Secondary electron interference from trigonal warping in clean carbon nanotubes

A. Dirnaichner *et al.*, PRL **117**, 166804 (2016)

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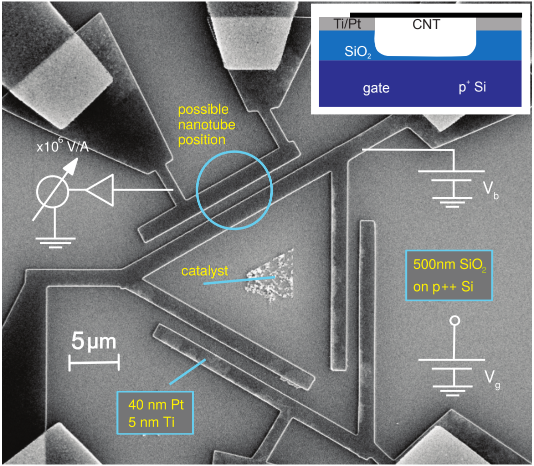
overgrown, “ultraclean” carbon nanotube device



- CNT growth *in situ* over Ti/Pt electrodes
- $V_g \lesssim 0$
  $\longrightarrow$ hole conduction
- no Coulomb blockade
- transparent contacts, weak scattering

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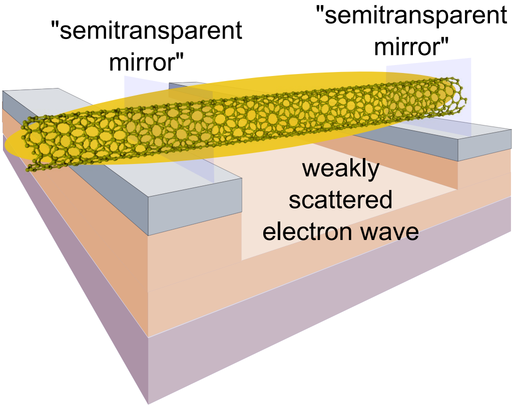
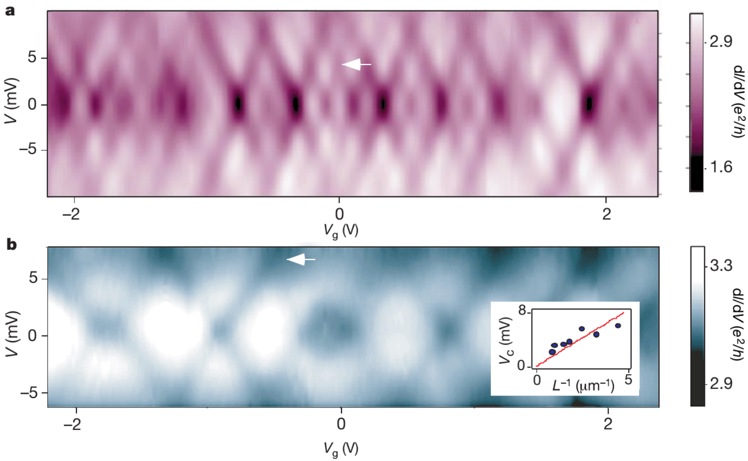
a carbon nanotube as Fabry-Pérot interferometer



- strong coupling of nanotube and contacts, no charge quantization
- weak scattering $\longrightarrow$ Fabry-Pérot interferometer for electrons

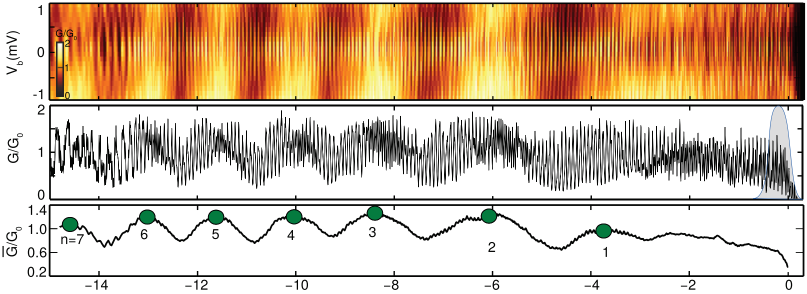
the initial observation

W. Liang *et al.*, Nature 411, 665 (2001)



- large conductance, oscillating in gate voltage V_g, bias voltage V_{sd}
- fixed interferometer geometry; we tune the electron wave vector
- dominant frequency corresponds to distance between contacts

our data — much larger energy range $\Delta E \simeq 0.4\,\text{eV}$



- narrow oscillation (↔ interferometer length)
- frequency doubling / beat
- slow modulation of the averaged conductance

⟶ nanotube is not just a one-channel system;

valley degeneracy, dispersion relation!

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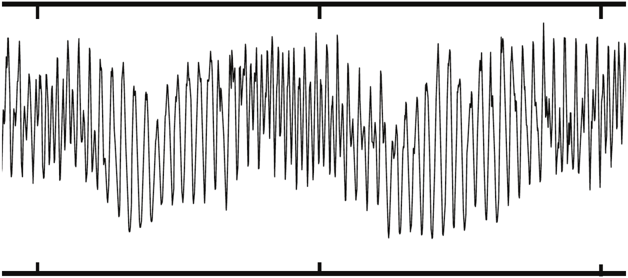

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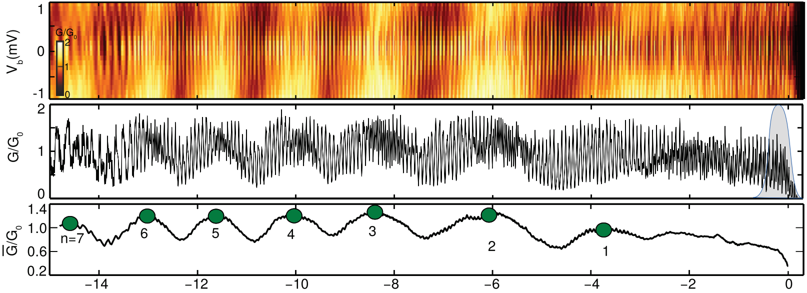

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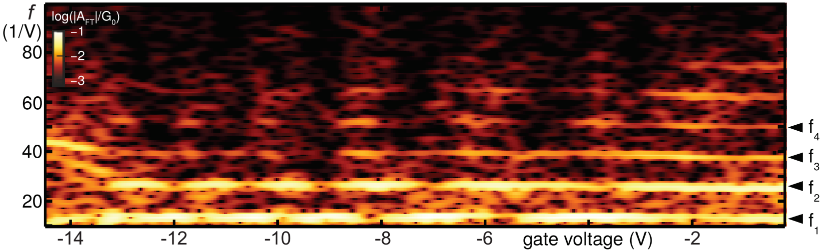
impurity scattering? no!



- discrete Fourier transform of interference pattern

  (apply sliding window to $G(V_g)$, plot transform as function of window position)

- only one fundamental frequency and its harmonics

⟶ no impurities that subdivide the nanotube

⟶ interference effects must be due to intrinsic nanotube structure

- from decay of harmonics, extract mean path of electrons $\longrightarrow \ell = 2.7\,\mu\text{m} \simeq 2.7L$

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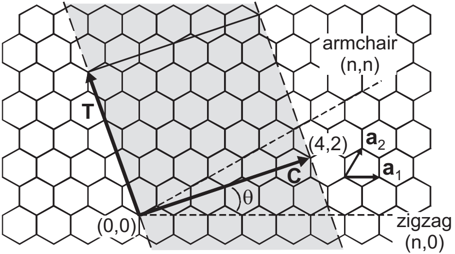
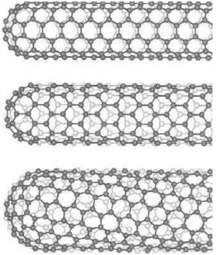
structure of single wall carbon nanotubes



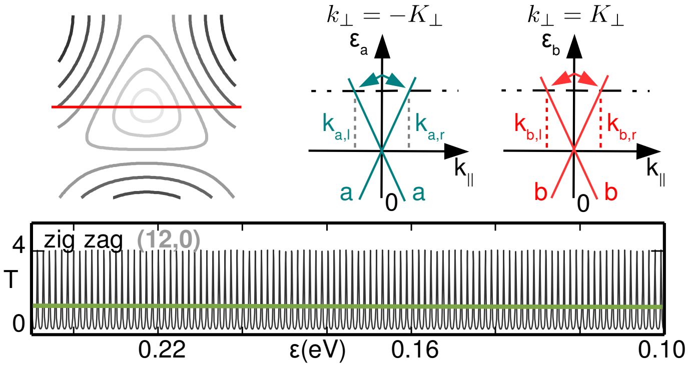


- typically, classification into armchair, zigzag, chiral
- chiral nanotubes can be further subdivided into armchair-like, zigzag-like

A. M. Lunde et al., PRB 71, 125408 (2005), M. Margańska et al., PRB 92, 075433 (2015)

- let's discuss the interferometer behaviour of these four groups
- band structure & symmetry, real-space tight binding calculations

interference in a zigzag nanotube



zigzag ($\theta = 0°$, (n,0)):

- Dirac cones around $k_\perp = \pm K_\perp$, $k_\parallel = 0$
- angular momentum conservation $\longrightarrow$ only backscattering within cone
- two channels, identical accumulated phase $\longrightarrow$ looks like one channel

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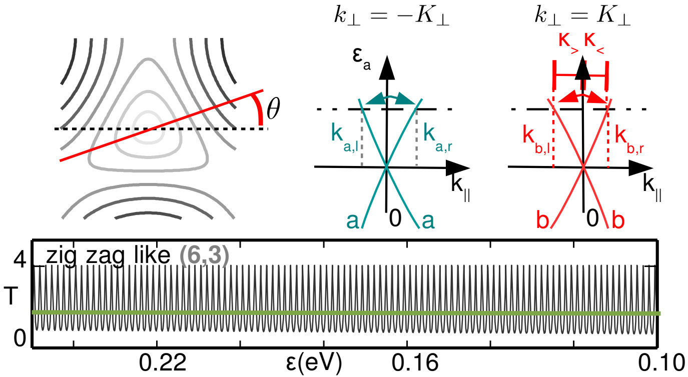
interference in a zigzag-like nanotube



zigzag-like ($0^\circ < \theta < 30^\circ$, $\frac{n-m}{3\,\mathrm{gcd}(n,m)} \notin \mathbb{Z}$):

- asymmetric Dirac cones around $k_\perp = \pm K_\perp$, $k_\parallel = 0$
- angular momentum conservation $\longrightarrow$ only backscattering within cone
- two channels, identical accumulated phase $\longrightarrow$ looks like one channel

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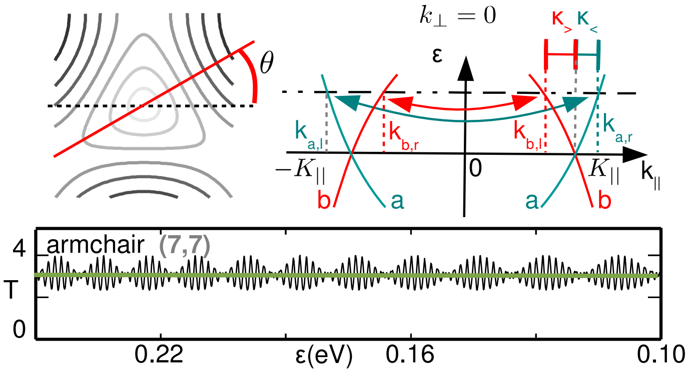
interference in an armchair nanotube



armchair ($\theta = 30^\circ$, (n,n)):

- Dirac cones at $k_\perp = 0$, $k_{||} = \pm K_{||}$
- parity symmetry $\longrightarrow$ only backscattering within a / b branch
- two channels, different accumulated phase, beat; $\overline{T}$ constant

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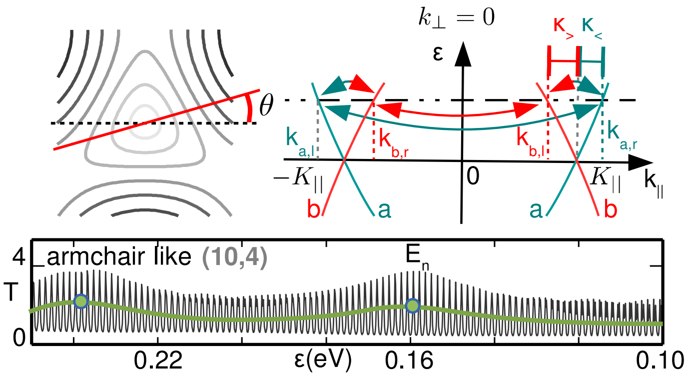
interference in an armchair-like nanotube



armchair-like ($0^\circ < \theta < 30^\circ$, $\frac{n-m}{3\,\mathrm{gcd}(n,m)} \in \mathbb{Z}$):

- Dirac cones at $k_\perp = 0$, $k_\| = \pm K_\|$
- NO parity $\longrightarrow$ two channels, different phase, mixing of channels
- beat plus slow modulation of $\overline{T}$

meaning of the average conductance maxima

- armchair-like CNT: phase difference of Kramers modes

$$\Delta\phi^\theta(E) = |\phi_a^\theta(E) - \phi_b^\theta(E)| = 2\left(\kappa_>^\theta - \kappa_<^\theta\right)L$$

$\kappa_{>,<}^\theta$: longitudinal wave vectors measured from K/K' points

- averaged conductance has maximum when $\Delta\phi^\theta(E) = 2\pi n$
- relevant parameter: chiral angle θ

  $\longrightarrow$ use this for chiral angle determination!

- extract from data maxima positions V_g^n of $\overline{G}(V_g)$
- convert V_g^n from gate voltage to energy
- compare with calculated maxima positions for given θ

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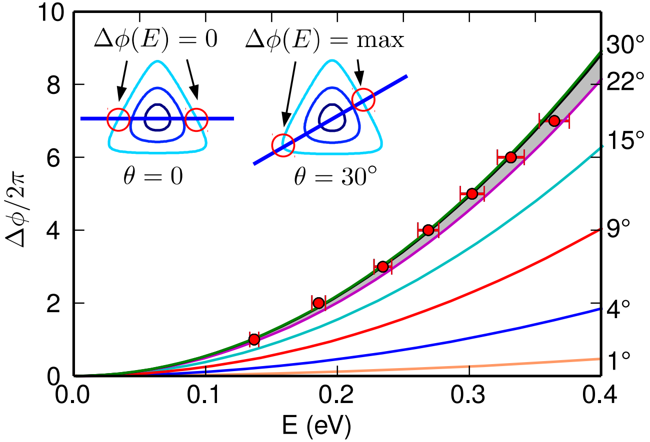
chiral angle determination



result for our device: $22^\circ \leq \theta < 30^\circ$

solution of a hard problem — chirality determination from transport

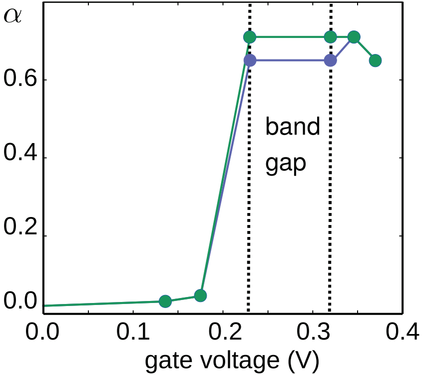
error sources

mainly: conversion of $\overline{G}$ maxima positions from gate voltage to energy

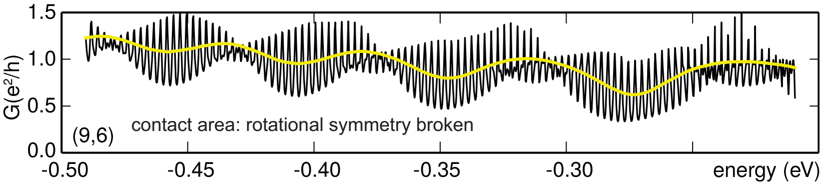
- band gap at $V_g > 0$, energy offset ΔE
- lever arm $\alpha(V_g)$ hard to determine, varies strongly close to band gap

→ $55\,\text{meV} < \Delta E < 60\,\text{meV}$

→ error bars



broken rotational symmetry at contacts



- at contacts, rotational symmetry broken
  $\longrightarrow$ argument for angular momentum conservation breaks down
- integrate this into tight-binding model: differing on-site energies for top and bottom of nanotube
- result: slow oscillations of $\overline{G}$ also recovered for zigzag-like nanotube!
- same evaluation of the chiral angle possible!

conclusions

- complex Fabry-Pérot interference observed over a large energy range
- theoretical analysis for different nanotube types, confirmed by real-space tight binding calculations
- interference pattern is due to trigonal warping of dispersion relation and mixing of Kramers channels
- slow modulation of averaged conductance $\overline{G}$ — robust, easily extracted
- $\overline{G}$ depends on chiral angle θ of the nanotube

- approach towards a hard problem —
  chirality determination from low-temperature transport

Thanks


Alois Dirnaichner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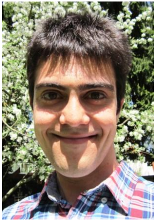
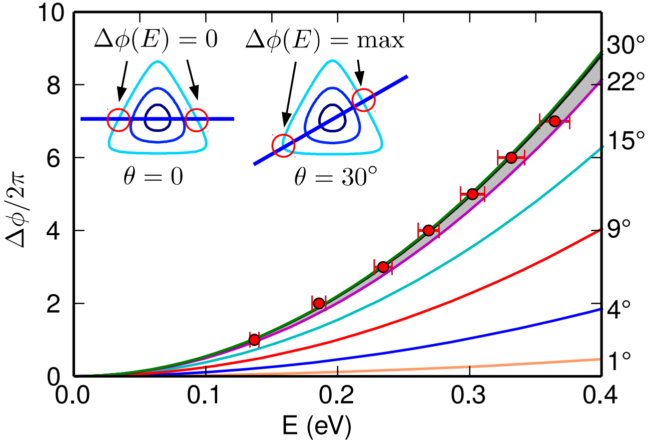

Nicola Paradiso


Milena Grifoni


Christoph Strunk

Thank you! — Questions?



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