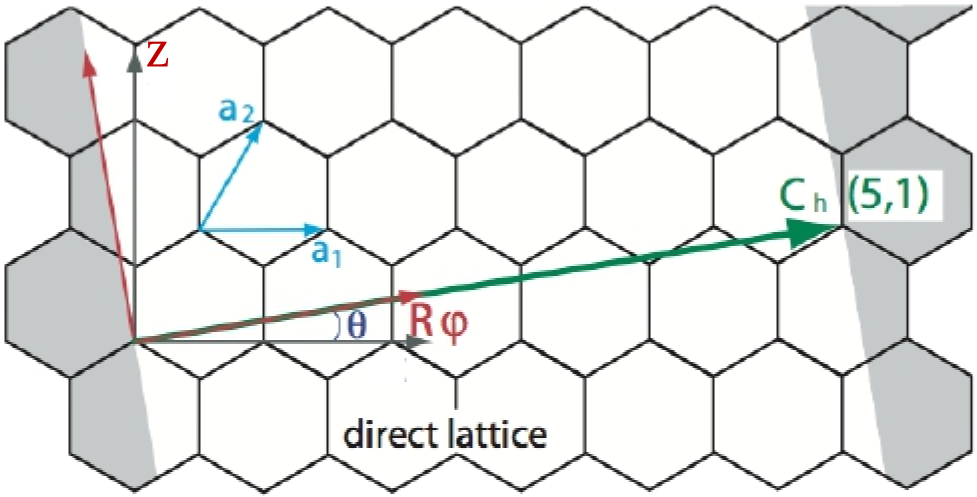
Graphene:a single atomic plane of carbon

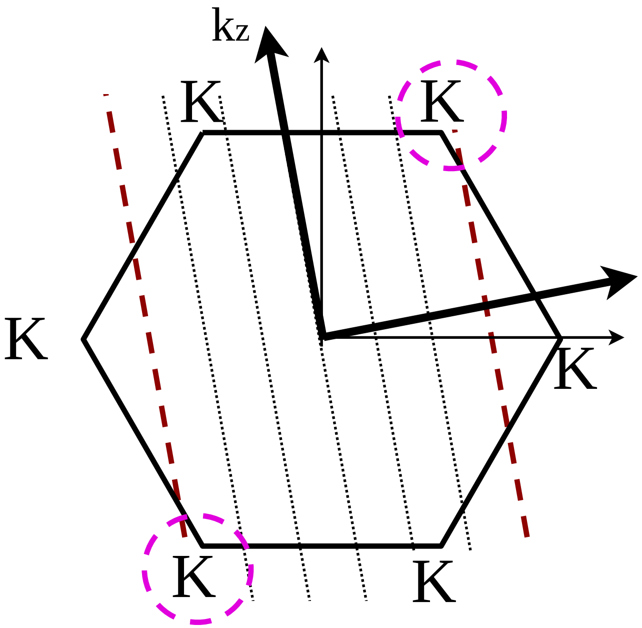


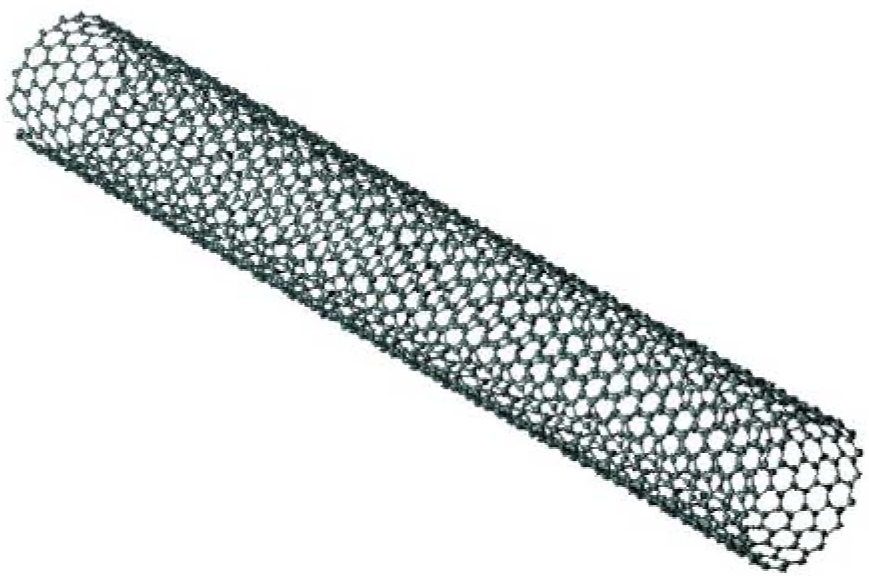
Conduction and valence bands touch at Fermi Level

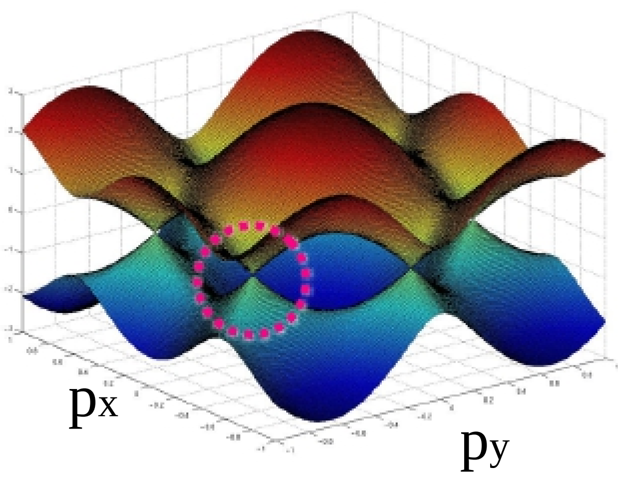


Nanotube formed by“rolling up” graphene

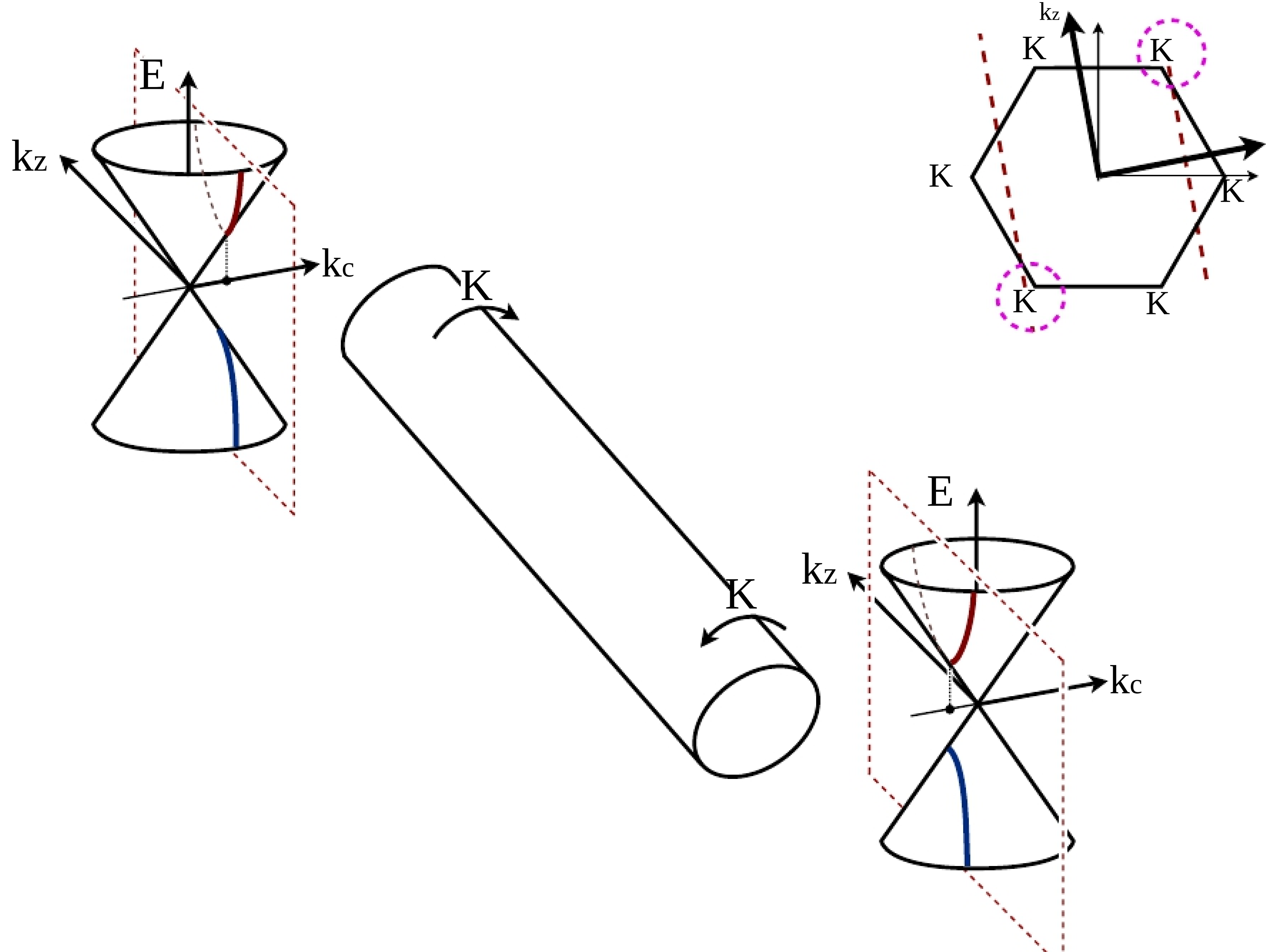




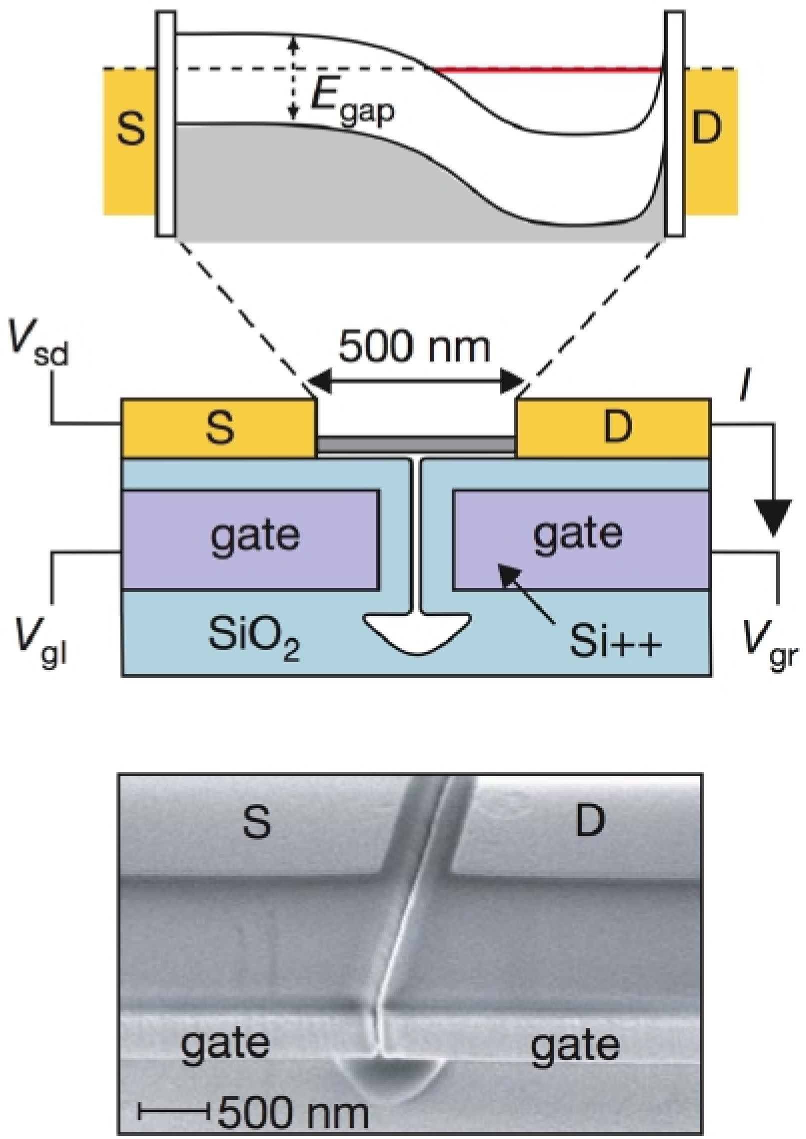




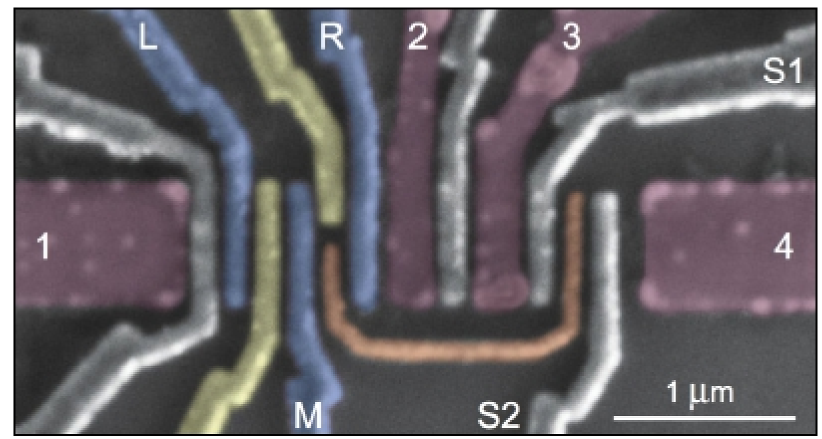
States nearKand K carry opposite circulating currents



Electrons confined to quantum dots via electrostatic gates



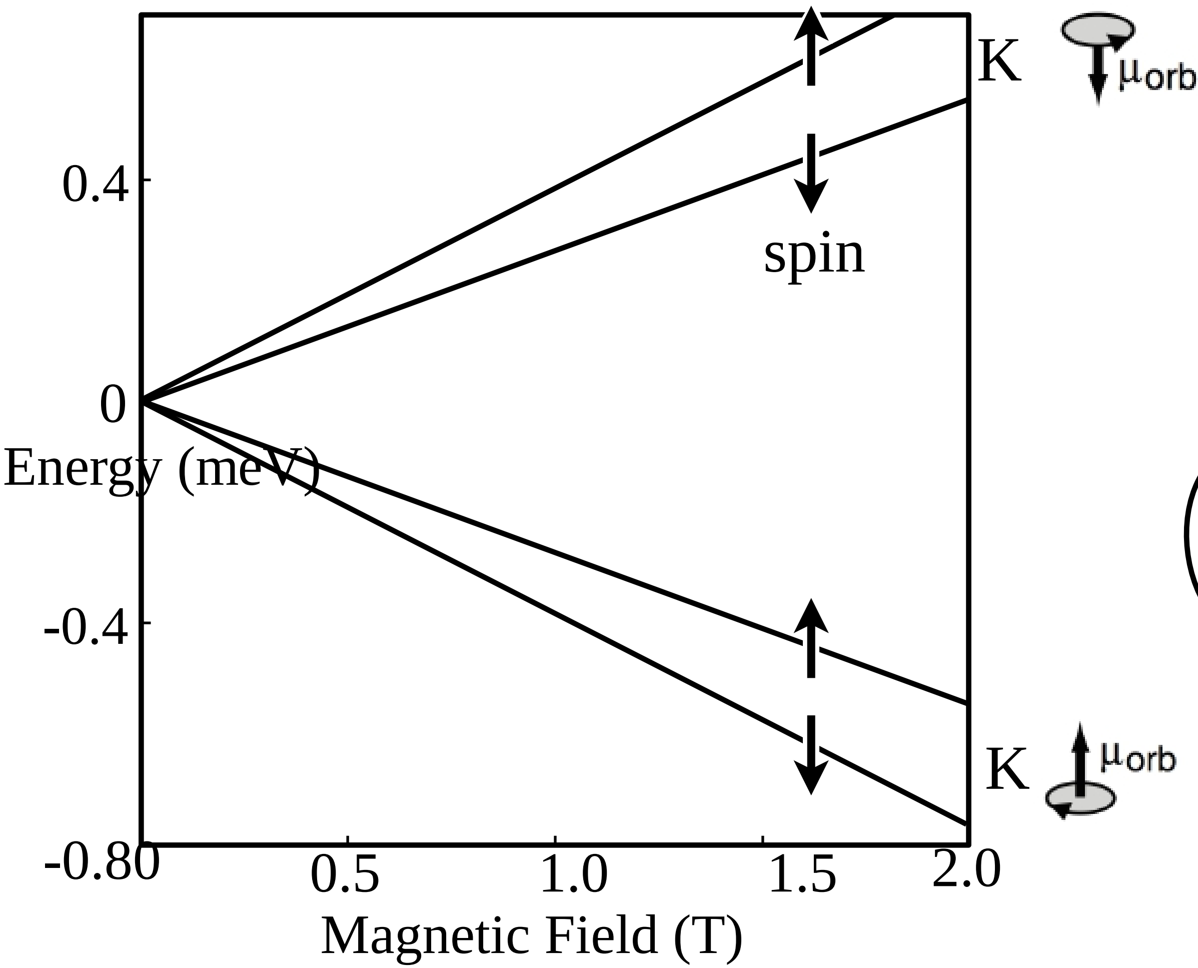
F.Kuemmeth,S.Ilani,D.C.Ralph,and P.L.McEuen,Nature **452**,448 (2008)

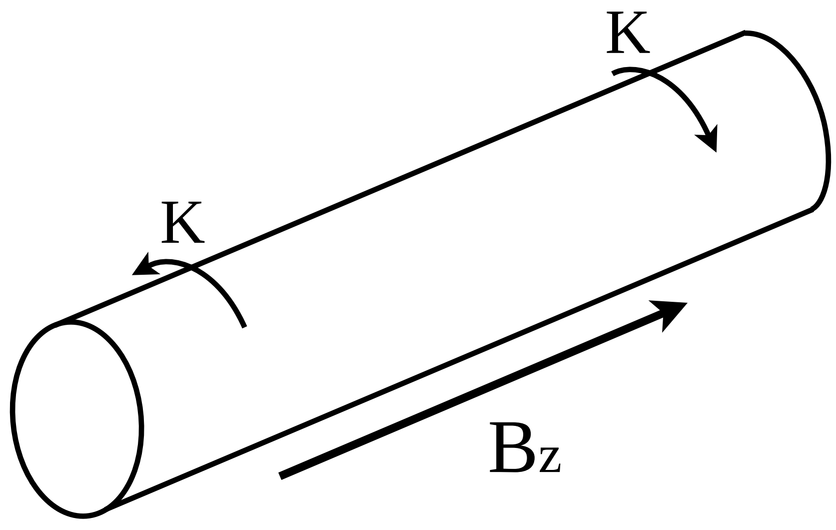


H.O.H.Churchill,et al.,Phys.Rev.Lett.**102**,166802 (2009)

Degeneracy lifted in applied field by orbital,spin moments

Single localized electron spectrum

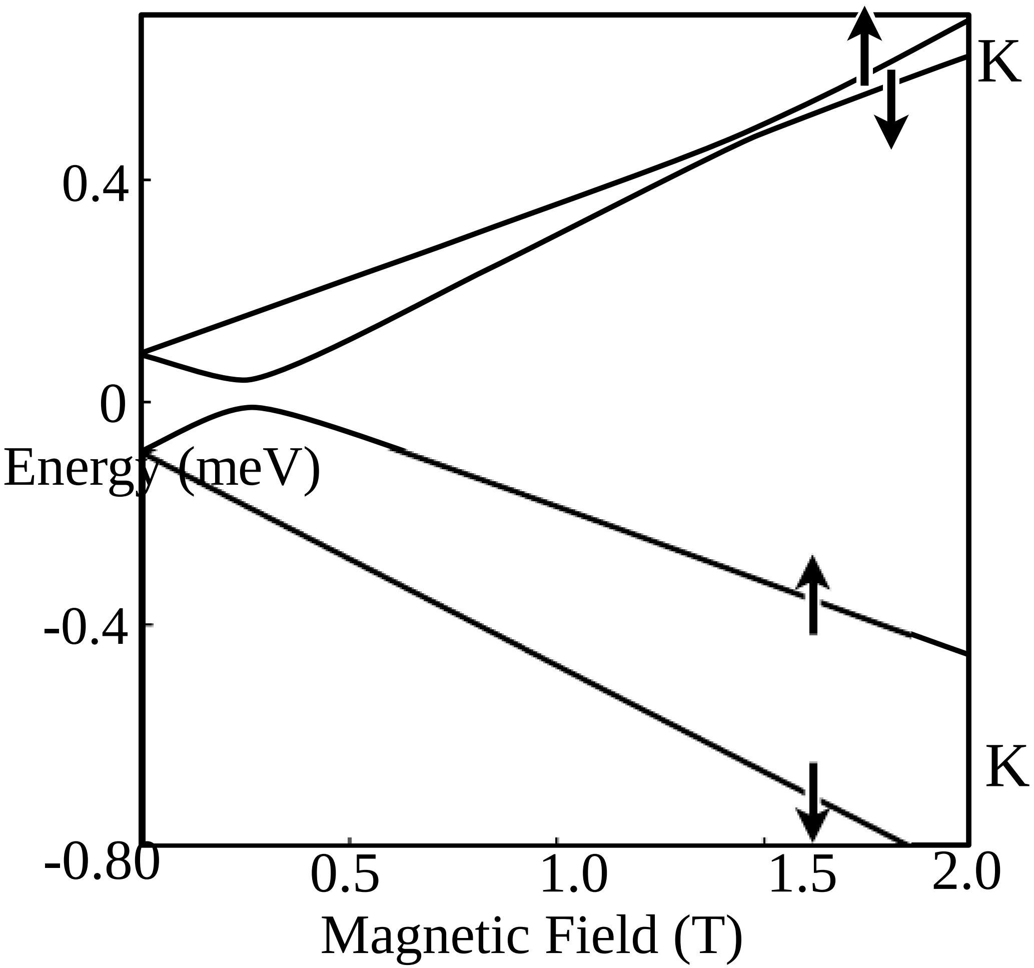




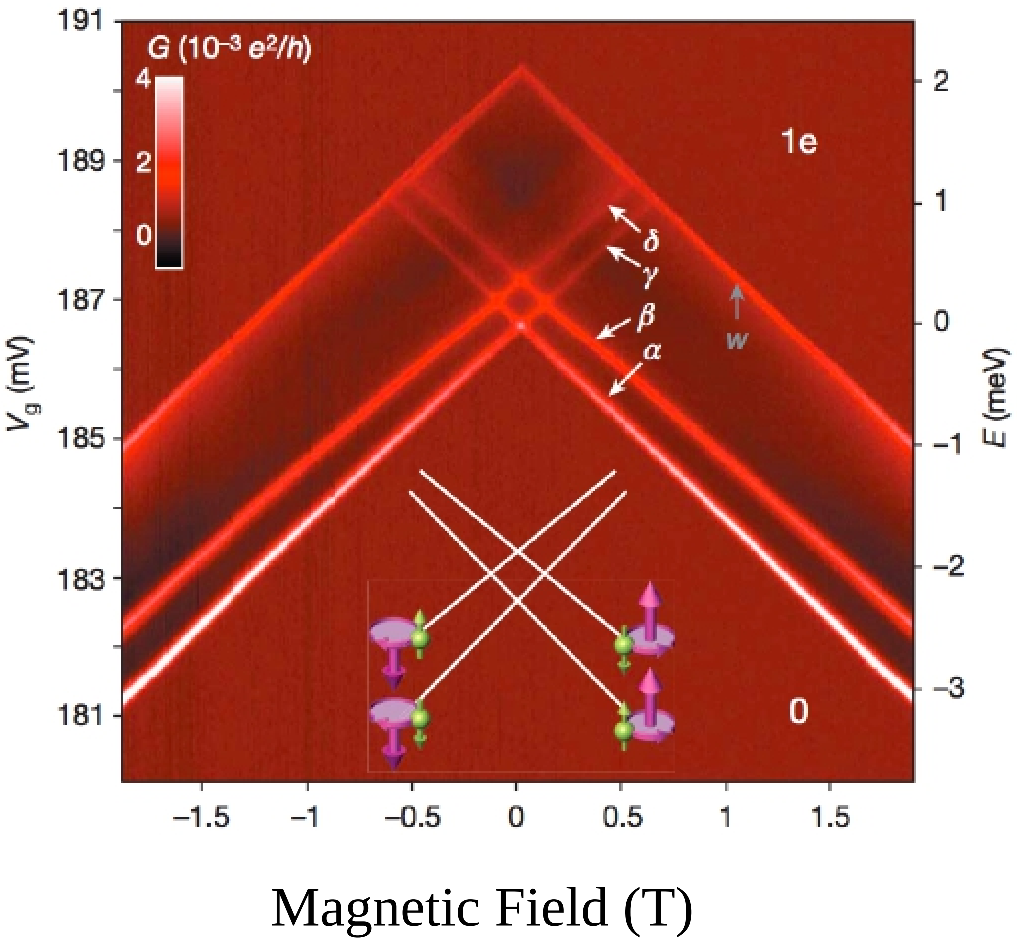
$$\mu_{orb} = \frac{eL}{2m_e} \quad 10\mu_B$$

Degeneracy partially lifted at B = 0 by spin-orbit coupling

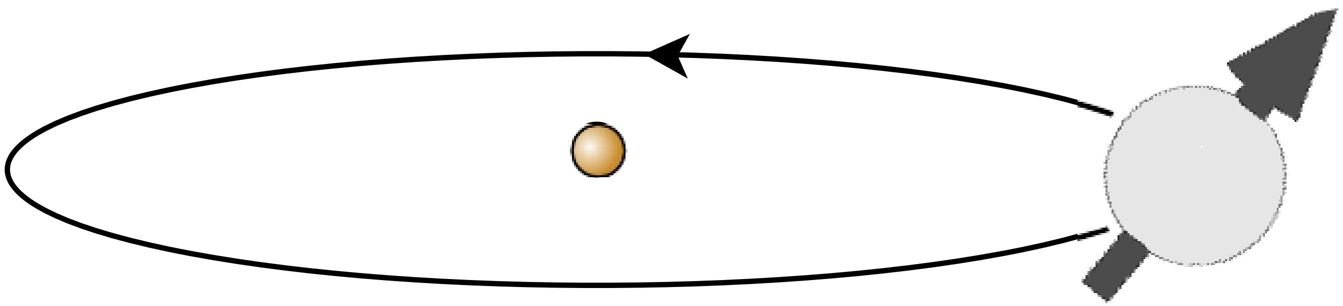
H.O.H.Churchill,et al.,Phys.Rev.Lett.**102**,166802 (2009)



F.Kuemmeth,S.Ilani,D.C.Ralph,and P.L.McEuen,Nature **452**,448 (2008)



Relativity: orbiting electron 'sees' magnetic field from nucleus

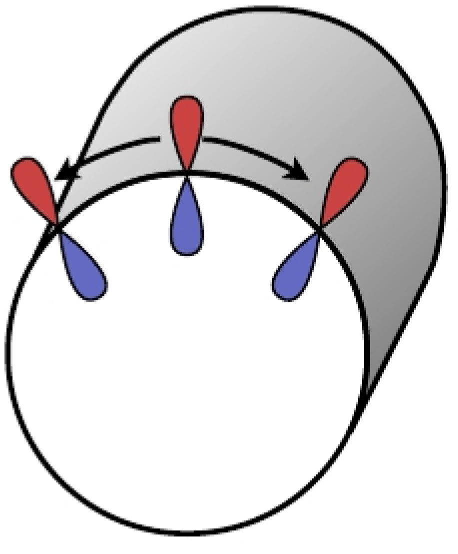


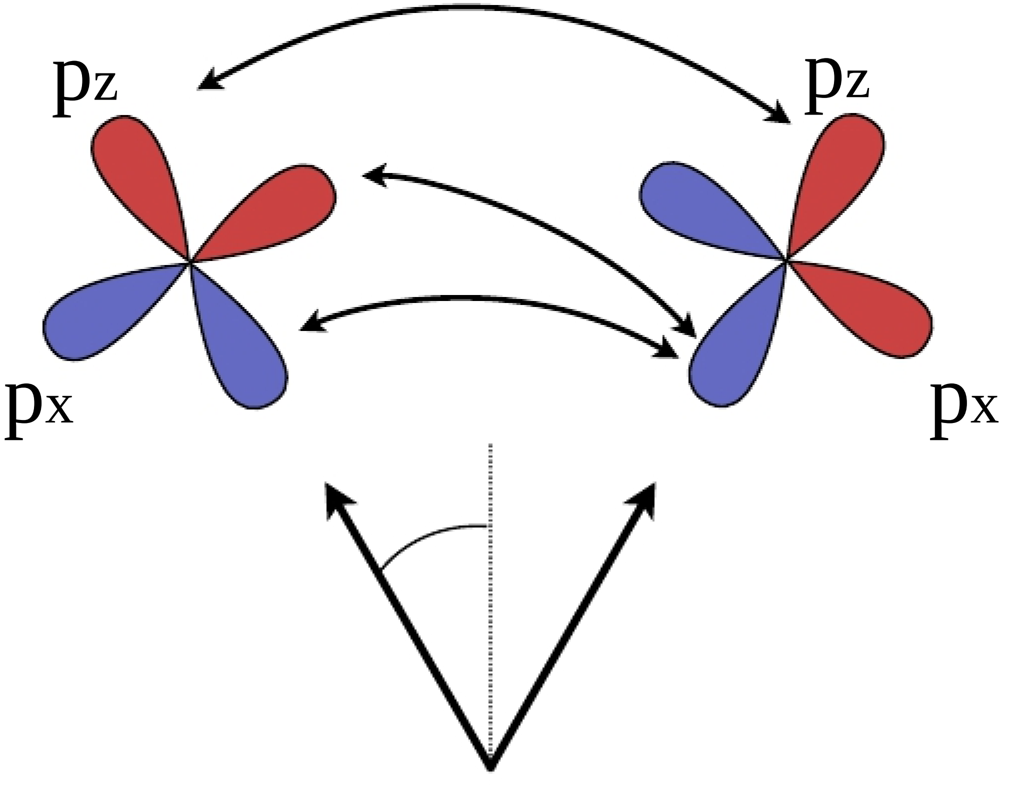
$$E_{SO} \leftarrow L \cdot S$$

orbital angular momentum (L)

spin (S)

(Atomic spin orbit) + (nanotube curvature) = sizable effect





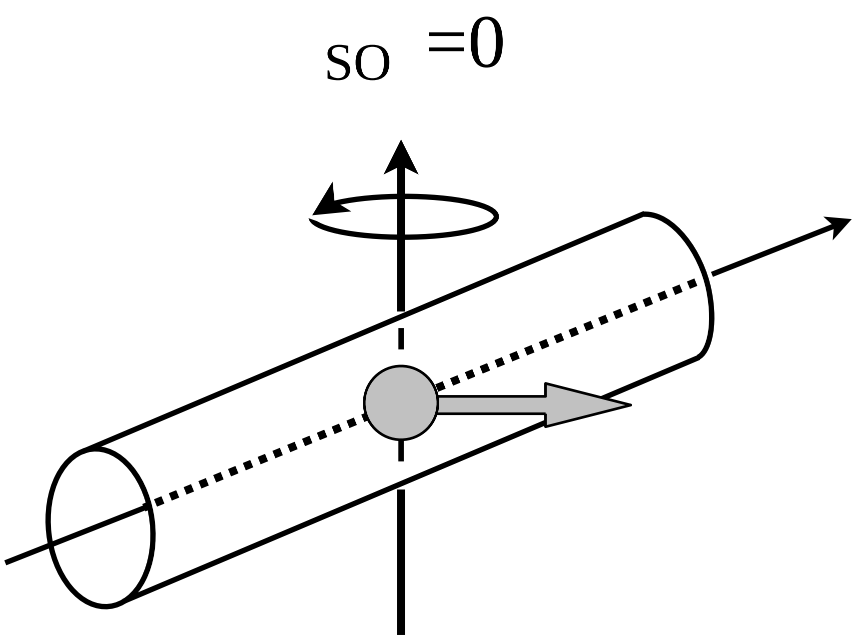
T.Ando,J.Phys.Soc.Japan **69**,1757 (2000)

D.Huertas-Hernando,F.Guinea,andA.Brataas,Phys.Rev.B **74**,155426 (2006)

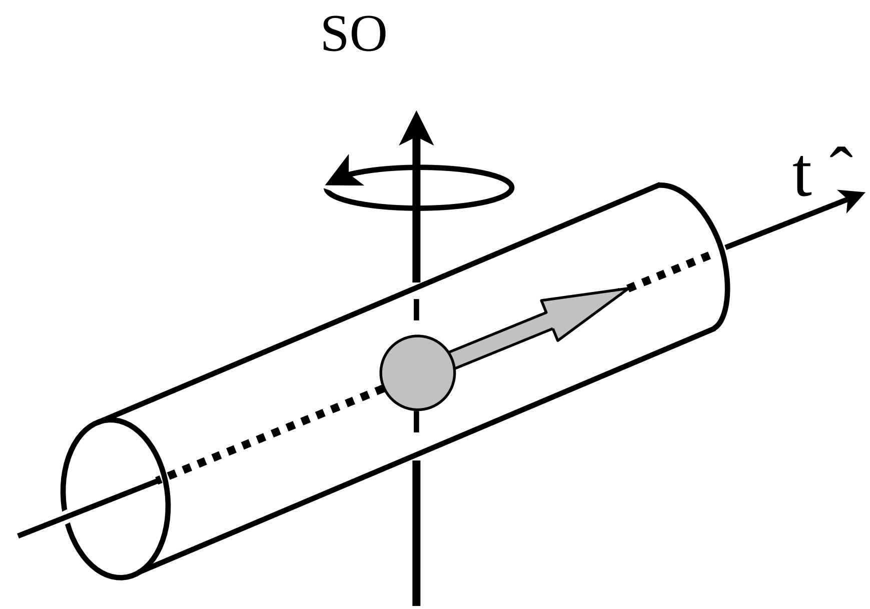
F.Kuemmeth,S.Ilani,D.C.Ralph,and P.L.McEuen,Nature **452**,448 (2008)

W.Izumida,K.Sato,and R.Saito,J.Phys.Soc.Japan **78**,074707 (2009)

Spin-orbit coupling"locks" spin to nanotube axis



Spin Stationary



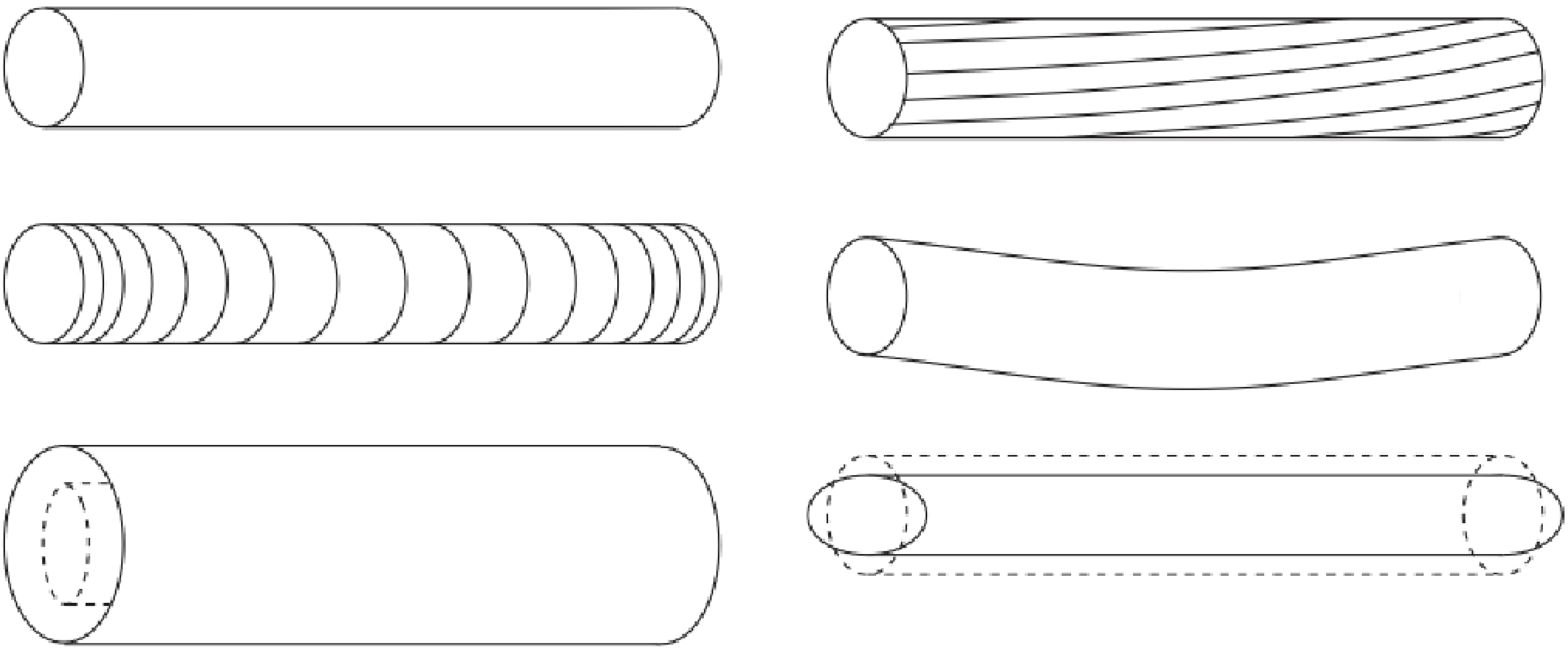
Spin Follows Tube

$$H_{SO} = \frac{SO}{2} \; {}_3(\hat{t} \cdot s)$$

+/- 1 for K/K' valley

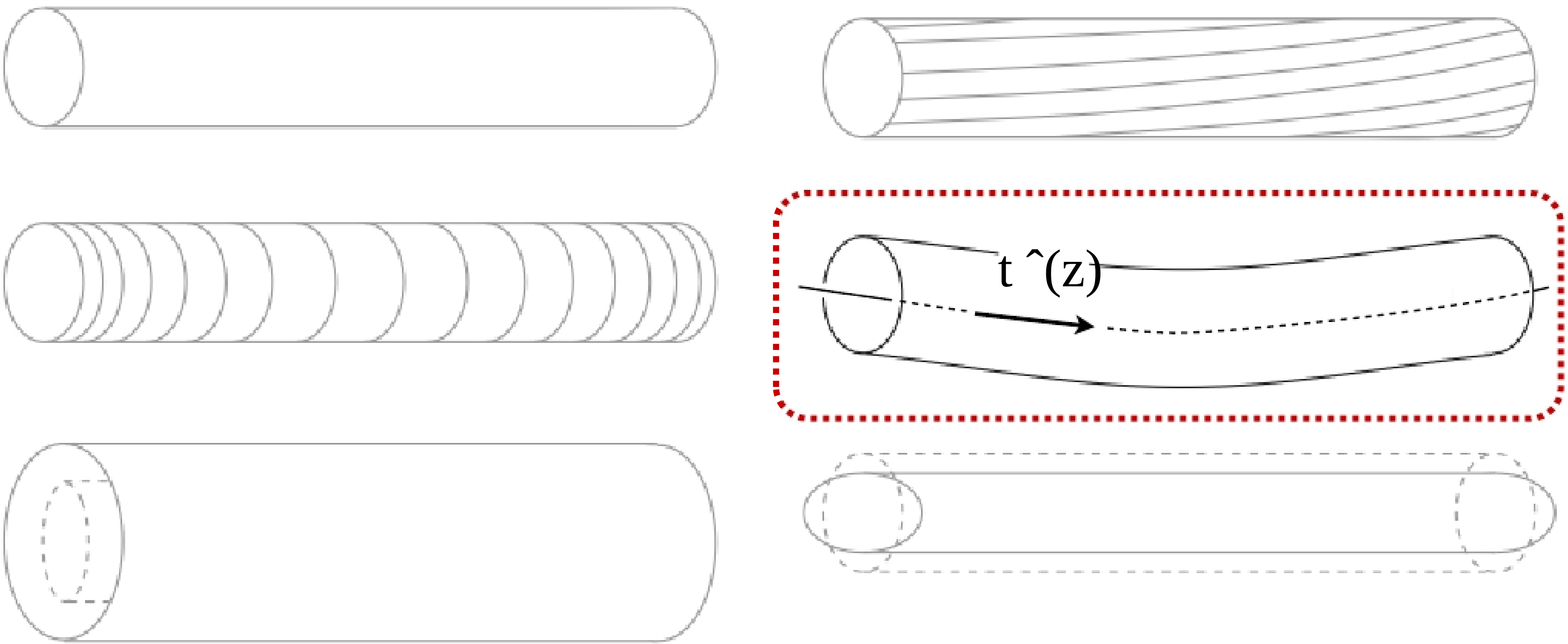
MR and E.I.Rashba,Phys.Rev.B **81**,125426 (2010)

Nanotube supports many vibrational modes



E.Mariani and F.von Oppen,Phys.Rev.B **80**,155411 (2009)
G.D.Mahan,Phys.Rev.B **65**,235402 (2002); H.Suzuura andT.Ando,Phys.Rev.B **65**,235412 (2002)

In flexural mode,local tube axis direction fluctuates



$_q = q^2$

E.Mariani and F.von Oppen,Phys.Rev.B **80**,155411 (2009)
G.D.Mahan,Phys.Rev.B **65**,235402 (2002); H.Suzuura andT.Ando,Phys.Rev.B **65**,235412 (2002)

Outline

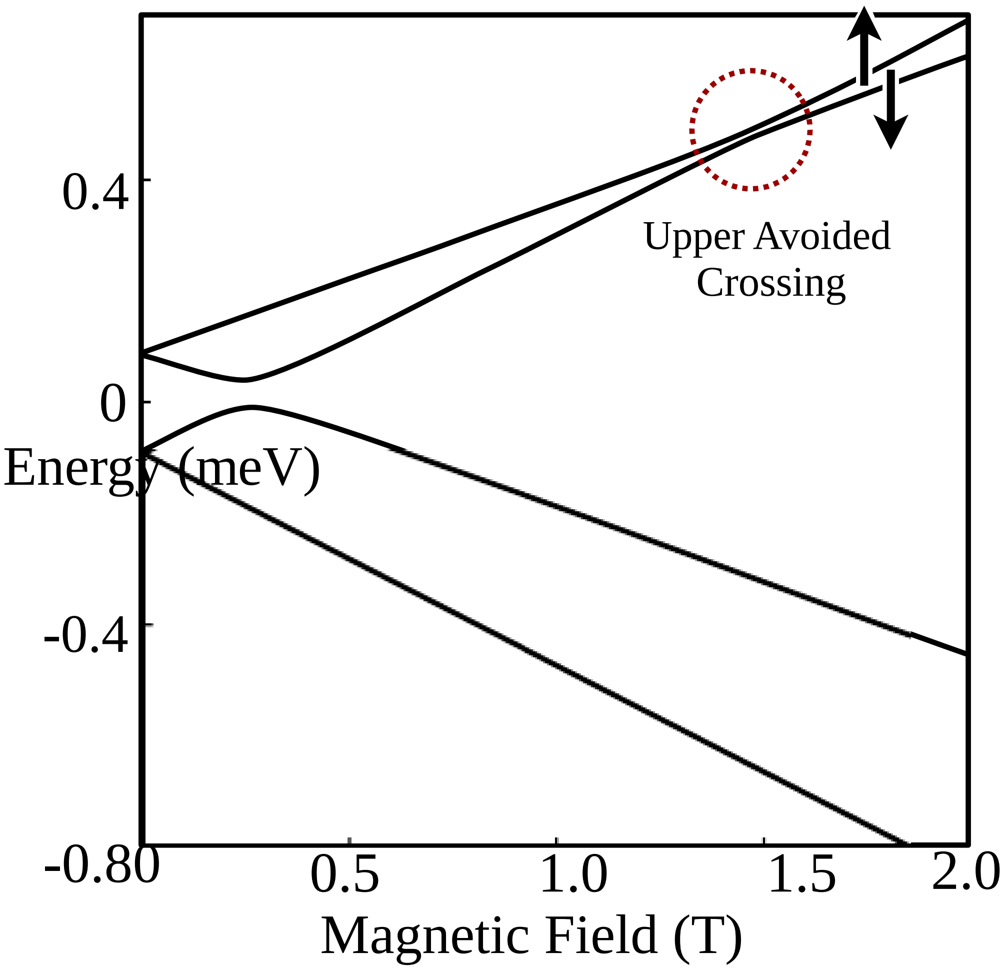
I. ~~Nanotubes basics,spin-orbit coupling and phonons~~

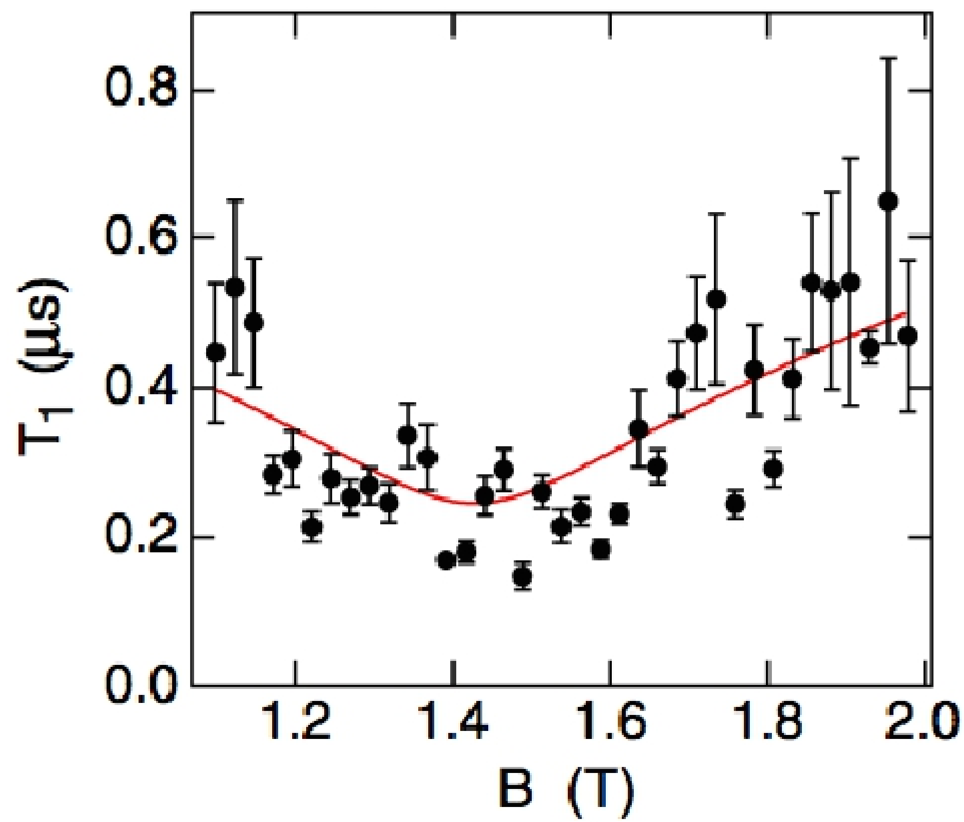
II.Electron spin relaxation in CNT quantum dots

III.Coupling to phonon“cavity” mode in suspended CNT

Observation:minimum in spin lifetime T1near narrow avoided level crossing

H.O.H.Churchill,et al.,Phys.Rev.Lett.**102**,166802 (2009)





Through spin-orbit interaction,spin couples to local direction of tube axis (deflection)

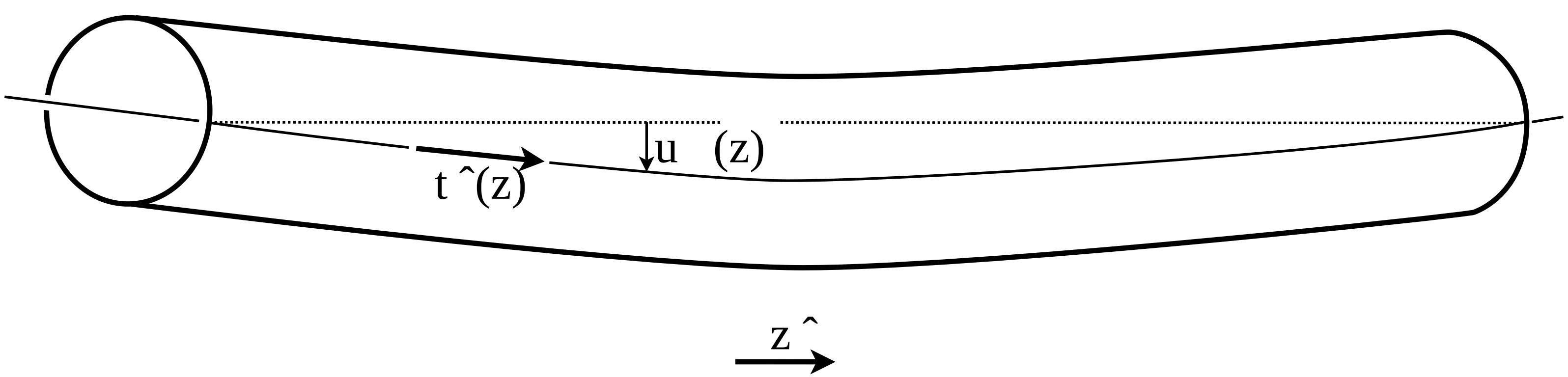
t ˆ(z) = z ˆ + du (z)/dz

Zero-order (unperturbed) Hamiltonian:

$$H_0 = \frac{SO}{2} \; 3 s_z \quad \mu_{orb} \; 3 B_z + \mu_B (s \cdot B)$$

Spin-deflection (phonon) coupling:

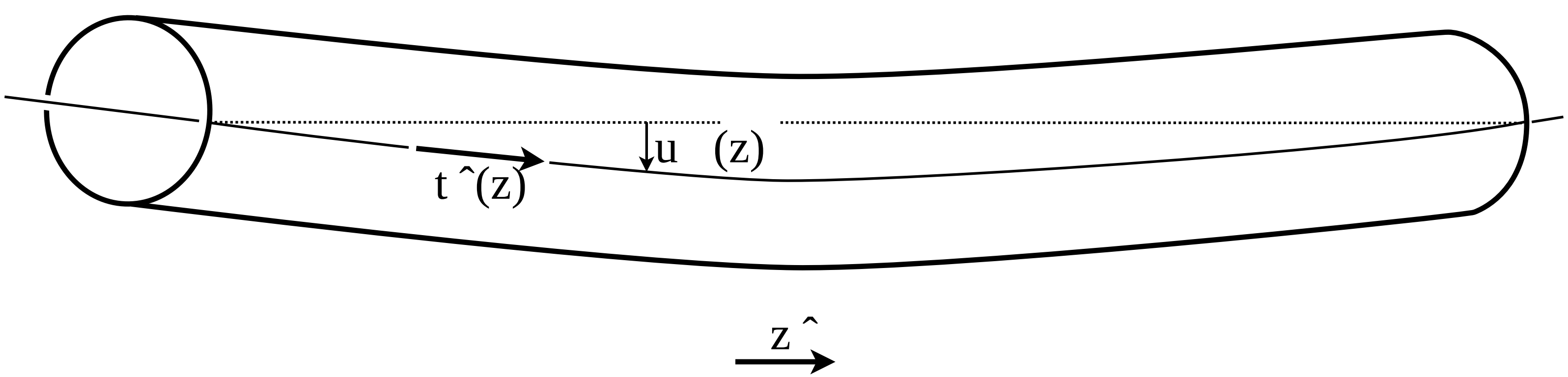
$$H_{s \; ph} = \frac{SO}{2} \; \frac{du}{dz} \cdot s \quad 3 \quad \mu_{orb} \; \frac{du}{dz} \cdot B \quad 3$$



Spin couples to phonons through deflections

$$u\ (z) = \sum_{q} \frac{}{2\ L_z\ \ q}\,\hat{x}\ (a_q\ + a^{\dagger}_{\ q})\,e^{iqz};\quad {}_q = \ \ q^2$$

	nanotube mass per unit length
L_z	nanotube length
$\hat{x}$	phonon polarization vector
$a^{\dagger}_{\ q}$	phonon creation operator



Calculate spin relaxation rate from Fermi's Golden Rule

$$W_{fi} = \frac{2}{\ {}^{2}} \left| \overline{\langle\ f | H_{s\ ph} | \ i \rangle} \right|^{2} \frac{L_z}{2} \left. \frac{dq}{d\ } \right|_{q=}$$

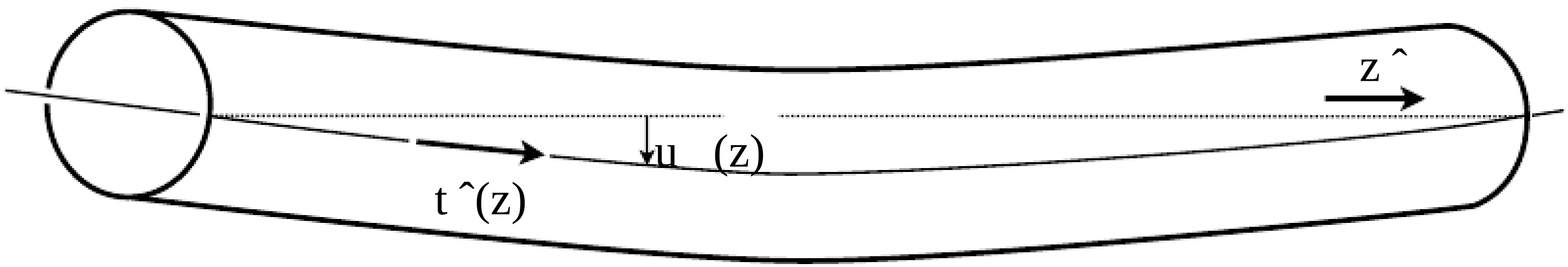
Overbar indicates average over thermal distribution of phonons

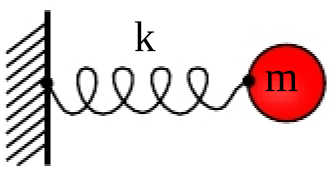
L_z	nanotube length
$\vert\ i$	electron initial state
$\vert\ f$	electron final state

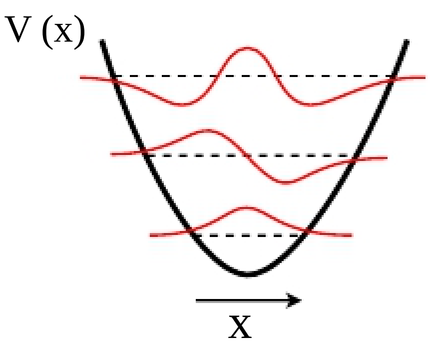
Vibration amplitudes grow large for long wavelengths

Normal modes: $u \quad Ae^{iqz}$, $\frac{du}{dz} \quad qA$

deflection brings down one factor of q







Vibration amplitude (rough estimate):

$$\frac{1}{2} m \quad ^2 \langle x^2 \rangle \quad \frac{1}{2} \langle E \rangle = \frac{1}{2} \quad (n + 1/2)$$

Low Temperature	High Temperature
$qA \quad q \cdot \frac{\quad}{M \quad_q} \quad$ const	$qA \quad q \cdot \frac{k_B T}{M \quad_{q}^{2}} \quad \frac{1}{q}$

$_q = \quad q^2$

Relaxation rate shows divergence at small energy transfer

$$W_{fi} = \frac{2}{\quad 2} \overline{| \; f \, | H_{s \quad ph} | \; i \; |^2} \, \frac{L_z}{2} \, \frac{dq}{d} \Big|_{q=}$$

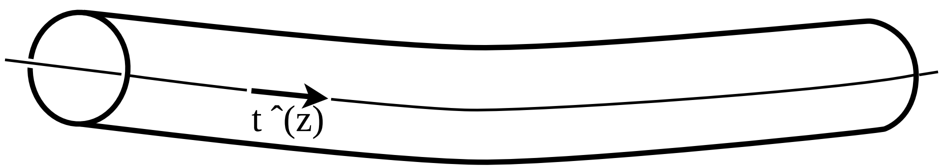
1)At low temperature, $\frac{du}{dz}$ const ;at high temperature, $\frac{du}{dz}$ $^{1/2}$

2)Van Hove singularity in density of states contributes factor of $^{1/2}$ to the rate

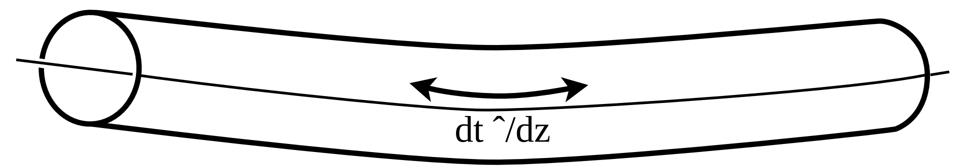
Low Temperature	High Temperature
$1/T_1 \quad ^{1/2}$	$1/T_1 \quad ^{3/2}$

Compare with“usual” deformation potential mechanism

Deflection q



Deformation q^2



Rate for deformation potential mechanism suppressed by relative factor q^2

Deflection	Deformation
<u>Low Temperature</u>	<u>Low Temperature</u>
$1/T_1 \propto$ $^{1/2}$	$1/T_1 \propto$ $^{1/2}$
<u>High Temperature</u>	<u>High Temperature</u>
$1/T_1 \propto$ $^{3/2}$	$1/T_1 \propto$ $^{1/2}$

D.V.Bulaev,B.Trauzettel,and D.Loss,Phys.Rev.B **77**,235301 (2008)

Outline

~~I.Nanotubes basics,spin orbit coupling and phonons~~

~~II. Electron spin relaxation in CNT quantum dots~~

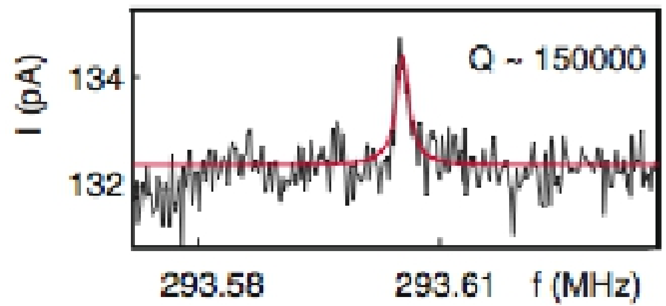
III.Coupling to phonon“cavity” mode in suspended CNT

Ultraclean suspended CNTs act as“phonon cavity”

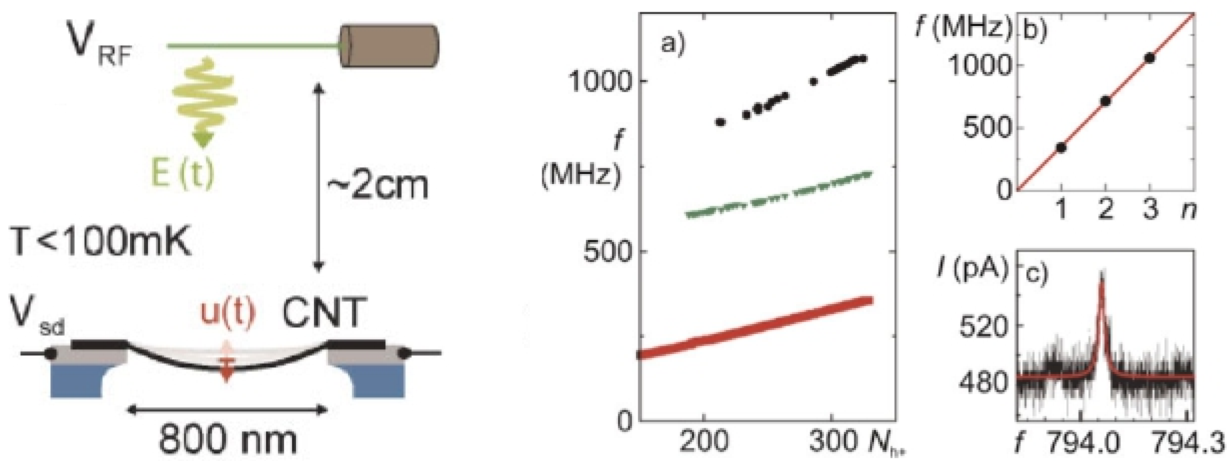
Strong Coupling Between Single-Electron Tunneling and Nanomechanical Motion

G. A. Steele,* A. K. Hüttel,† B. Witkamp, M. Poot, H. B. Meerwaldt, L. P. Kouwenhoven, H. S. J. van der Zant

G.A.Steele et al.,Science **325**,1103 (2009)



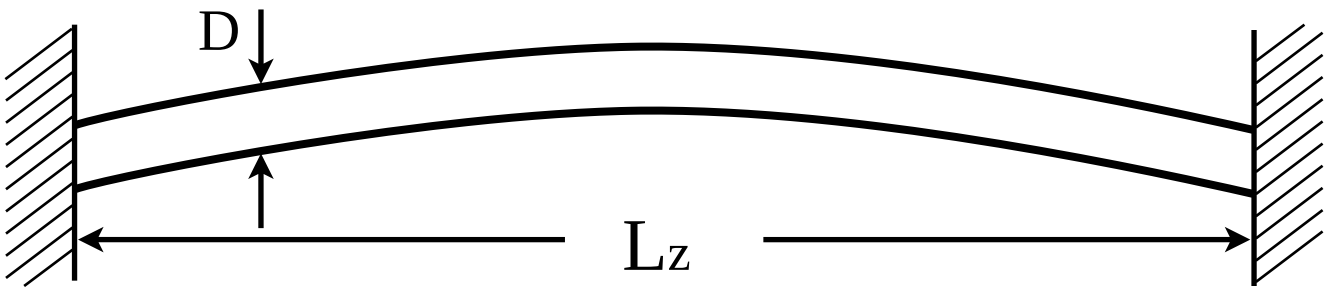
A quality factor exceeding 10^5



A.K. H¨uttel, et al., Phys. Status Solidi B 247, 2974 (2010).

see also:B.Lassagne et al.,Science **325**,1107 (2009)

Outlook:strong (coherent) coupling regime within reach



q Lz

→q = q2

Coupling strength:

H → g(→+a ˆ + → a ˆ†), g = SO / 2 2M 10 neV

Zeeman energy,oscillator frequency:

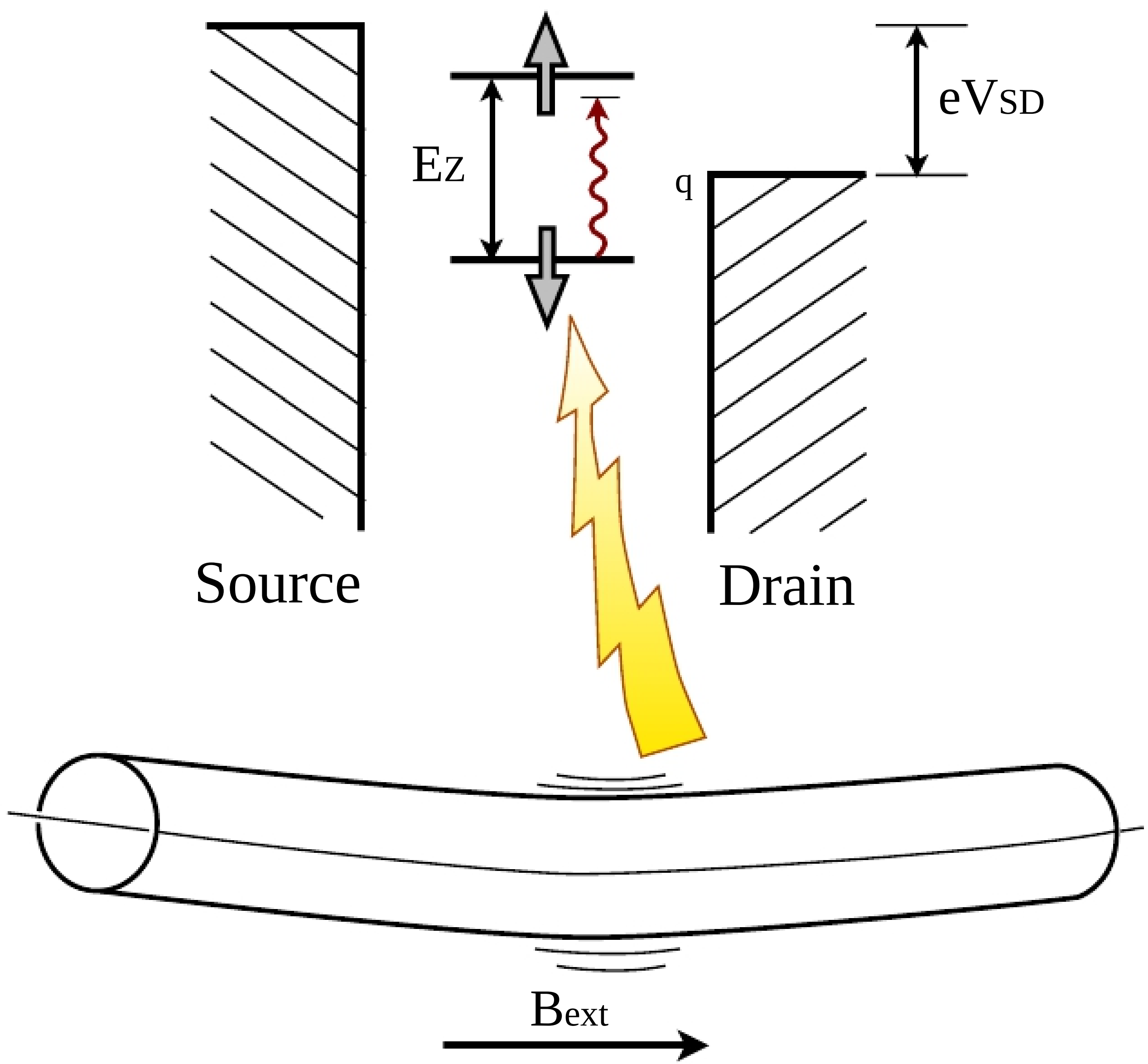
Ez q kBT = 10 μeV

Coupling parameter:

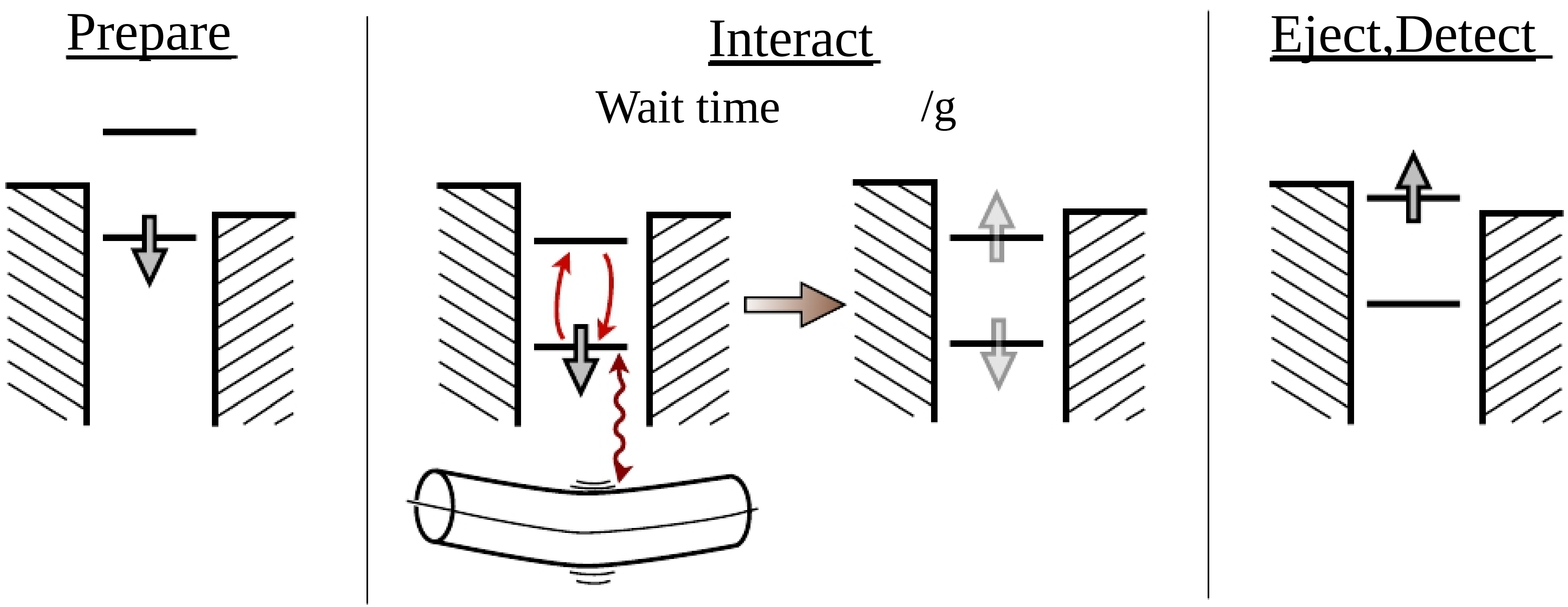
g Q / q 10 100

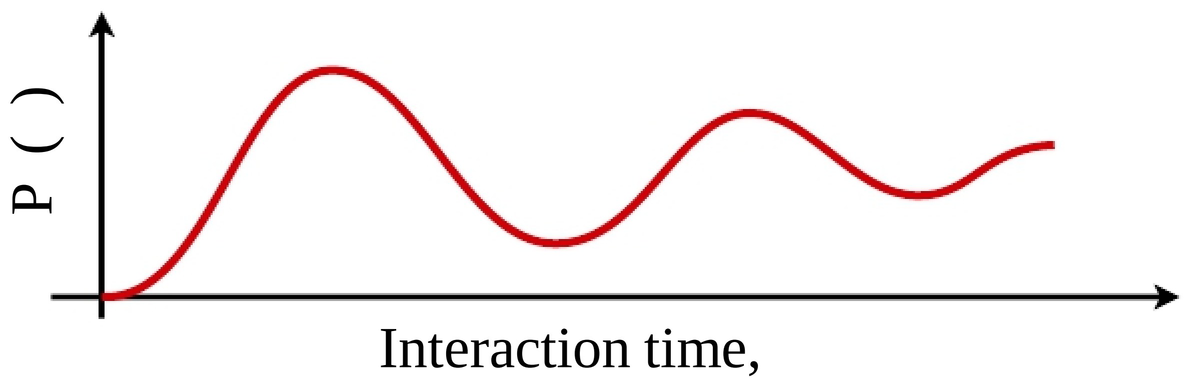
M = DLz→s
s = 10 24 kg/nm 2
10 4 μeVnm 2
Q 10 5

Coupling leads to enhancement of transport near resonance



Pulsed gate measurements may reveal coherent oscillations





Sense motion of CNT via coupling to microwave cavity?

Concern:typical vibration amplitudes in 1-10 pm range

Possible solution:use large electron number to get sizable dipole moment

Gate-dependent spin–orbit coupling in multielectron carbon nanotubes

T. S. Jespersen[1*†], K. Grove-Rasmussen[1,2*†], J. Paaske[1], K. Muraki[2], T. Fujisawa[3], J. Nygård[1] and K. Flensberg[1]
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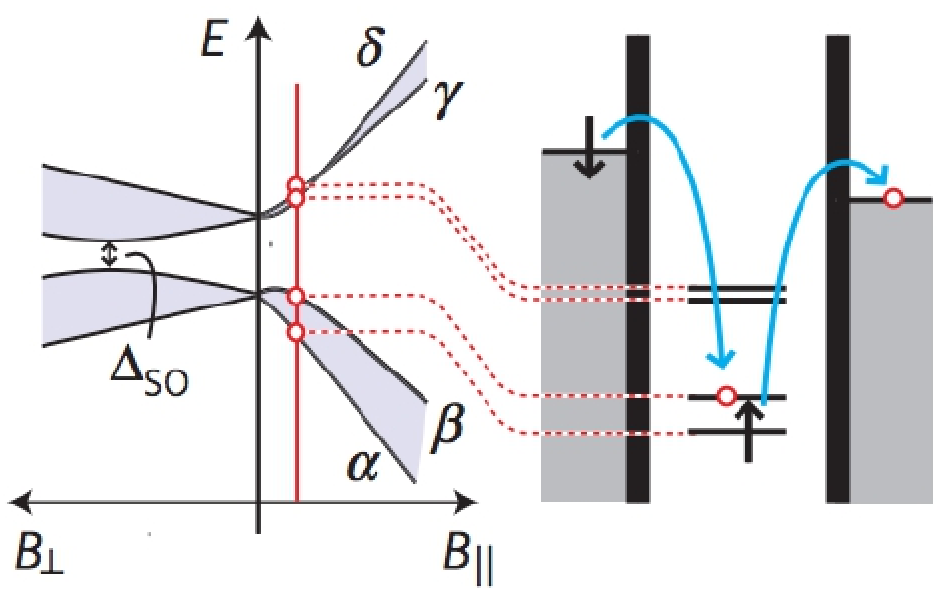
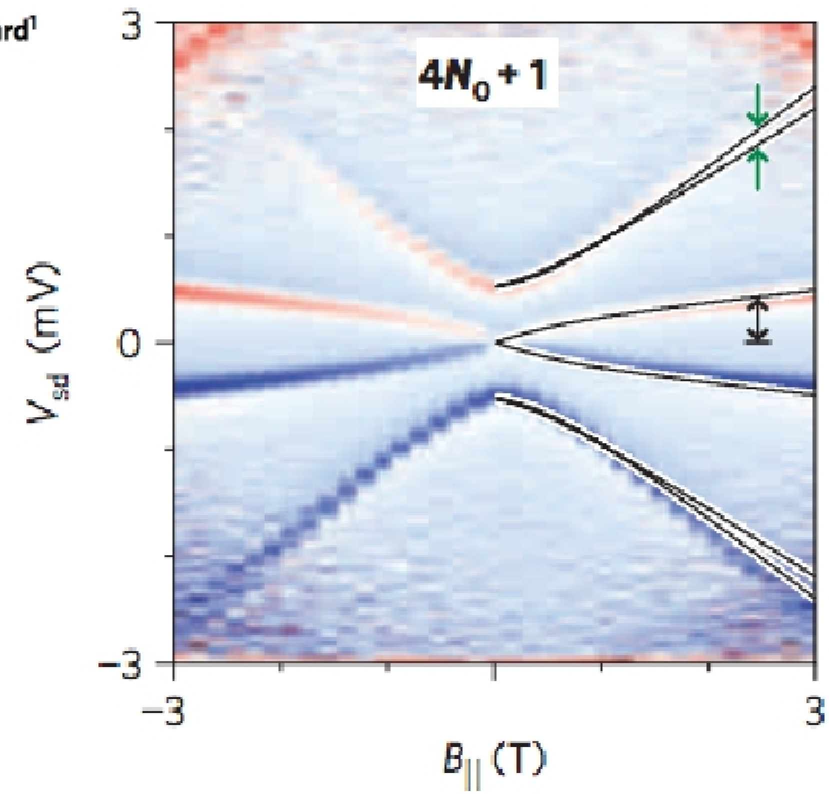


$4N_0$ 180



Quantum dots in suspended CNTs might make good qubits

- CNTs can be grown nearly nuclear spin free
- Phonon cavity eliminates bath density of states at qubit energy
- Coupling to external antenna for electrical control,readout
- ? Measurement sensitivity?
- ? Multi-qubit coupling?
- Difficult to fabricate