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Workshop on Nano-Opto-Electro-Mechanical Systems Approaching the Quantum Regime

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Longitudinal Vibrations of Suspended Carbon Nanotubes - Franck-Condon effect, cotunneling and nonequilibrium

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Longitudinal vibrations of suspended carbon nanotubes - Franck-Condon effect, cotunneling, and nonequilibrium

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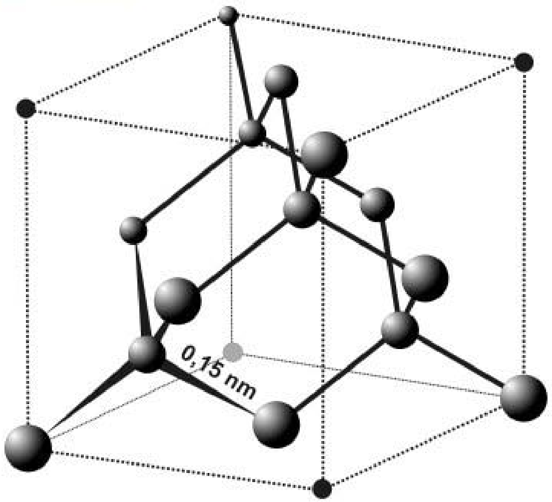
Abdus Salam International Centre for Theoretical Physics, Trieste 2010

Carbon, as we know it



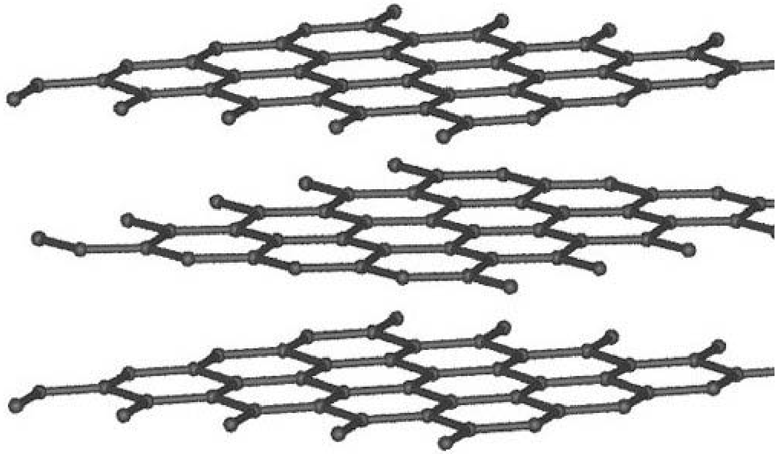
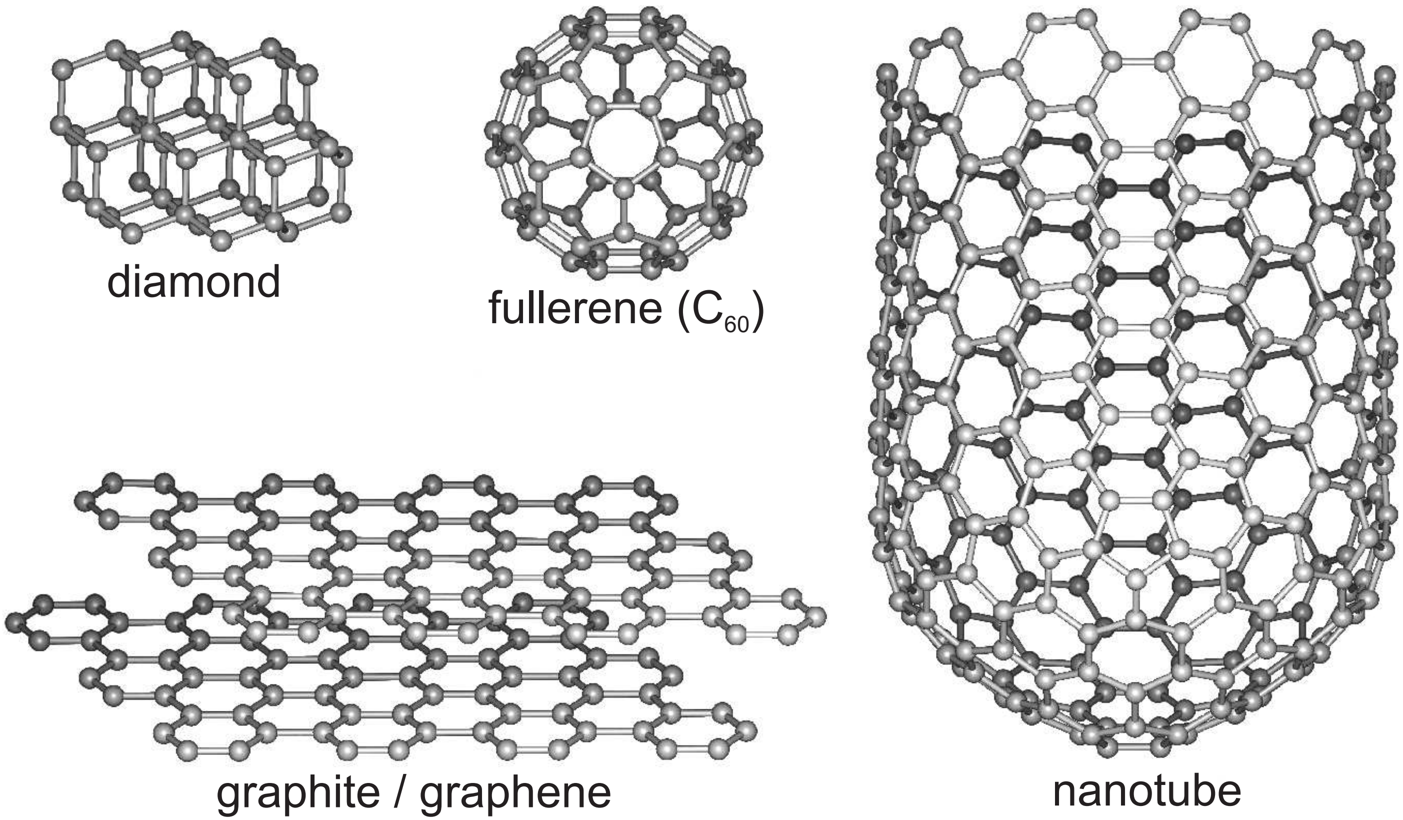


image source: Wikipedia

Carbon nanotubes: a more exciting form of carbon



Carbon nanotubes

- different production methods; often:
  - use small catalyst particles
  - hot gas, with carbon feed (e.g. CH_4)
  - nucleation of tube structure

- many different structures
  - single-wall, double-wall, multi-wall
  - zigzag, armchair, chiral (how the sheet is “wrapped together”)

Mechanical properties of carbon nanotubes

- stiffer than steel
- resistant to damage from physical forces
- very light

- Young's modulus $E = \frac{F/A}{\Delta L/L}$:

  $E_{\mathrm{CNT}} \simeq 1.2\,\mathrm{TPa}, \quad E_{\mathrm{steel}} \simeq 0.2\,\mathrm{TPa}$

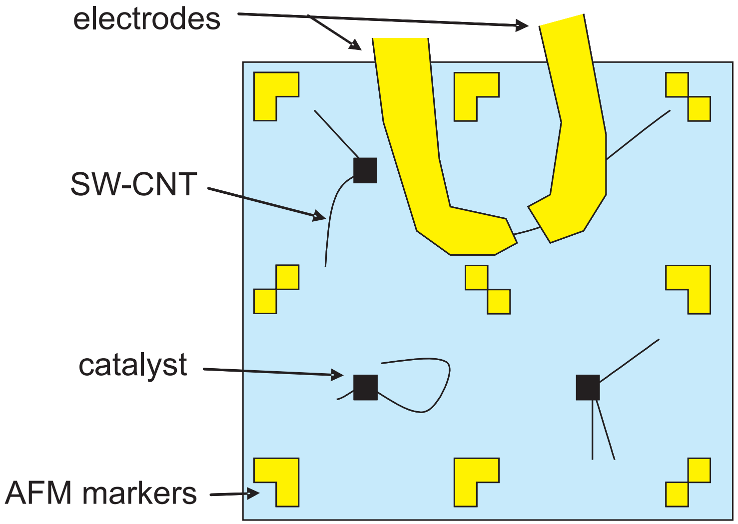
- Density:

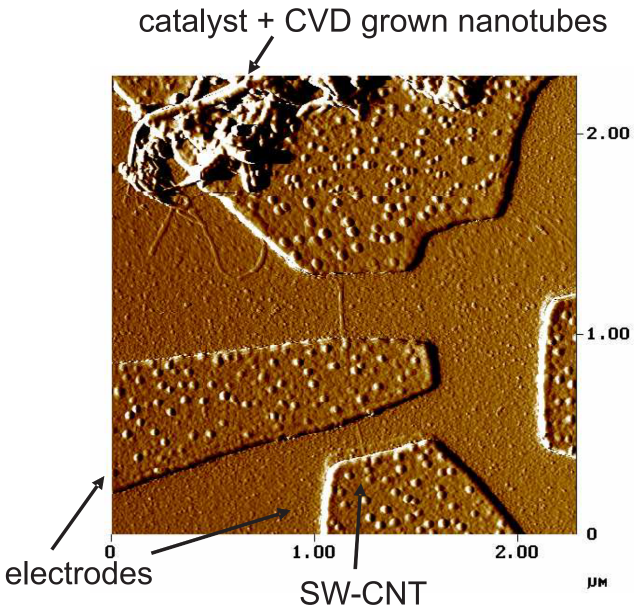
  $\rho_{\mathrm{CNT}} \simeq 1.3\,\frac{\mathrm{g}}{\mathrm{cm}^3}, \quad \rho_{\mathrm{Al}} \simeq 2.7\,\frac{\mathrm{g}}{\mathrm{cm}^3}$

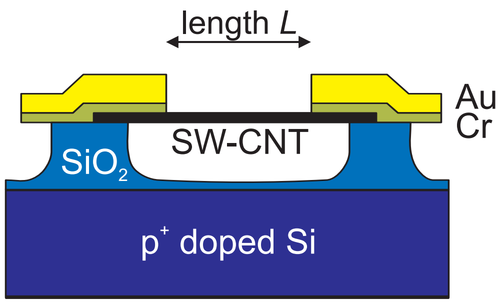
- (still) "material of dreams"

Suspended carbon nanotube sample fabrication

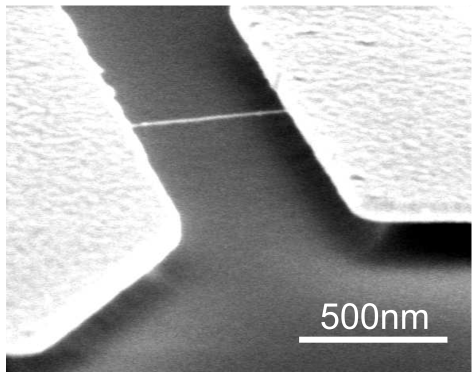
"the old way of doing things"







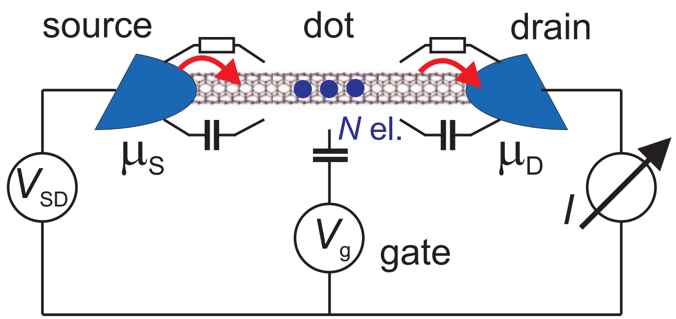
electrodes as etch mask

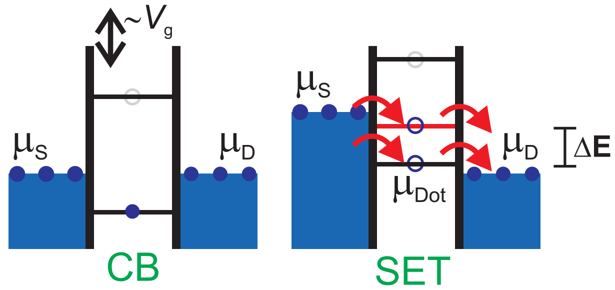


A. K. Hüttel *et al.*, New J. Phys. **10**, 095003 (2008)

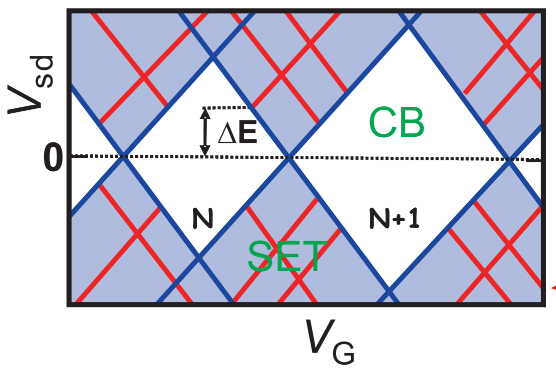
Low-temperature transport measurements

- Tunnel barriers between leads and nanotube
- Low temperature $k_B T \ll e^2/C$: formation of a quantum dot





stability diagram: $\frac{dI}{dV_{SD}}(V_g, V_{SD})$

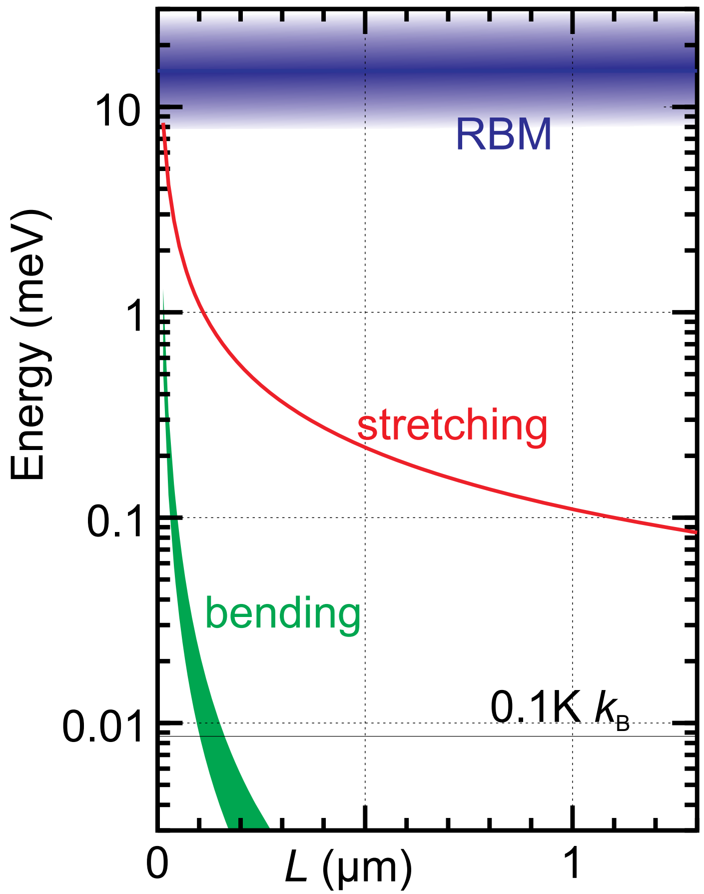


CB - Coulomb blockade “diamonds”
SET - single electron tunneling

Excited states visible at finite bias!
Spectroscopy of the electronic system

A. K. Hüttel *et al.*, New J. Phys. **10**, 095003 (2008)

Vibration modes of carbon nanotubes

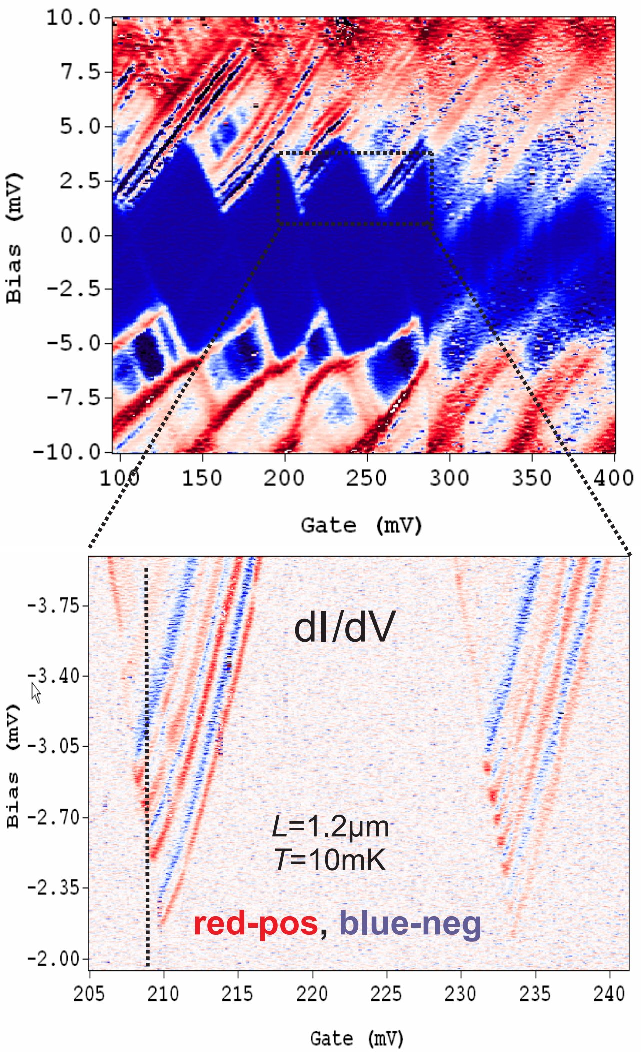


- radial breathing mode(s)
- stretching (longitudinal) mode:
  $h\nu \propto L^{-1}$
  $h\nu = 1100 \ldots 110\,\mu$eV,
  $\nu = 270 \ldots 27$ GHz
  (for 100 nm … 1 μm)
- bending (transversal) mode:
  $h\nu \propto L^{-2}$
  $h\nu = 10 \ldots 0.1\,\mu$eV,
  $\nu = 2.4$ GHz … 24 MHz
  (for 100 nm … 1 μm)
  $h\nu \propto d$, also tension-dependent

purely electronic excitations have different energy scale

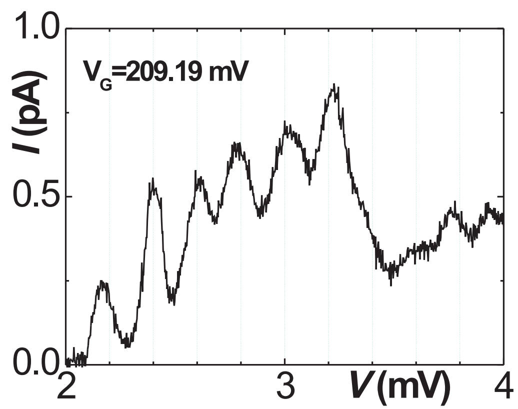
A. K. Hüttel *et al.*, New J. Phys. **10**, 095003 (2008)

The stretching mode – visible in electronic transport



- Low-energy excitations
- Equally spaced, $\hbar\omega = 140\,\mu$eV
- Identical for different charge states

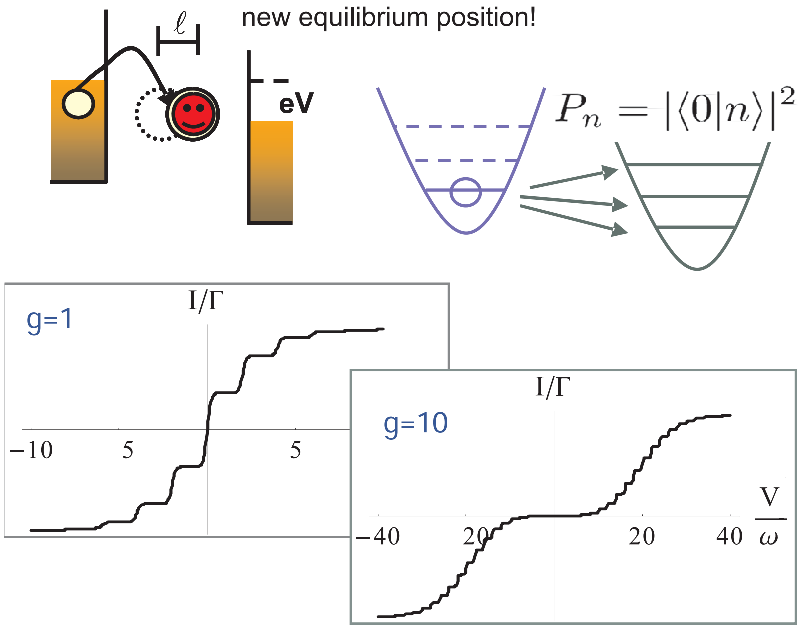
- Stretching mode as harmonic oscillator



S. Sapmaz *et al.*, PRL **96**, 026801 (2006)

Electron-vibron coupling, Franck-Condon physics

$$\hat{H} = \frac{\hat{p}^2}{2m} + \frac{1}{2} m\omega_0^2 \hat{x}^2 + \lambda \hat{x} \qquad g = \frac{\lambda^2}{2} = \frac{1}{2}\left(\frac{\ell}{\ell_0}\right)^2 \qquad \ell_0 = \sqrt{\frac{\hbar}{m\omega_0}}$$



$$\Gamma \longrightarrow \Gamma_{el} \underbrace{\left|\langle \Psi_{\text{after}} | \Psi_{\text{before}} \rangle\right|^2}_{P_{nm}}$$

$$P_{n0} = \left|\langle \Psi(x-\ell) | \Psi(x) \rangle\right|^2 = \frac{e^{-g} g^n}{n!}$$

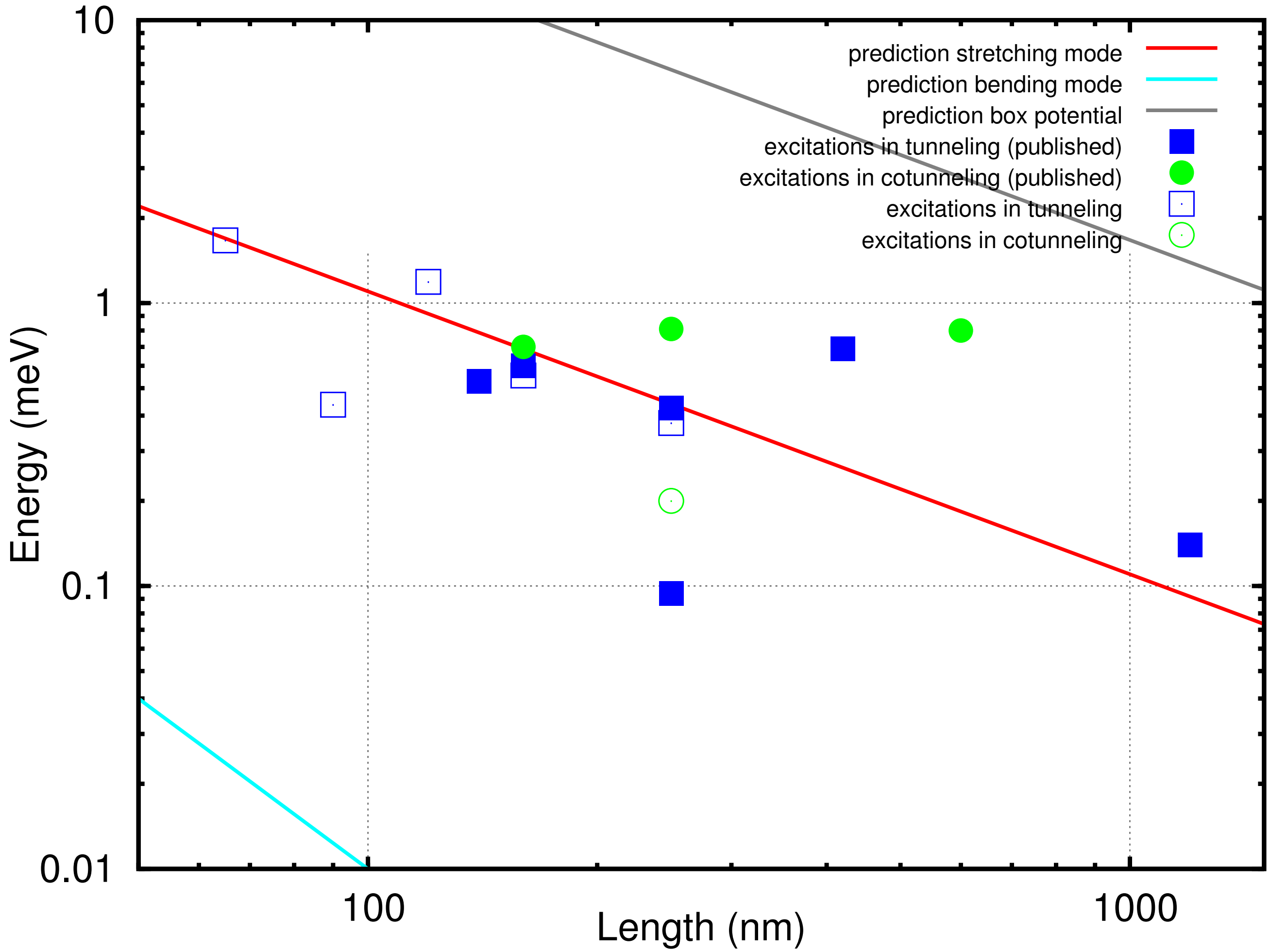
no effect for $g < 0.1$

additional steps in $I(V_{sd})$ for $g > 0.1$

phonon blockade of transport for $g > 1$, $V_{sd} < g\hbar\omega_0$

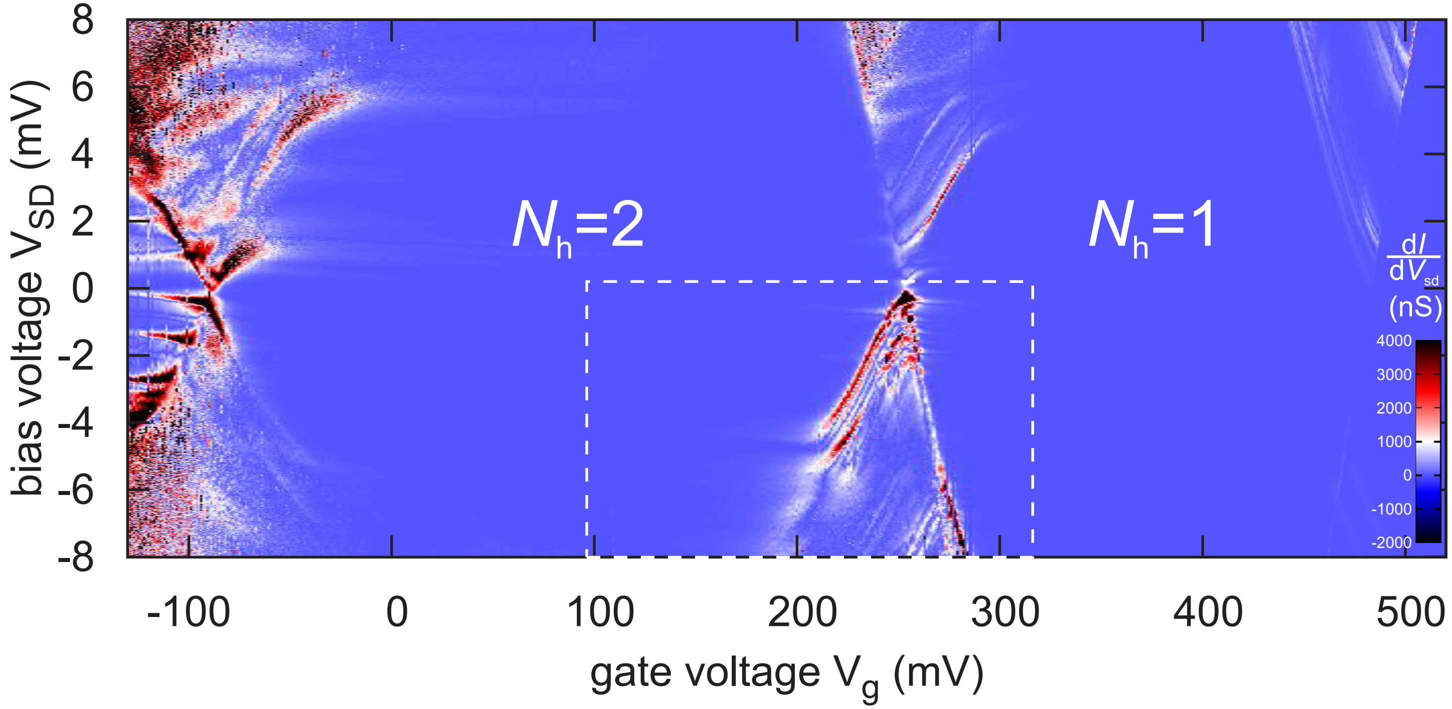
S. Braig and K. Flensberg, PRB **68**, 205324 (2003)
M. C. Luffe *et al.*, PRB **77**, 125306 (2008), K. Flensberg, March Meeting 2006 slides

Vibrational excitations observed so far



S. Sapmaz *et al.*, PRL **96**, 026801 (2006); A. K. Hüttel *et al.*, New J. Phys. **10**, 095003 (2008); A. K. Hüttel *et al.*, PRL **102**, 225501 (2009); R. Leturcq *et al.*, Nat. Phys. **5**, 327 (2009)

$L = 250$ nm SC nanotube, few-hole regime

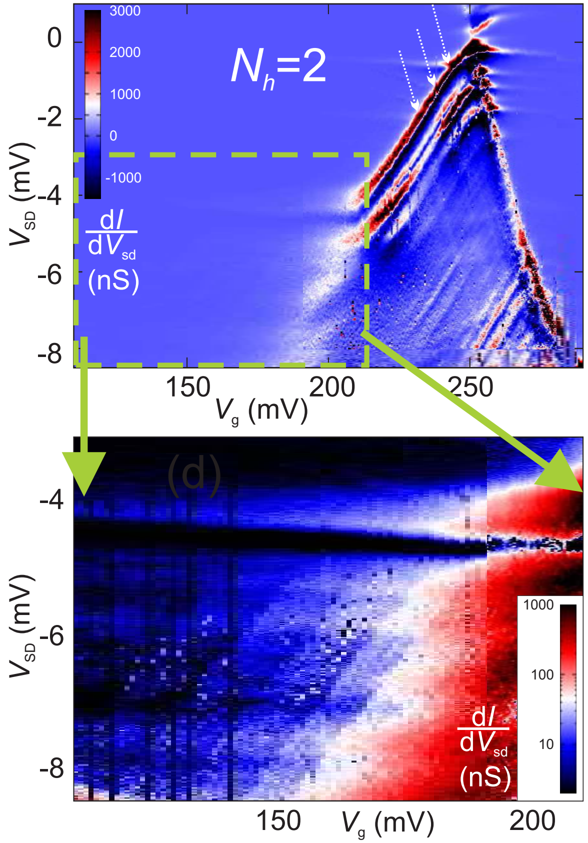


$E_{gap} = 0.2$ eV $\rightarrow d = 3.7$ nm, $\hbar\omega_{RBM} \simeq 7.8$ meV, maybe (0,46), $\varepsilon \simeq 6.2$ meV
length $L = 250$ nm $\rightarrow$ expected $\hbar\omega_{bend} \simeq 0.002$ meV, $\hbar\omega_{stretch} \simeq 0.44$ meV

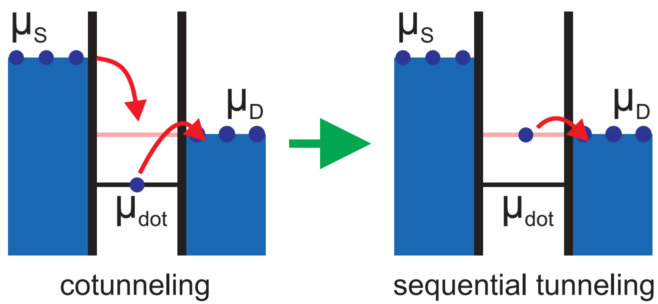
bending lines $\rightarrow$ shifting potential minima, DQD-like properties

A. K. Hüttel *et al.*, PRL **102**, 225501 (2009)

Stretching mode in SET and cotunneling ($1 \leq N_{h^+} \leq 2$)



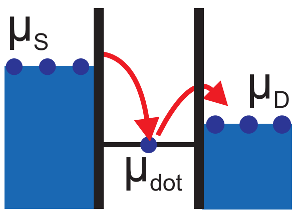
- excitations in SET, positive slope: harmonic, $\Delta\varepsilon = 0.42\,\text{meV} \simeq \hbar\omega_{\text{stretch}}$
- harmonic excitations in cotunneling!
- Cotunnel-assisted sequential tunneling, “CO-SET”



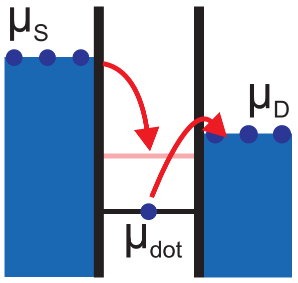
A. K. Hüttel *et al.*, PRL **102**, 225501 (2009)

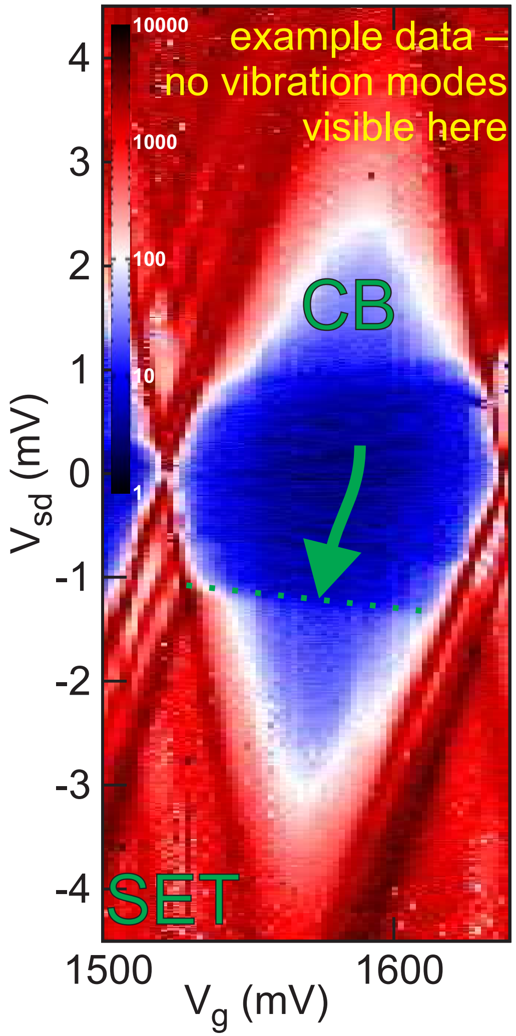
Reminder: cotunneling – second-order process

- current in Coulomb blockade:
  "several electrons tunneling at once"
- two-electron processes:
  - elastic:



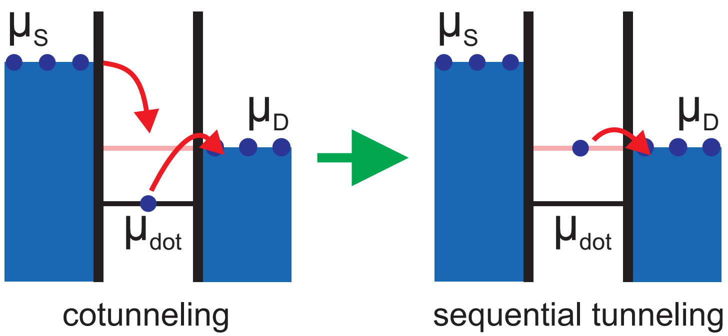
  - inelastic (green arrow):





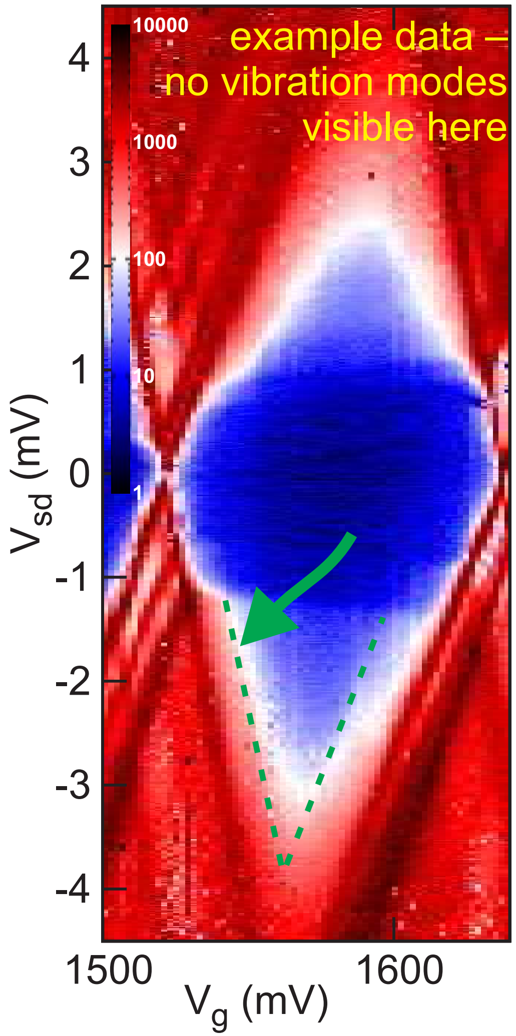
Cotunnel-assisted sequential tunneling (CO-SET)

- inelastic cotunneling, followed by a tunnel-out process



- requires energy storage
- this is the process we've seen

- requires energy storage: tunnel-out must be faster than relaxation



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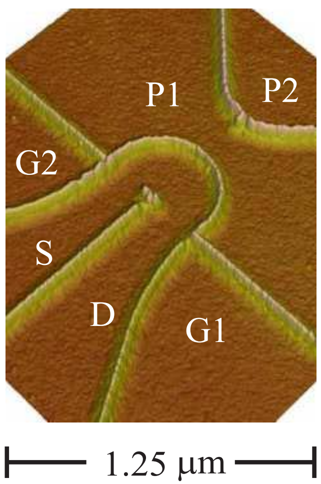
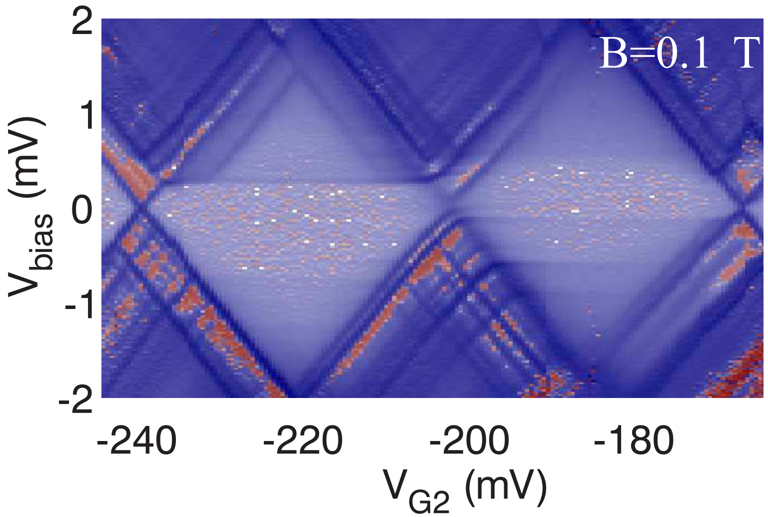
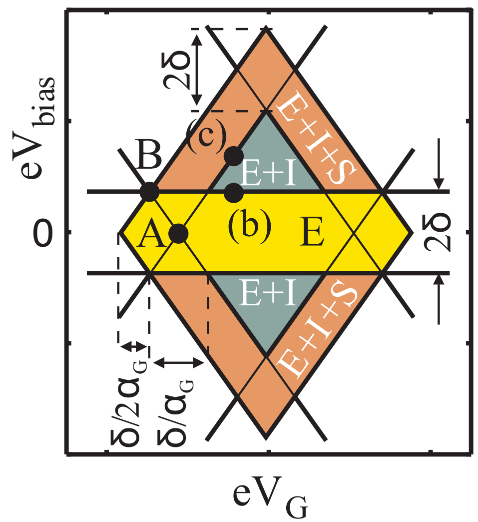




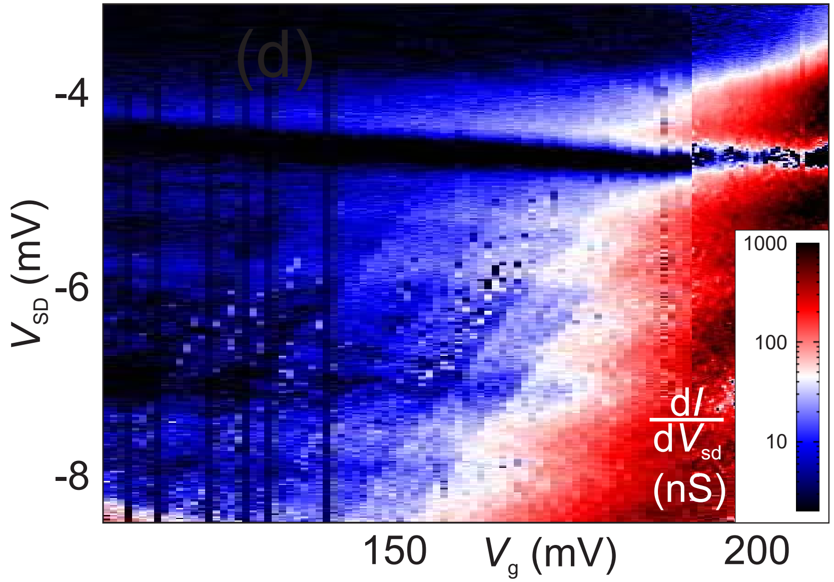


- first observed and explained by Schleser *et al.* ∼2005

  electronic excitations in GaAs/AlGaAs quantum dots

R. Schleser *et al.*, PRL **94**, 206805 (2005)

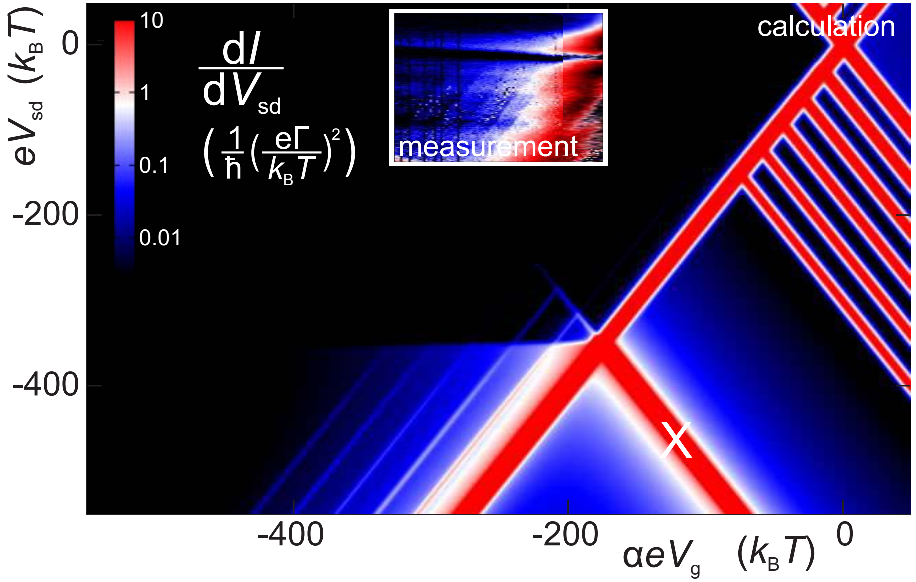
Measurement detail

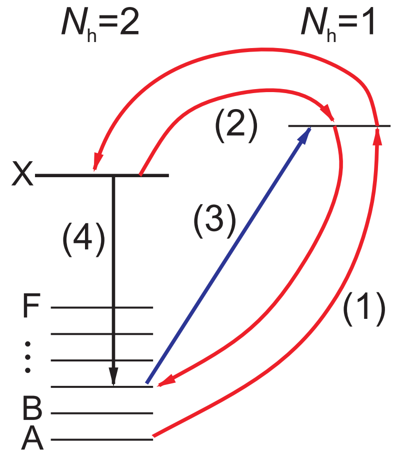


- CO-SET current sets in at additional (electronic) excited state X
- Tunnel rates coupling an 2h state to 1h ground state:
  small for 2h ground state, large for 2h excited state X
- Real-time transport theory calculations, M. Leijnse & M. Wegewijs
- Vibration mode is pumped by multiple inelasic cotunnel processes involving X (e.g. sequence (1) → (2) → (3))

A. K. Hüttel *et al.*, PRL **102**, 225501 (2009); M. Leijnse & M. Wegewijs, PRB 78, 235424 (2008)

Numerical calculation





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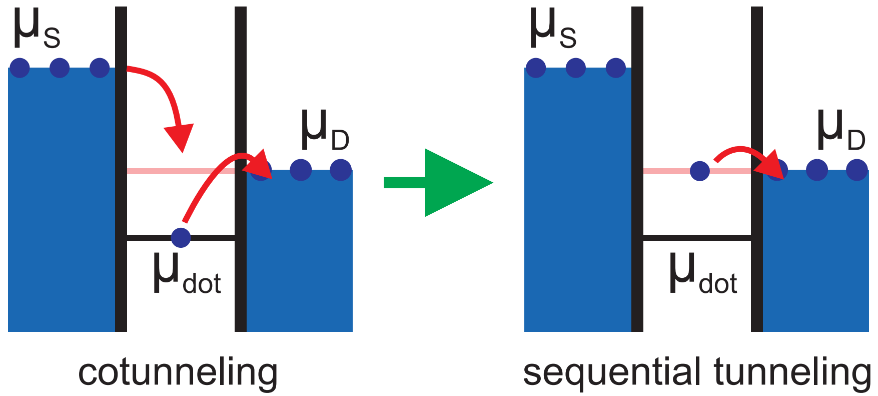
CO-SET process requires energy storage, nonequilibrium



- Vibration mode must remain excited until tunnel-out
- Vibrons are pumped as in a three-level laser!

- Comparison of timescales & tunnelling rates
  $\longrightarrow$ first (weak) lower boundary for mechanical quality factor
  $\longrightarrow$ $Q_{\mathrm{stretch}} \gtrsim 30$

- Known values for transversal CNT mode:

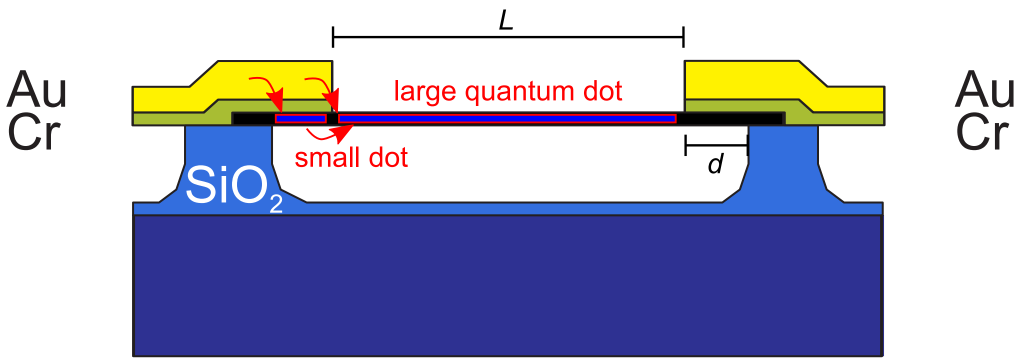
$$Q_{\mathrm{bend,RT}} \lesssim 2000, \quad Q_{\mathrm{bend,20mK}} \lesssim 150000$$

A. K. Hüttel *et al.*, PRL **102**, 225501 (2009); A. K. Hüttel *et al.*, Nano Lett. **9**, 2547 (2009)

Open question #1: Nature of the excited state X

- simplest possibility: orbital excited state of the nanotube quantum dot
  - different orbital wavefunction
  - different tunnel couplings
  - ⟶ our model idea should work fine

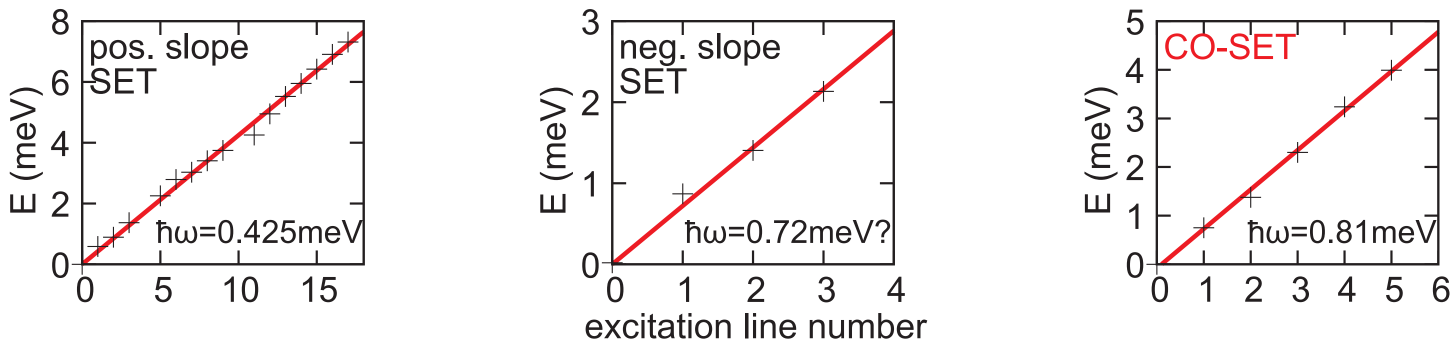
- alternative explanation: potential side minimum / double quantum dot
  - possible since the suspended nanotube is partially covered by the contacts
  - bending resonance lines in Coulomb diamonds: shifting potential minima
  - ⟶ our model idea should still work fine!



Some speculations about a “phaser”

- idea: use analogy with the 3-level laser
- current pumps vibration via the electronic excited state
- use a double quantum dot to generate this level structure
- feed a mechanical mode faster than it can decay, population inversion
- ?

Open question #2: Frequency doubling



- pos. slope SET excitations: $\hbar\omega = 0.42\,\text{meV}$
- CO-SET and neg. slope SET excitations: $\hbar\omega \simeq 0.8\,\text{meV}$

- few-carrier system
- adding a hole redistributes the entire charge on the nanotube
- up to now, all measurements of the Franck-Condon sidebands were in the metallic limit

Some speculations about 1D Wigner crystals

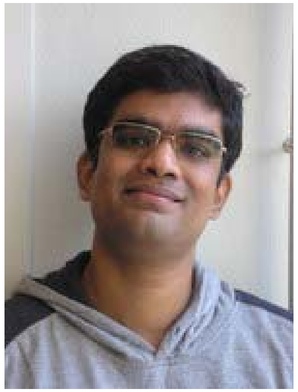
- few charge carrier limit
- one-dimensional chain of electrons or holes
- different charge number $\longrightarrow$ completely different charge distribution
- influence of charge distribution on the electrostatic forces inducing the vibrations
- dynamic interaction?
- electronic system much faster than vibration
  $\longrightarrow$ can regard mechanical oscillator fixed for each point in time
- ?

The team at Molecular Electronics & Devices, Delft and theory friends

Thanks!

Herre van der Zant

Benoit Witkamp



Hari Pathangi

Menno Poot

Martin Leijnse

Maarten Wegewijs

& Samir Etaki, Yaroslav Blanter, Fabio Pistolesi, Ivar Martin, Sami Sapmaz, Pablo Jarillo-Herrero, Raymond Schouten, Hidde Westra, ...

Meanwhile, things have moved on a bit...

... and me as well, back to Bavaria

- new research group at Universität Regensburg
- spin injection and spin transport in carbon nanotubes
- carbon nanotubes with superconducting contacts
- and now (since funding has finally come):
  carbon nanotubes as nano-electromechanical hybrid systems

- **postdoc position available**

Universität Regensburg

FAKULTÄT FÜR PHYSIK

Institute for experimental and applied physics

Postdoc position in NEMS available!

You have already been working successfully with **millikelvin RF** equipment in your PhD research, and have a good understanding of **low temperature physics** as well as **gigahertz technology**? Ideally, you are coming from a research group specialized in **superconductor-related mesoscopic physics**, quantum information, or cavity QED? You are interested in contributing to a young and dynamic team, trying to push the limits of what is doable in nano-electromechanical systems?

Then you might be just about right here. Your job will be to build up a low-temperature high frequency measurement setup in a state-of-the-art dilution refrigerator, and conduct measurements on **coupled superconductor-carbon nanotube systems**. You will be supported by a PhD student and a MSc student. We expect your work to lead to reeeally great publications!

Your salary will be based on the German TV-L E13. Regensburg university has a strong focus on nanophysics, in particular on spin phenomena and carbon-based systems. The natives are friendly, and while our university buildings feature classic 1965 concrete, the medieval city of Regensburg is a jewel on its own, with a vibrant young atmosphere. Both mountains and Munich airport are not far away.

Interested? Have a look at **http://www.physik.uni-r.de/forschung/huettel/** and contact **Andreas K. Hüttel** (e-mail: **andreas.huettel@physik.uni-r.de**) for more information!