Shaping electron wave functions in a carbon nanotube with a parallel magnetic field[1]

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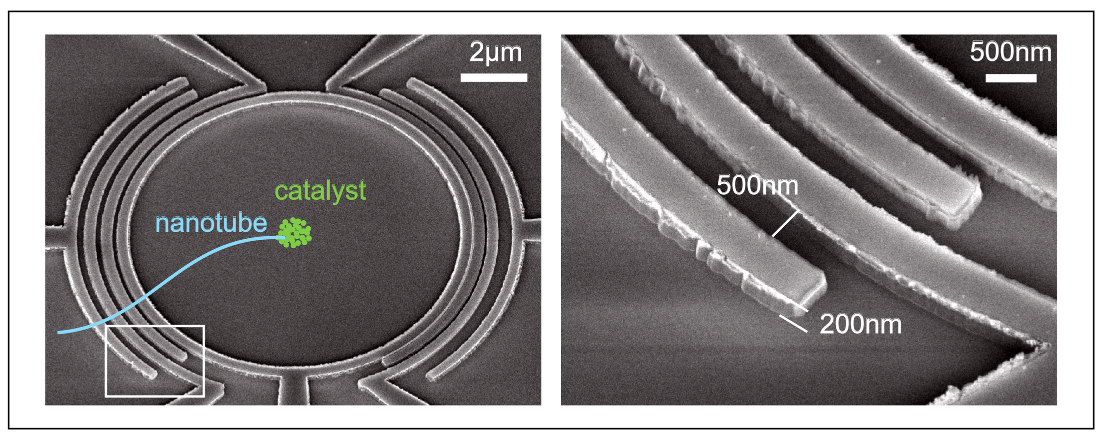
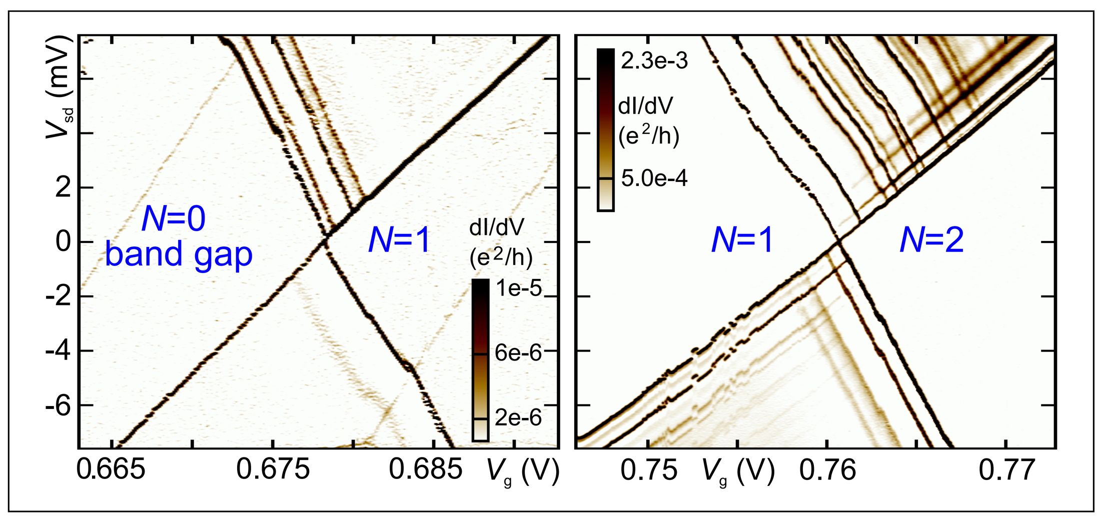
Emmy Noether-Programm DFG

Ultraclean carbon nanotubes



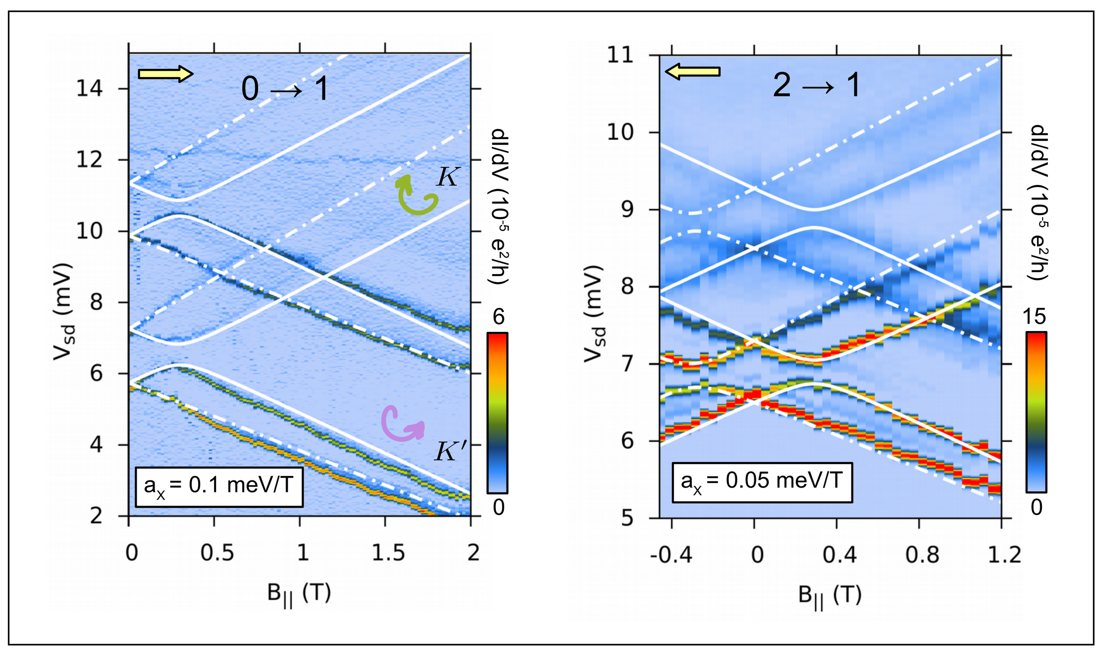
- first prepare metal structures and trenches
- then grow nanotubes across leads
- no lithography or wet chemistry afterwards
- → no chemical or mechanical damage
- → no resist residues, no e-beam irradiation
- clean few-electron system [1, 2, 3, 4]
- spectroscopy of one- and two-electron states



N=1: Low field behaviour

- linearized single particle Hamiltonian

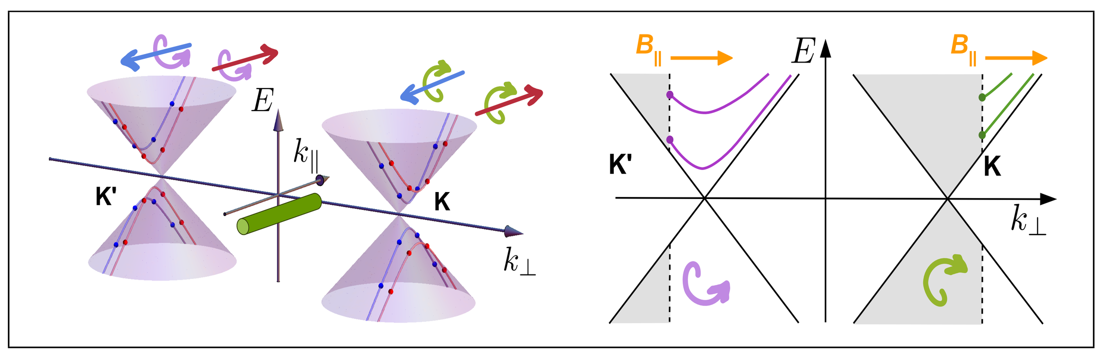
$$\hat{H}_{\mathrm{CNT}} = \underbrace{\varepsilon_d \hat{I}_\sigma \otimes \hat{I}_\tau}_{\text{“shell”}} + \underbrace{\frac{\Delta_{KK'}}{2} \hat{I}_\sigma \otimes \hat{\tau}_z}_{\text{valley mixing}} + \underbrace{\frac{\Delta_{SO}}{2} \hat{\sigma}_z \otimes \hat{\tau}_x}_{\text{spin-orbit interaction}} + \underbrace{\frac{g_s \mu_B |\vec{B}|}{2} (\cos\varphi\, \hat{\sigma}_z + \sin\varphi\, \hat{\sigma}_x) \otimes \hat{I}_\tau}_{\text{Zeeman effect}} + \underbrace{g_{\mathrm{orb}} \mu_B |\vec{B}| \cos\varphi\, \hat{I}_\sigma \otimes \hat{\tau}_x}_{\text{orbital angular moment}}$$



- extract high-level parameters Δ_{SO}, $\Delta_{KK'}$, $\Delta_\parallel$, ...
- fit requires additional corrections

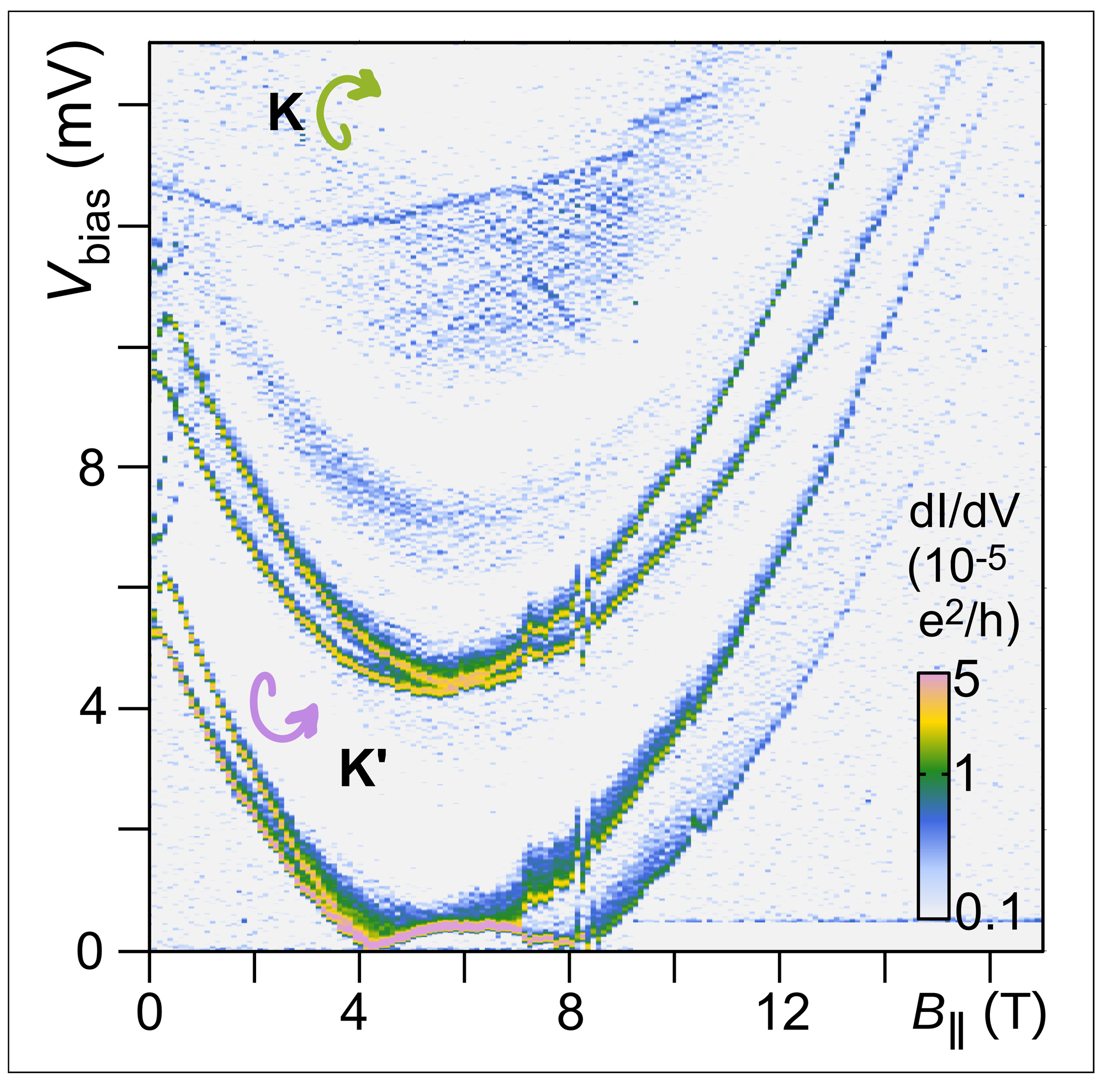
Full dispersion relation [5]

- $B_\parallel$ “scans” Dirac cone



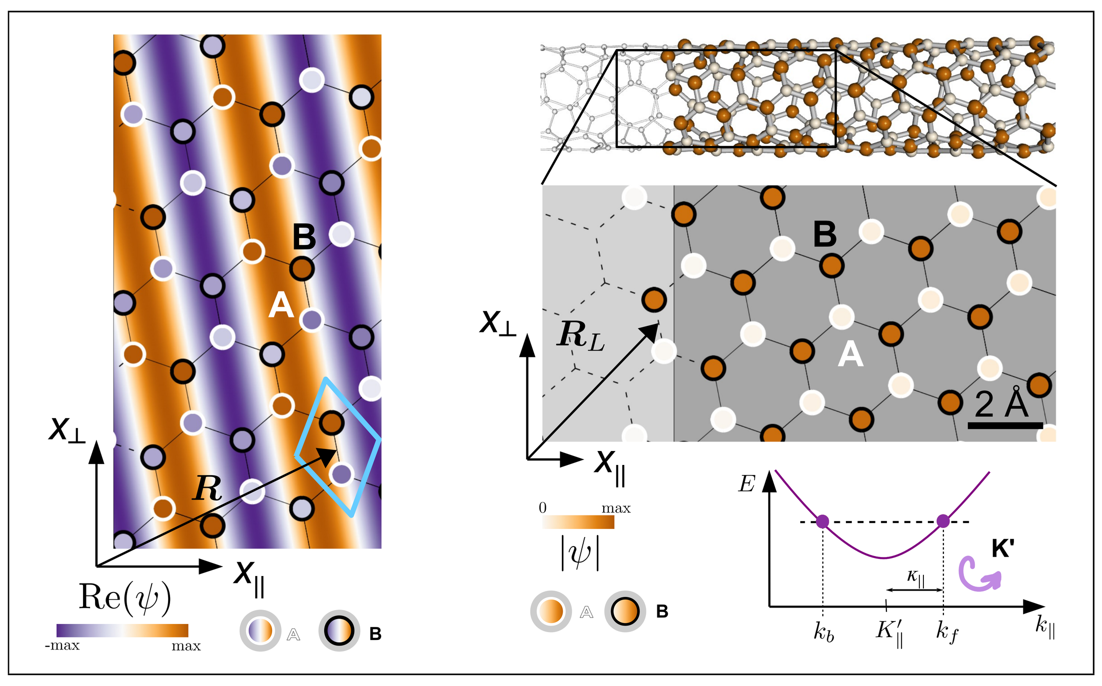
$$E_\pm(\tau,\sigma,\kappa_\parallel,B_\parallel) = \tau\sigma\varepsilon_{SO} + \sigma\mu_B B_\parallel + \hbar v_F \sqrt{\left(\tau\Delta k_\perp + \sigma\Delta k_{SO} + \frac{\pi R}{\phi_o} B_\parallel\right)^2 + \kappa_\parallel'^2}$$

N=1: High field behaviour



- K conductance peaks fade out very quickly
- K' conductance increases, then decreases

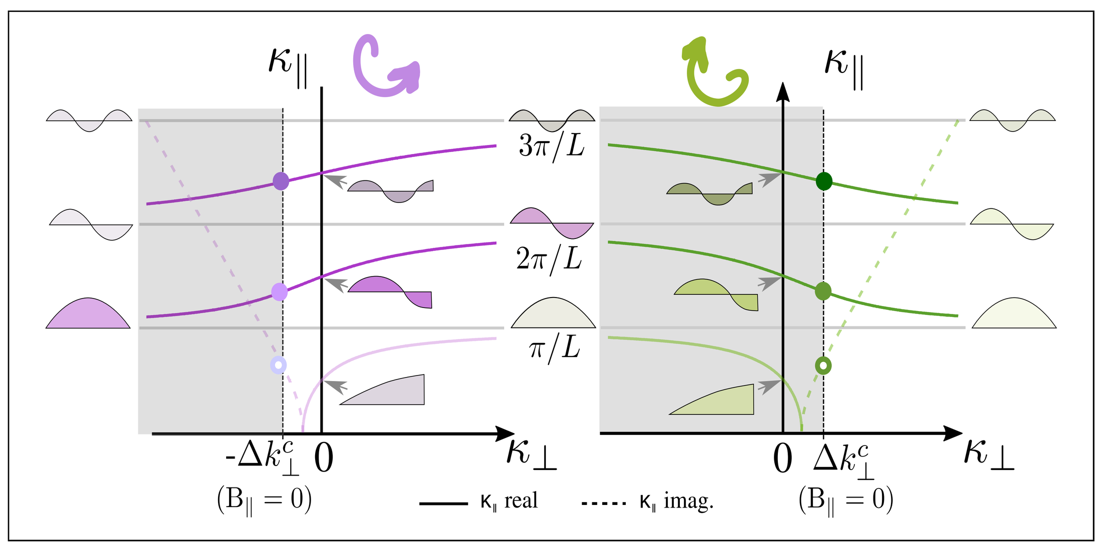
Boundary conditions



- bipartite lattice ⟶ different phase on the two sublattices (advanced / retarded)
- construct standing waves (forward + backward)
- no superposition makes wavefunction vanish on both sublattices at both ends
- minimize dangling bonds ⟶ one sublattice has majority at one end, other at the other end
- not a quantum “box”, more a “$\lambda/4$ resonator”; “cross-quantization” of $\kappa_\perp$ and $\kappa_\parallel$

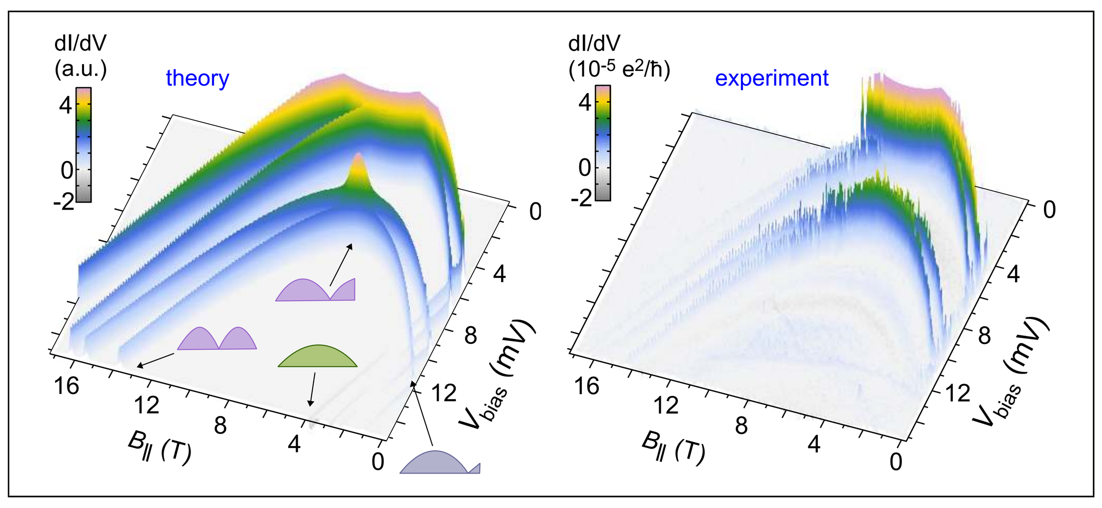
$$e^{2i\kappa_\parallel L} = \frac{\tau\kappa_\perp + i\kappa_\parallel}{\tau\kappa_\perp - i\kappa_\parallel}$$

Wave function shapes in $B_\parallel$



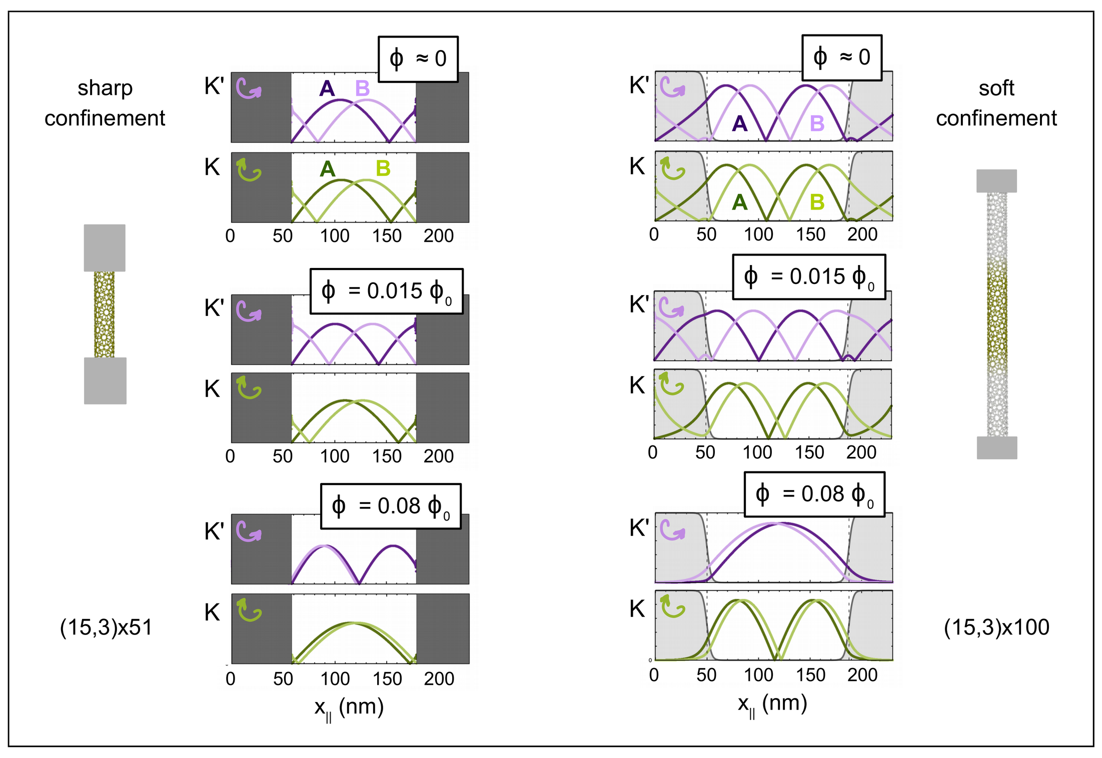
- magnetic field $B_\parallel$ selects $\kappa_\perp$ (vertical dotted line)
- field shifts nodes of wave function to the end; “$\lambda/4$ to $\lambda/2$” tuning

Impact on conductance



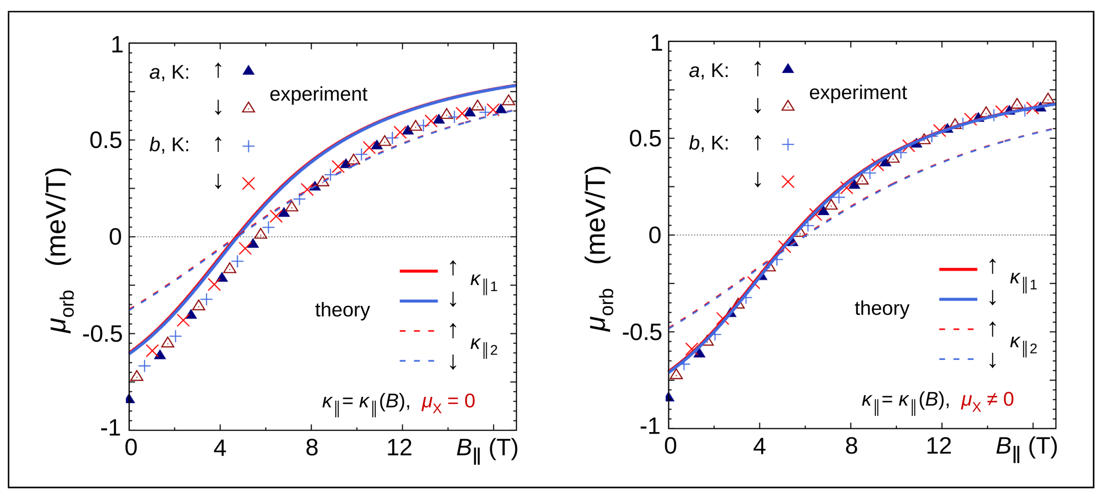
- tunnel coupling ↔ wave function amplitude at the nanotube ends
- introduce into model ⟶ very good agreement
- (initially) downsloping lines: from ∼ “$\lambda/2$” shape to “$\lambda/4$”, then to “$\lambda/2$”; dI/dV increases, then decreases again
- upsloping lines: dI/dV decreases fast, wave-function approaches “$\lambda/2$” shape

Soft confinement potential

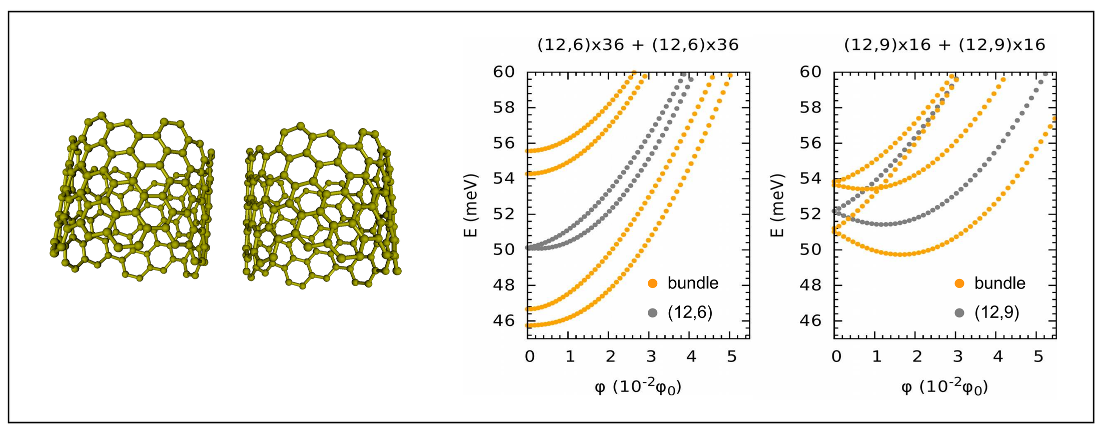


- qualitatively same result for wave functions

Origin of the second shell?



- anomalous magnetic moment, “offset”?
- low-lying (1.6 meV) second shell: same $\kappa_\parallel$ (!)
- additional degeneracy; bundle of two CNTs?



References

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