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
- $V_g \lesssim 0$ → 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 $\rightarrow$ Fabry-Pérot interferometer for electrons

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The initial observation


- 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 ($\leftrightarrow$ interferometer length)
- frequency doubling / beat
- slow modulation of the averaged conductance
  \[\rightarrow \text{nanotube is not just a one-channel system; valley degeneracy, dispersion relation!}\]

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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
  $\rightarrow$ no impurities that subdivide the nanotube
  $\rightarrow$ interference effects must be due to intrinsic nanotube structure

• from decay of harmonics, extract mean path of electrons $\rightarrow \ell = 2.7\,\mu m \simeq 2.7L$

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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

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interference in a zigzag nanotube

zigzag ($\theta = 0^\circ$, (n,0)):

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

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interference in a zigzag-like nanotube

\[ k_{\perp} = -K_{\perp} \]

\[ k_{\perp} = K_{\perp} \]

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

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

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interference in an armchair nanotube

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

- Dirac cones at \(k_\perp = 0, k_\parallel = \pm K_\parallel\)
- parity symmetry \(\rightarrow\) only backscattering within a / b branch
- two channels, different accumulated phase, beat; \(\bar{T}\) constant

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interference in an armchair-like nanotube

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

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

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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 \(\theta\)

\[\longrightarrow\text{ use this for chiral angle determination!}\]

• extract from data maxima positions \(V_{g}^n\) of \(G(V_{g})\)
• convert \(V_{g}^n\) from gate voltage to energy
• compare with calculated maxima positions for given \(\theta\)

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

desolution of a hard problem — chirality determination from transport

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

- band gap at $V_g > 0$, energy offset $\Delta E$
- lever arm $\alpha(V_g)$ hard to determine, varies strongly close to band gap
  $\rightarrow$ $55 \text{meV} < \Delta E < 60 \text{meV}$
  $\rightarrow$ error bars
broken rotational symmetry at contacts

- at contacts, rotational symmetry broken
  $\rightarrow$ 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 $\tilde{G}$ 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 $\bar{G}$ — robust, easily extracted
• $\bar{G}$ depends on chiral angle $\theta$ of the nanotube

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

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