Not a quantum box: tuning the shape of an electron in a carbon nanotube quantum dot[1]

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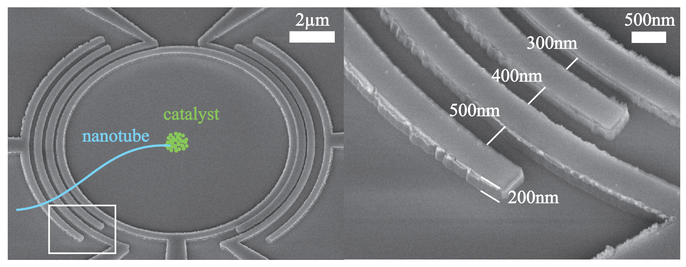
Transport spectrum, $T \approx 25\,\mathrm{mK}$

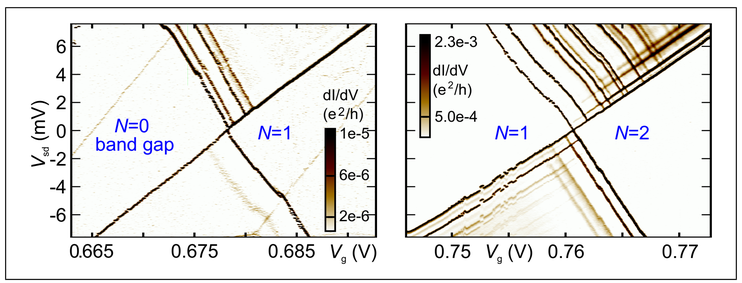


- Carbon nanotubes grown *in situ* across contacts

→ No chemical or mechanical damage

→ No resist residues, no e-beam irradiation

- Clean few-electron system [2, 3, 1]
- Spectroscopy of one- and two-electron states



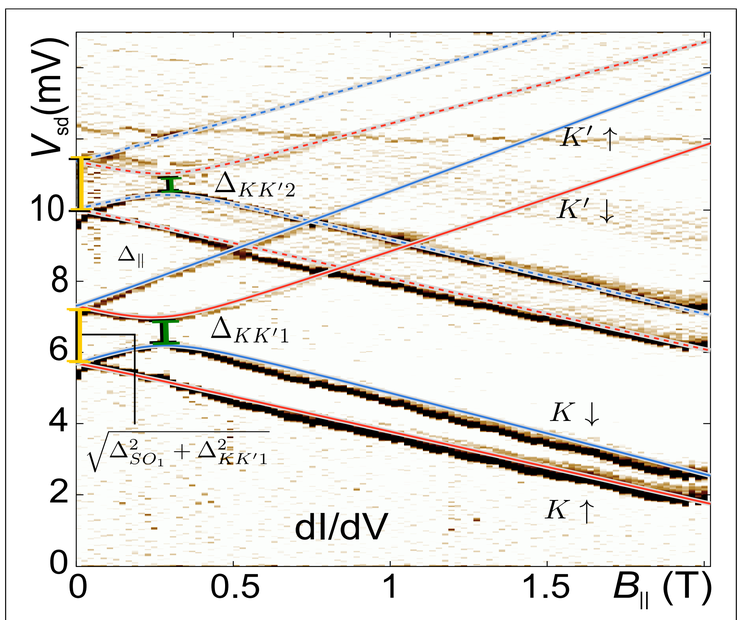
Low-field behaviour

- Linearized single particle Hamiltonian

$$\hat{H}_{\mathrm{CNT}} = \underbrace{\varepsilon_d \hat{I}_\sigma \otimes \hat{I}_\tau}_{\text{“shell”}} + \underbrace{\frac{\Delta_{\mathrm{KK'}}}{2} \hat{I}_\sigma \otimes \hat{\tau}_z}_{\text{valley mixing}} + \underbrace{\frac{\Delta_{\mathrm{SO}}}{2} \hat{\sigma}_z \otimes \hat{\tau}_x}_{\text{spin-orbit interaction}} +$$

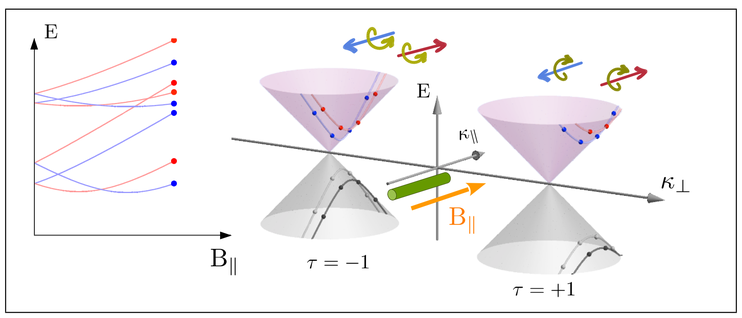
$$+ \underbrace{\frac{g_s \mu_B |\vec{B}|}{2} (\cos\varphi\, \hat{\sigma}_z + \sin\varphi\, \hat{\sigma}_x) \otimes \hat{I}_\tau}_{\text{Zeeman effect}} +$$

$$+ \underbrace{g_{\mathrm{orb}} \mu_B |\vec{B}| \cos\varphi\, \hat{I}_\sigma \otimes \hat{\tau}_x}_{\text{orbital angular moment}}$$



- High-level parameters Δ_{SO}, $\Delta_{\mathrm{KK'}}$, $\Delta_{||}$, ...
- Fit has additional corrections

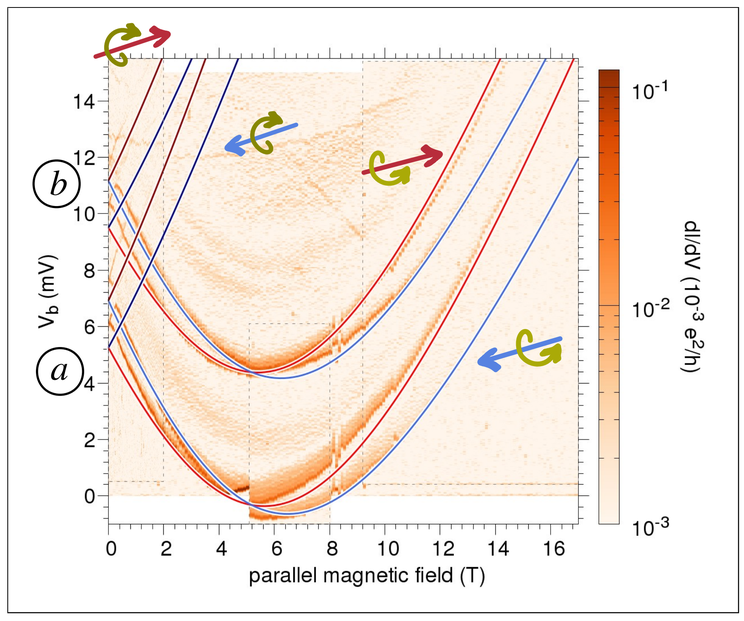
Full dispersion relation [4]



$$E_\pm(\tau,\sigma,\kappa_{||},B_{||}) = \tau\sigma\varepsilon_{\mathrm{SO}} + \sigma\mu_B B_{||} +$$

$$+ \hbar v_F \sqrt{\left(\tau\Delta k_\perp + \sigma\Delta k_{\mathrm{SO}} + \frac{\pi R}{\phi_o} B_{||}\right)^2 + \kappa_{||}'^2}$$

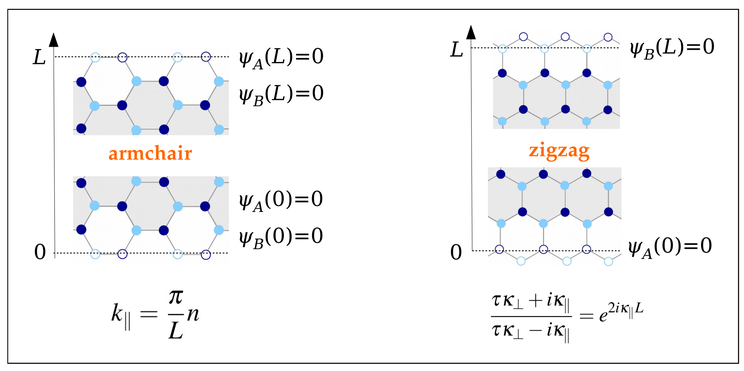
High field behaviour



Questions

- Amplitude variation of the conductance peaks
  - Magnetic field dependence of tunnel rates
  - Modification of electronic wave function?
- Deviation of the slopes $\mathrm{d}E/\mathrm{d}B_{||}$
  - Anomalous magnetic moments?
- Second “longitudinal shell” (?) at very low energy
  - Shell spacing / momentum quantization not consistent with a box potential

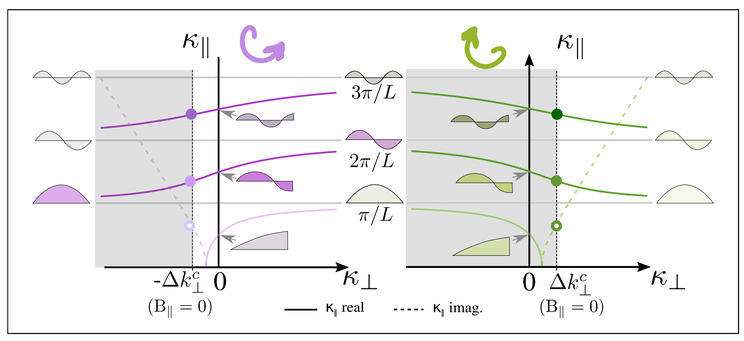
Boundary conditions [5]



$$k_{||} = \frac{\pi}{L} n \qquad \frac{\tau\kappa_\perp + i\kappa_{||}}{\tau\kappa_\perp - i\kappa_{||}} = e^{2i\kappa_{||}L}$$

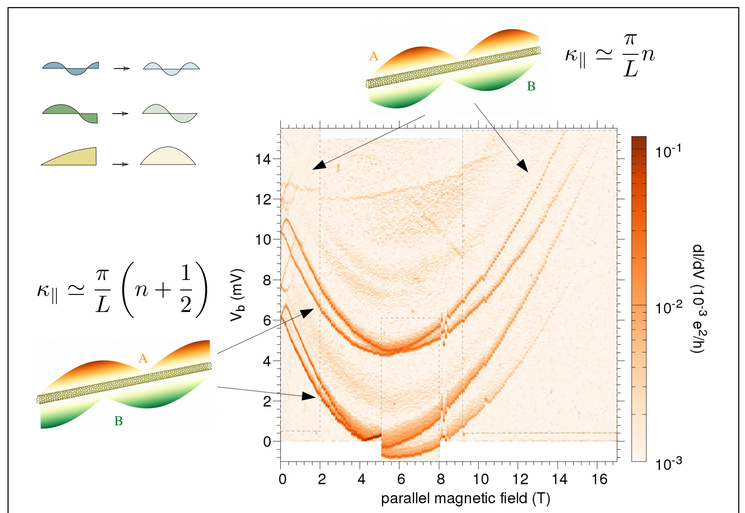
Zigzag nanotube:

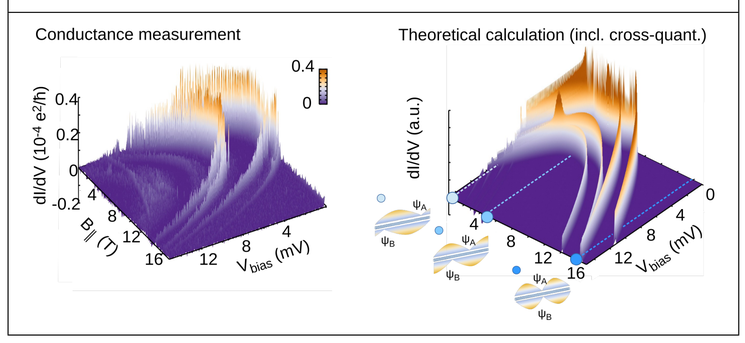
- Cut, minimizing dangling bonds ⟶ one sublattice at one end, the other at the other end!
- “Cross-quantization” of $\kappa_\perp$ and $\kappa_{||}$
- Not a quantum “box”, more a “$\lambda/4$ resonator”
- Very similar for chiral nanotubes



- Set of real solutions $\kappa_{||}(\kappa_\perp)$
- Magnetic field $B_{||}$ selects $\kappa_\perp$ (vertical dotted line)
- Field shifts nodes of wave function to the end; “$\lambda/4$ to $\lambda/2$” tuning
- $B_{||}$ modifies the quantum dot — lead coupling, and thereby the tunnel rates

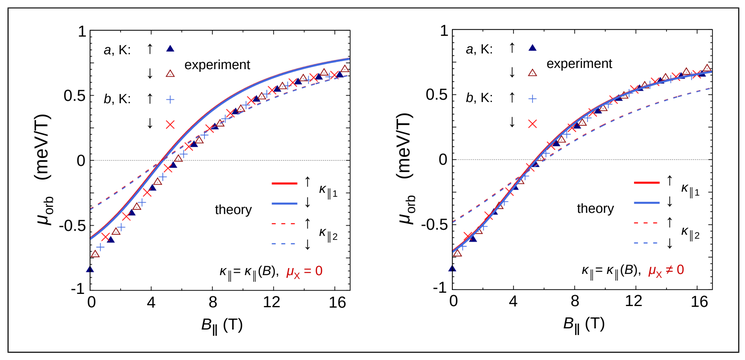
Wave function shapes in $B_{||}$





- (Initially) downsloping lines, ↷: from $\sim \lambda/2$ to $\lambda/4$ to $\lambda/2$; $\mathrm{d}I/\mathrm{d}V$ increases, then decreases
- Upsloping lines, ↻: $\mathrm{d}I/\mathrm{d}V$ decreases fast

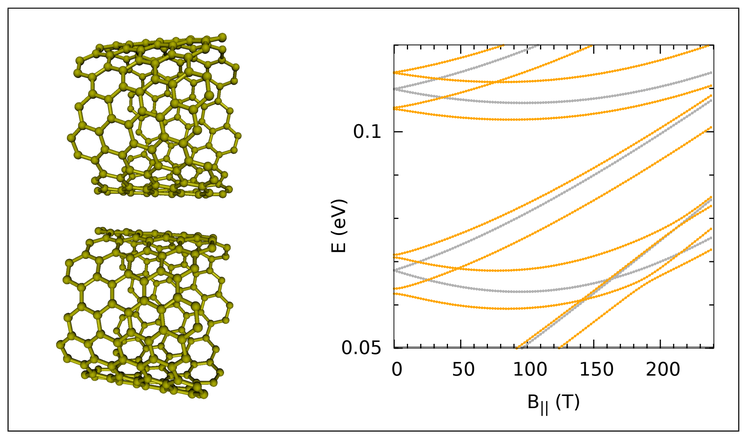
Energy / magnetic moment



- Fit improves with cross-quantization
- Magnetic moment “offset”?
- Low-lying (1.6 meV) second shell: same $\kappa_{||}$ (!)

Origin of the second shell?

- Additional degeneracy at same $\kappa_{||}$
- Bundle of two CNTs?



References

[1] M. Margańska *et al.*, in preparation (2017)
[2] D. R. Schmid *et al.*, Phys. Rev. B **91**, 155435 (2015)
[3] A. Dirnaichner *et al.*, PRL **117**, 166804 (2016)
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[5] M. Marganska *et al.*, Phys. Rev. B **83**, 193407 (2011)
[6] M. del Valle *et al.*, Phys Rev. B **84**, 165427 (2011)

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