Charge Dynamics of Fullerenes and Nanotubes

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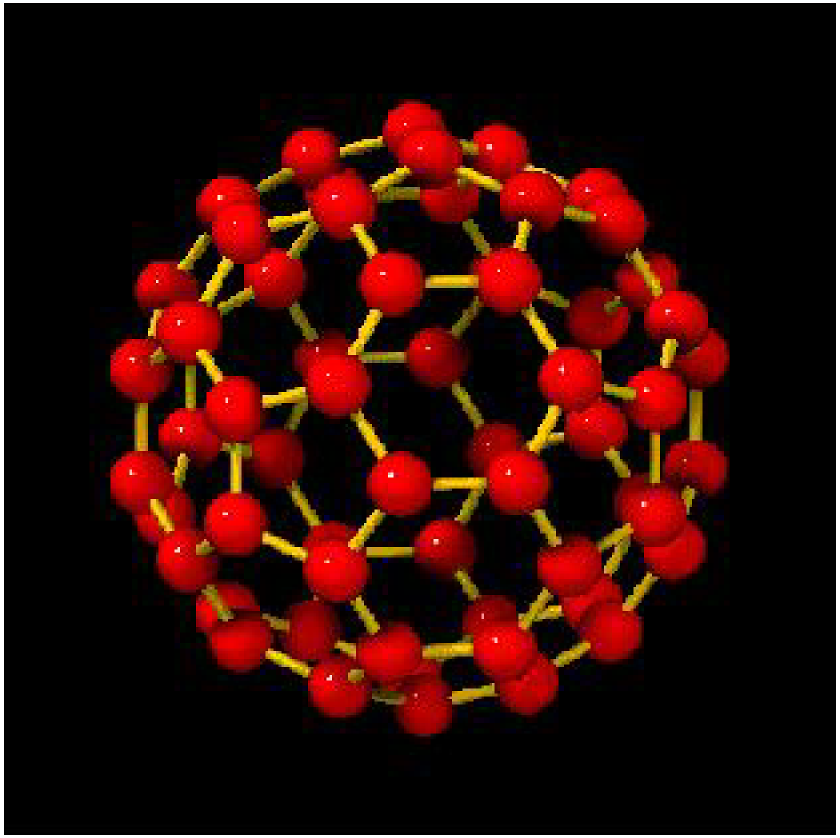
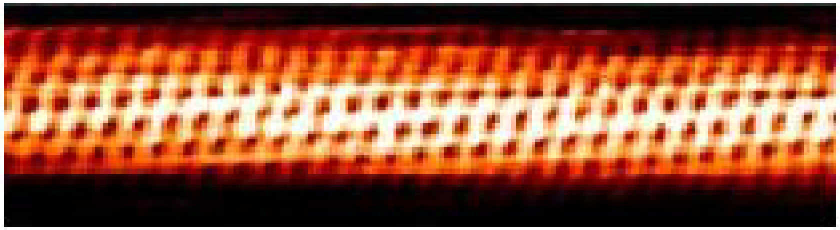
Buckminsterfullerene C_{60} and Carbon Nanotubes

- The discovery of fullerenes C_{60}, as well as of carbon-nanotubes, opens new routes for science and technology.
- Fullerenes-based materials display a rich variety of physical phenomena as superconductivity, broken-symmetry ground states, non-Fermi liquid behaviour and dimensionality crossover effects.
- **Motivation:**
  - Study of the electrodynamic response of fullerenes and carbon-nanotubes





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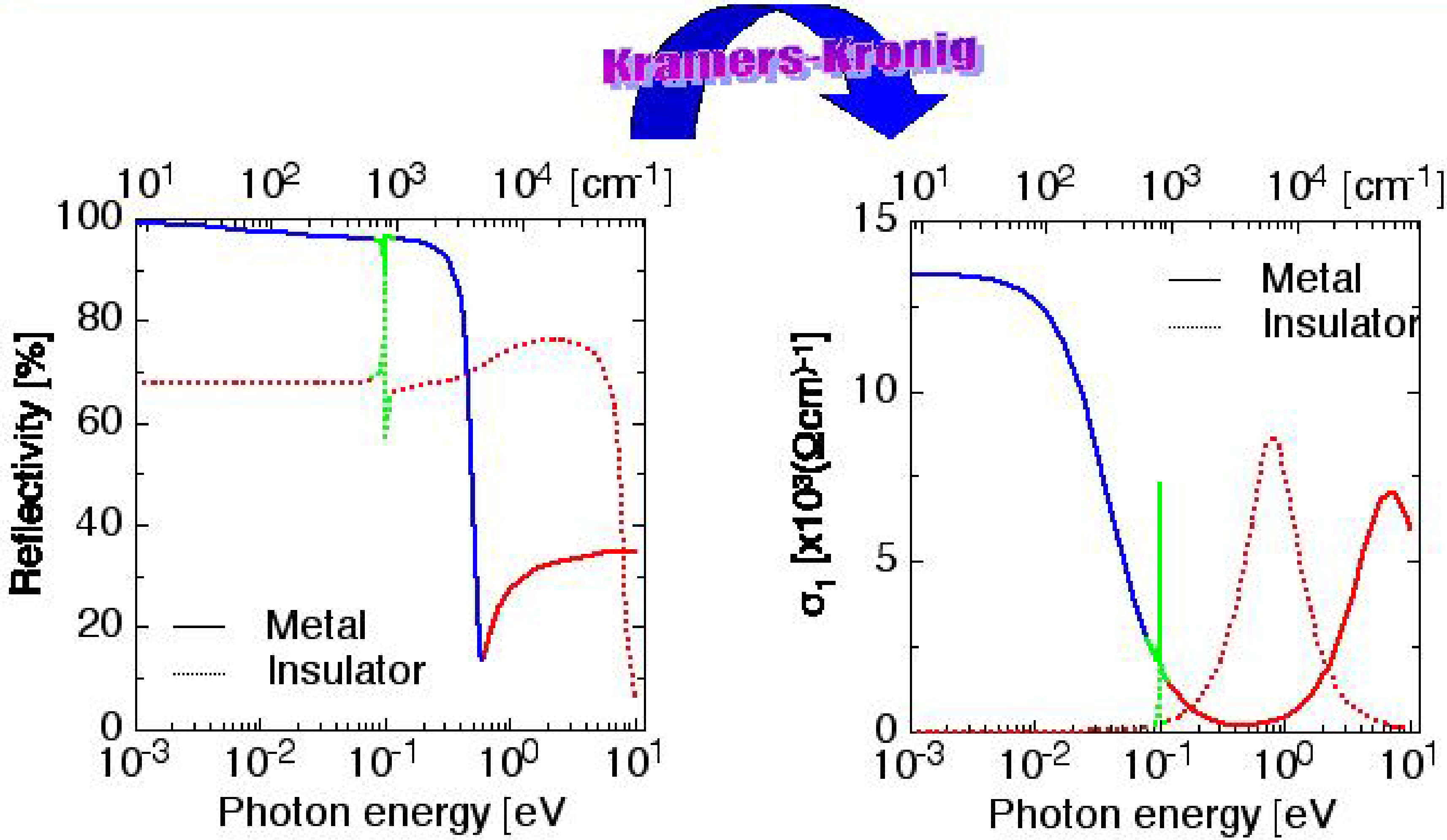
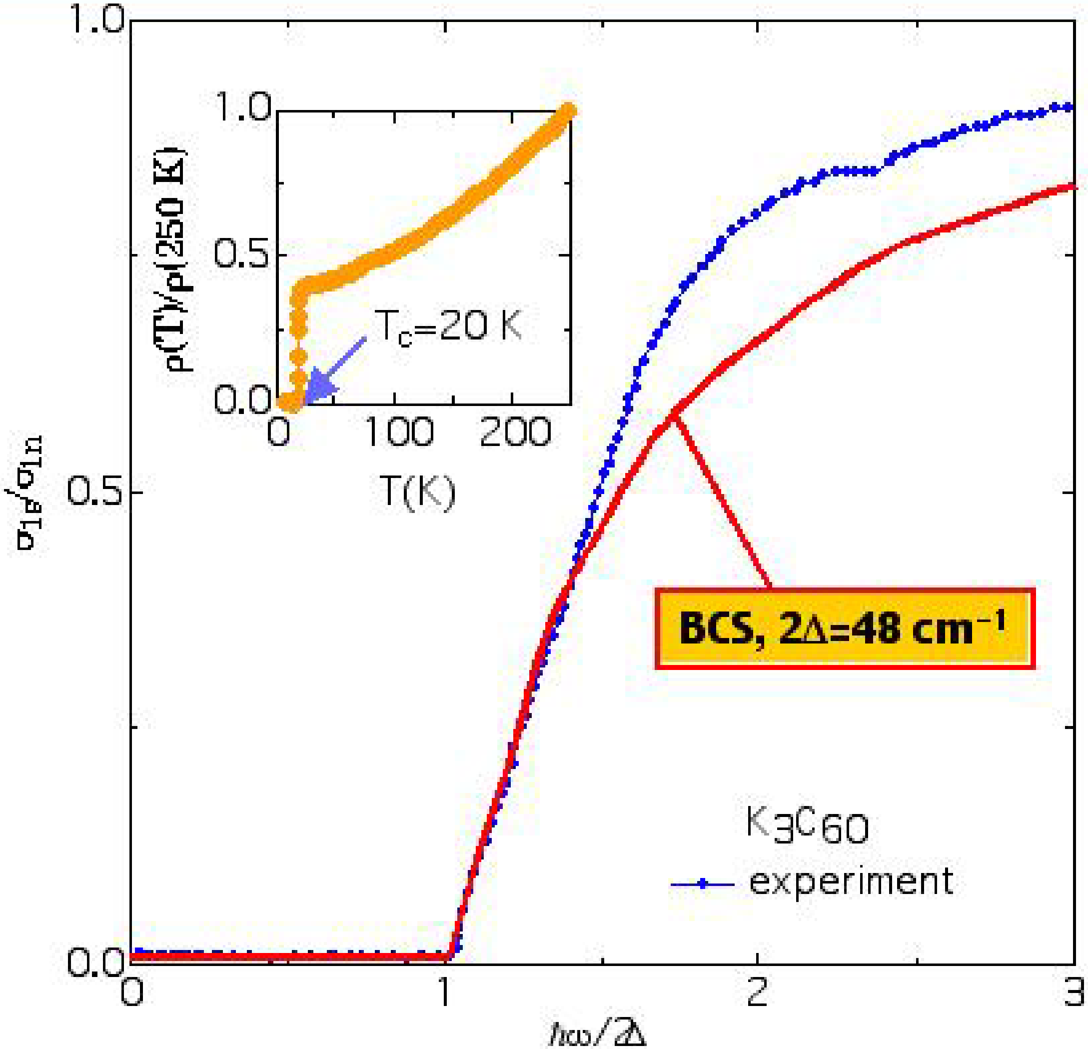
Reflectivity and Optical Conductivity



http://www.solidphys.ethz.ch/spectro/

The Optical Conductivity of K_3C_{60}



Degiorgi et al., Nature 369, 541 (1994)

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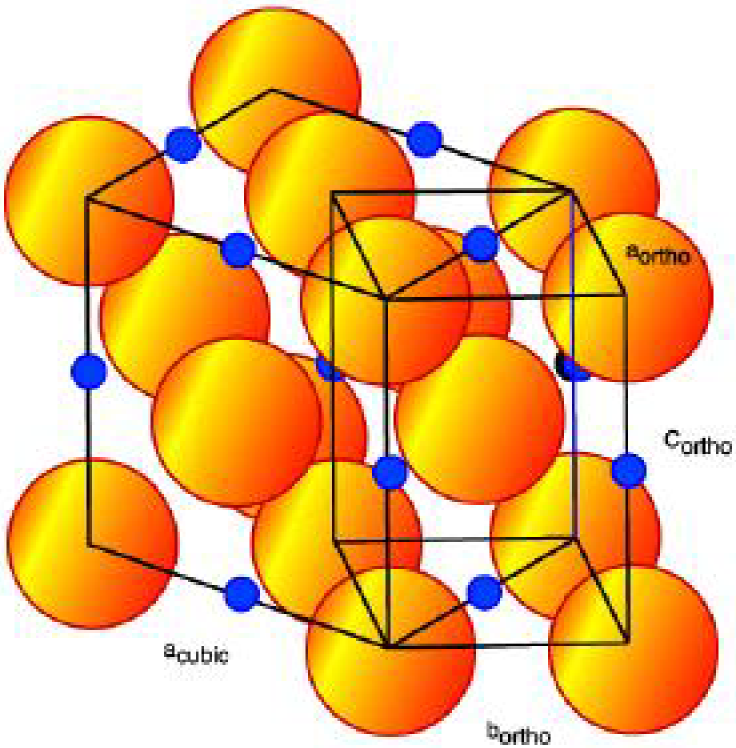
$(AC_{60})_n$: Quasi One-Dimensional Fullerene



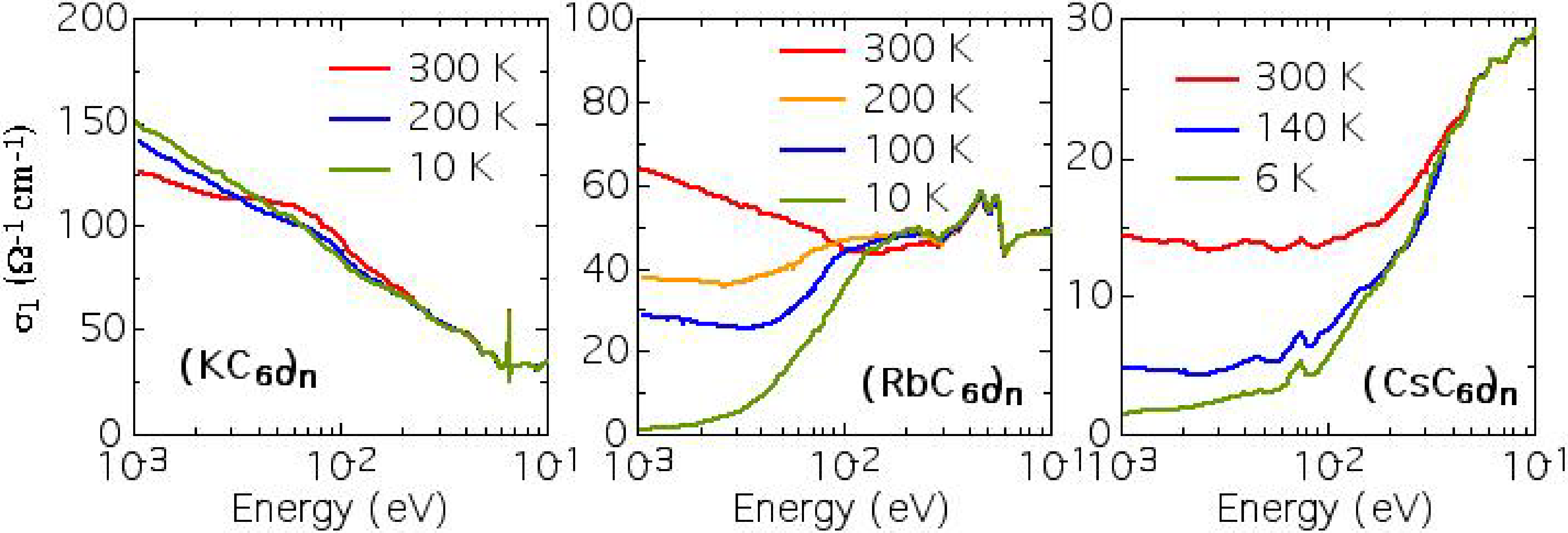
- $(AC_{60})_n$ undergo a structural phase transition at about 400 K.
- By slowing cooling from 500 K to ambient temperatures the fcc structure disappears and an orthorhombic lattice structure appears.
- The structural phase transition is induced by the formation of linear C_{60} polymers.

➡ This suggests a quasi-one-dimensional electronic structure.

➡ The Rb and Cs polymers display a metal-insulator phase transition at about 50 K. (SDW?)

Stephens et al., Nature 370, 636 (1994)

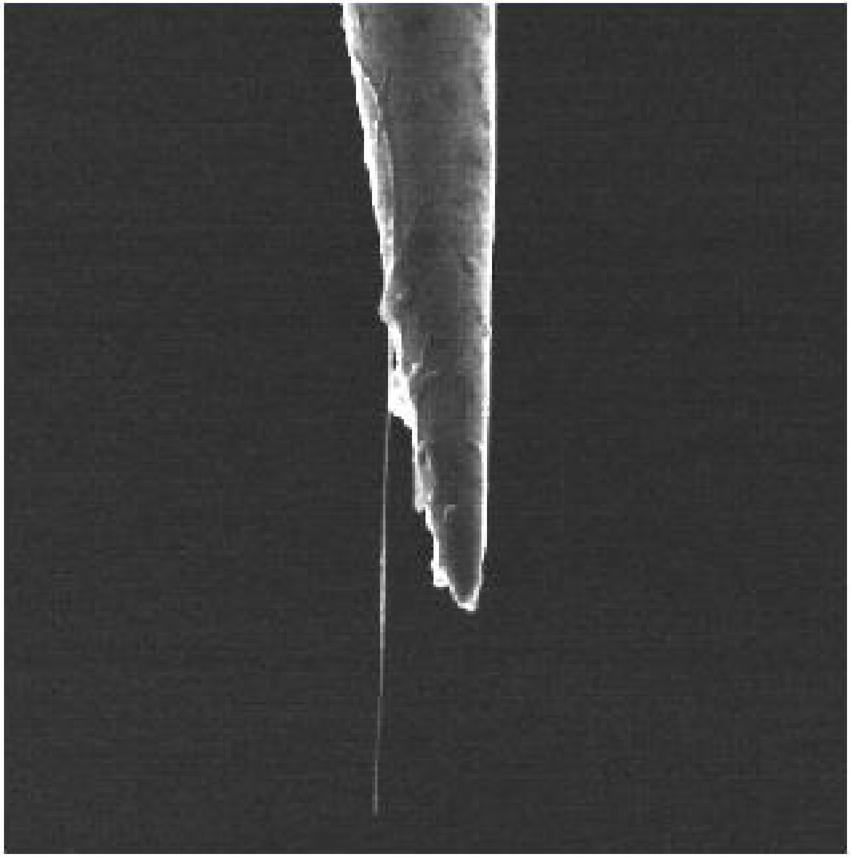
The Optical Response of $(AC_{60})_n$

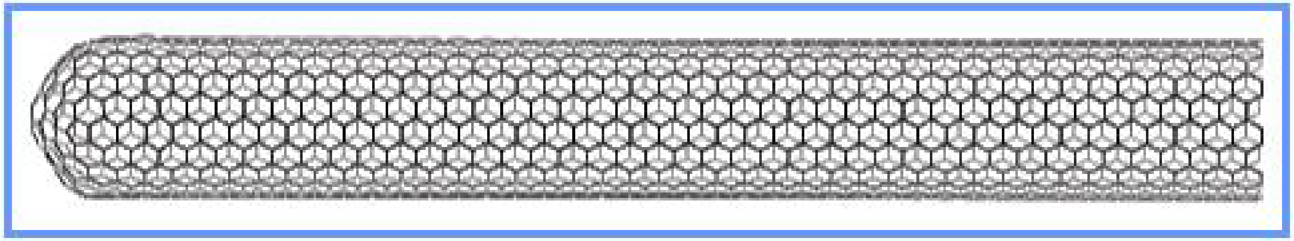


Bommeli et al., Phys. Rev. B51, 14794 (1995)

Carbon Nanotubes

- One dimensional quantum wire
- "Have to be good for something":
  - Wires for nanosized electronic devices
  - Charge-storage devices in batteries
  - Tiny electron guns for flat-screen televisions
  - Nanosize tweezers…….





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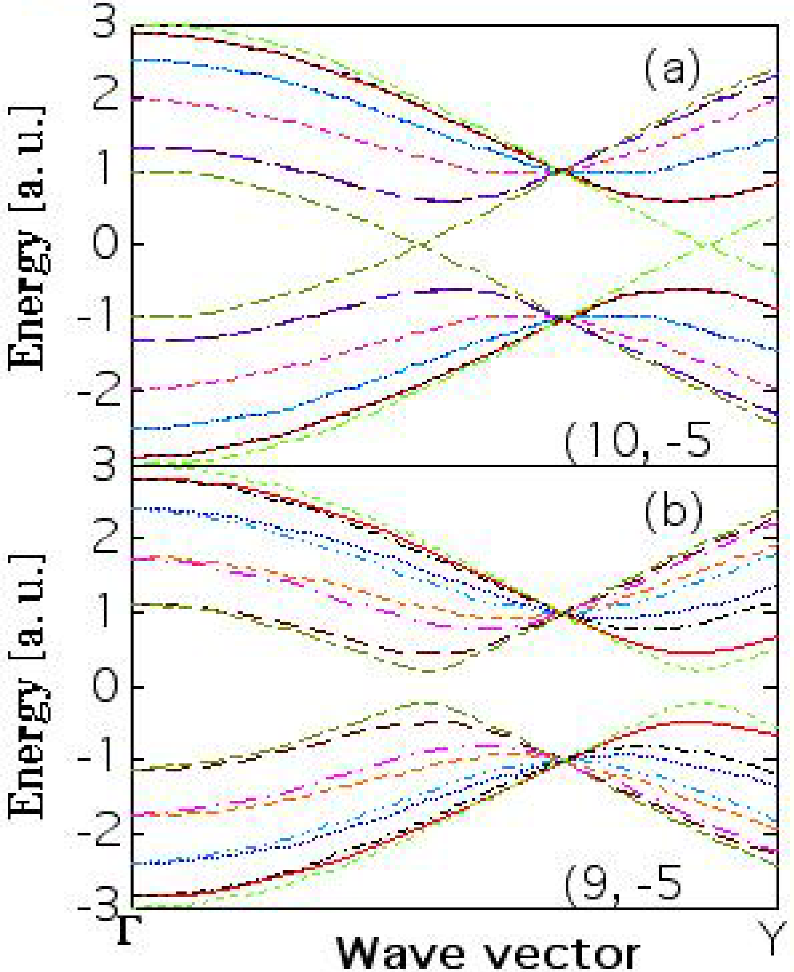
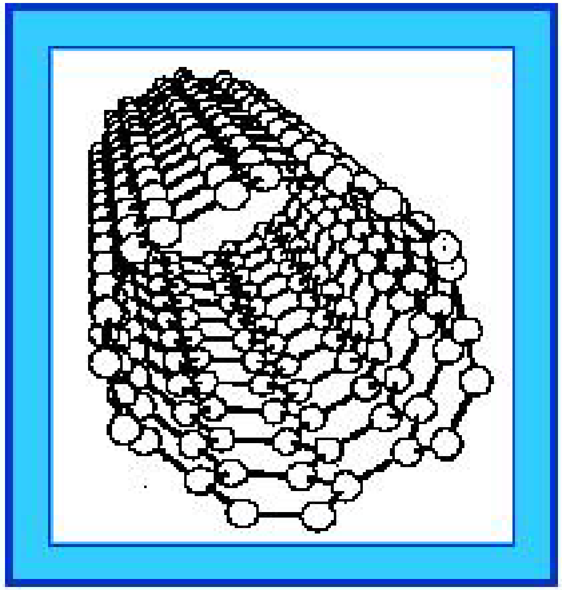
Electronic Band Structure of Carbon Nanotubes

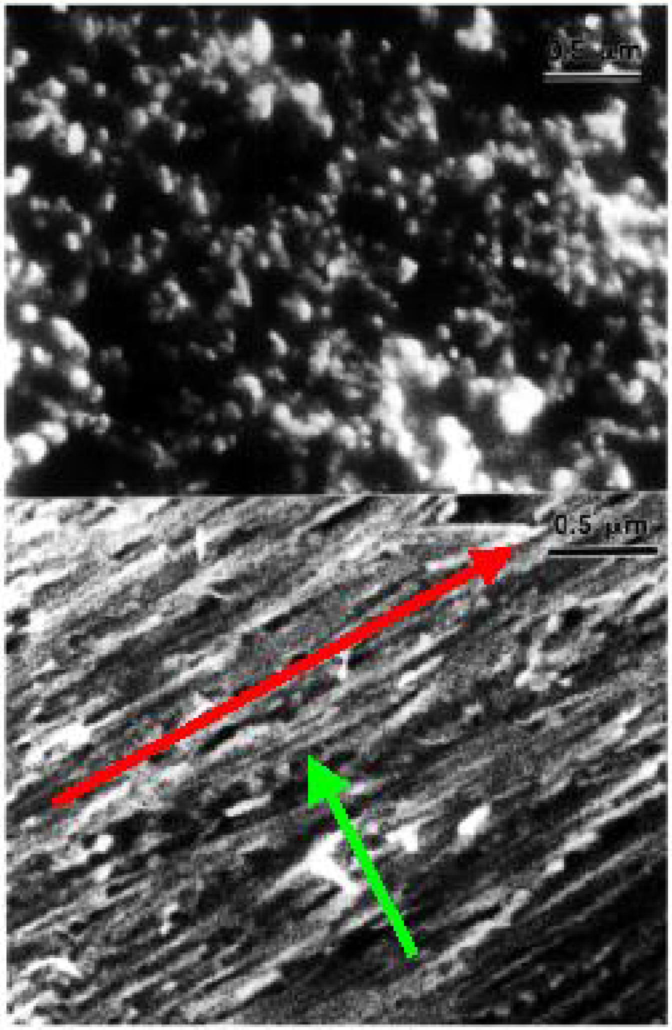




(n,n) SWNTs (armchair) are metallic, whereas (n,0) (zigzag) and (n,m) (chiral) are semiconducting.
(n,n) SWNTs develop pseudogap caused by intertube coupling.

Tasaki et al., private communication

Multi-Walled Carbon Nanotubes



- The tubes are deposited on a teflon surface and preferentially oriented perpendicular to the surface.
- When the surface is slightly rubbed with a thin teflon sheet or aluminum foil, the surface becomes silvery.
- Scanning electron microscopy shows that the surface is densely covered with nanotubes, which are oriented.
- The nanotubes are 1 to 5 µm long and 10±5 nm in diameter.

➡ Optics should reveal the intrinsic anisotropy in the electrodynamic response of the nanotubes.

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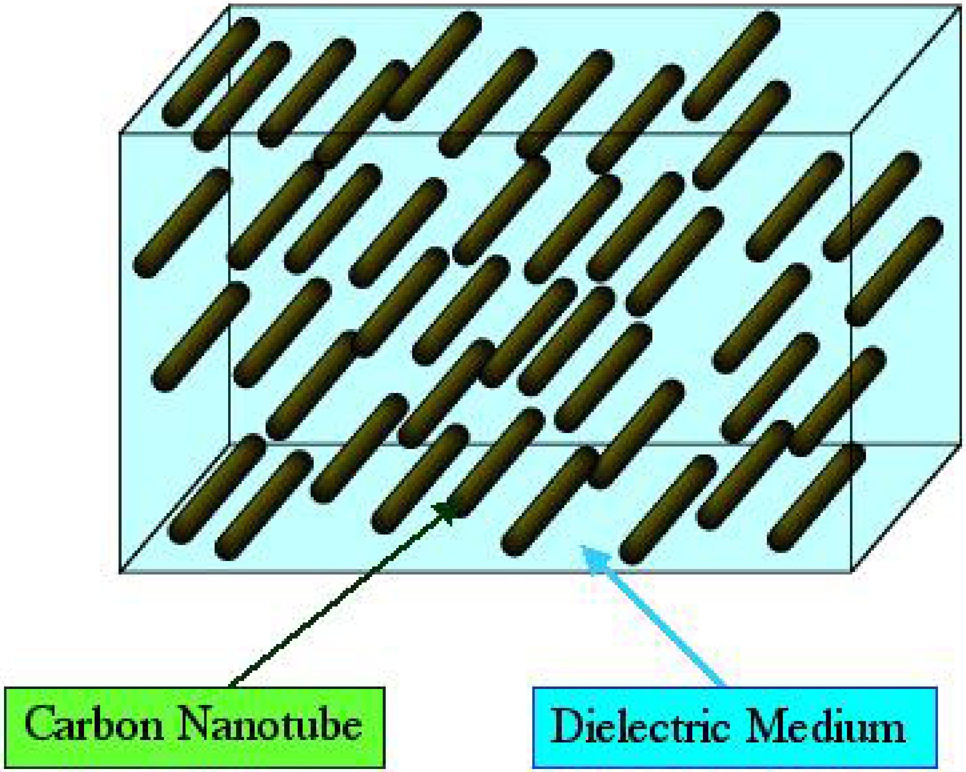
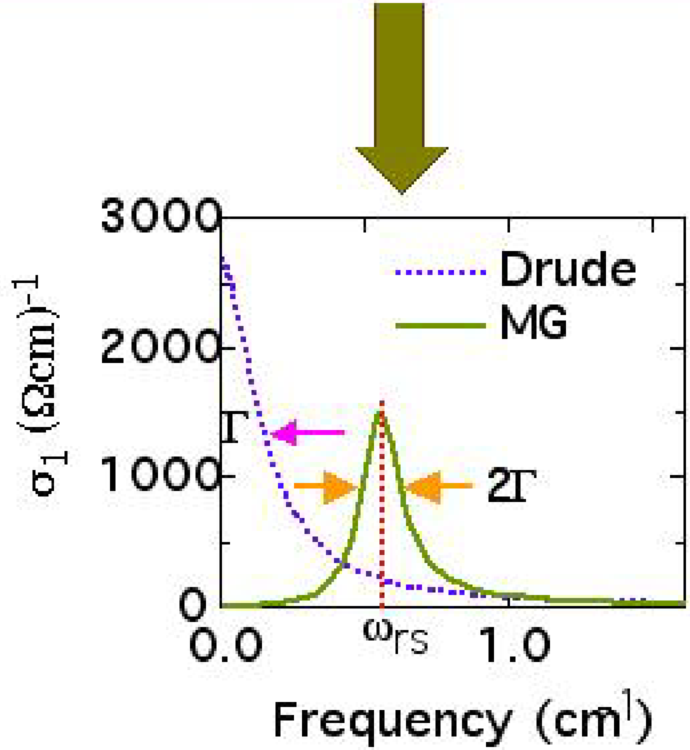
de Heer et al., Science 268, 845 (1995)

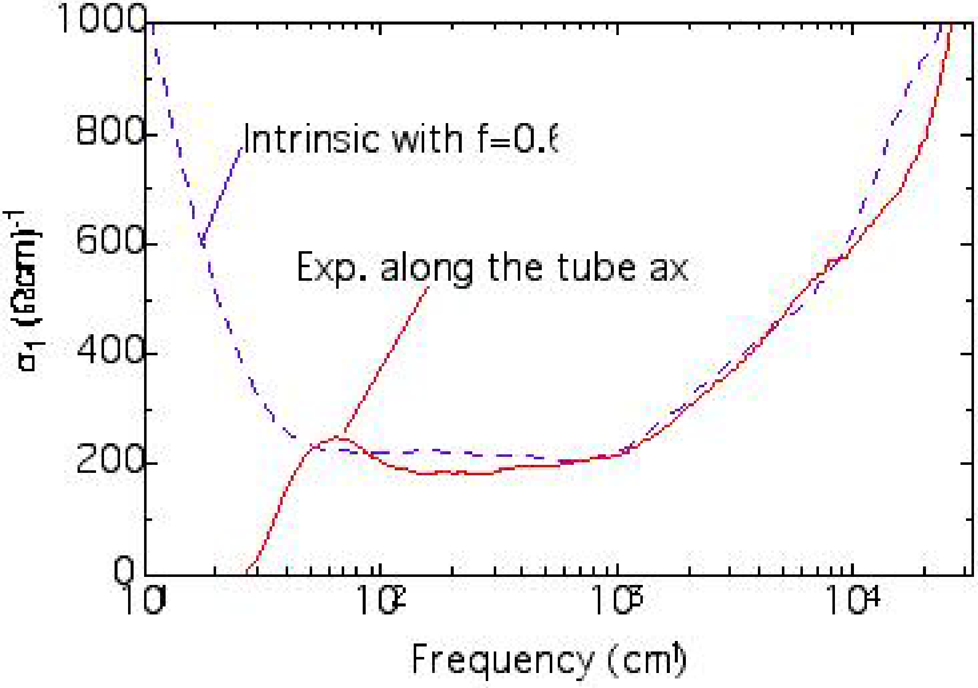
Effective Medium for Carbon Nanotubes

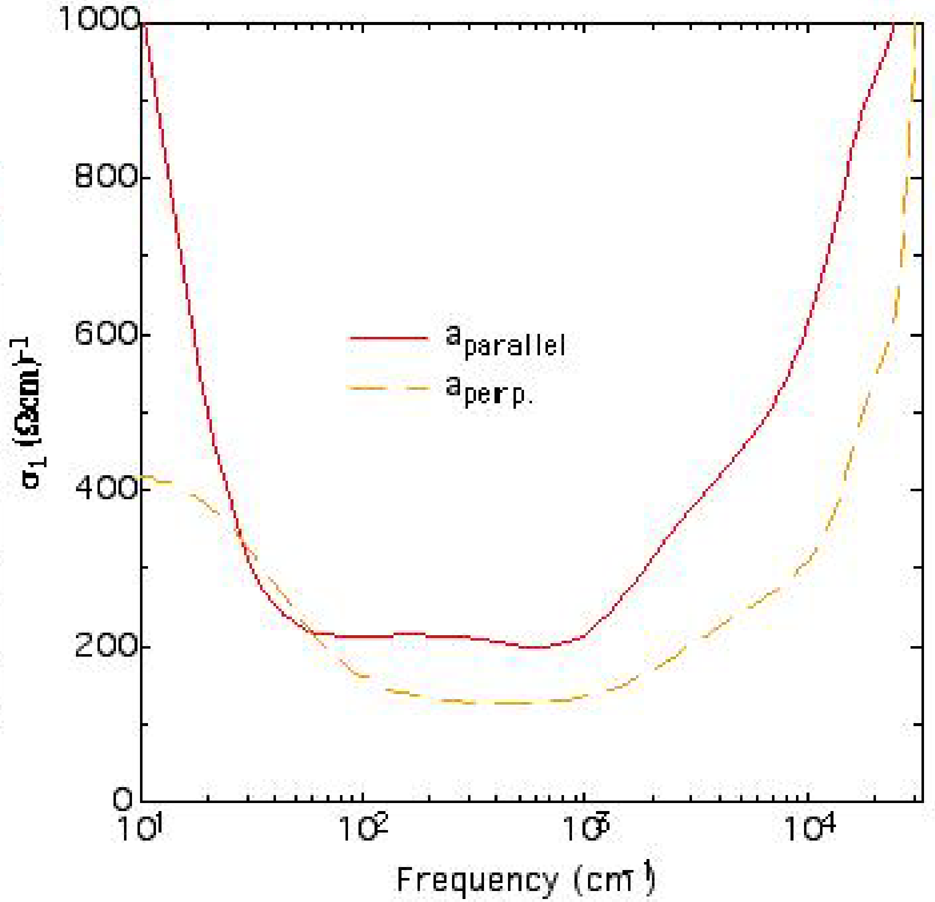
$$\varepsilon_{eff} = \varepsilon_i \frac{\left(N + f(1-N)\right)\varepsilon_m + (1-N)(1-f)\varepsilon_i}{N(1-f)\varepsilon_m + \left(fN + 1 - N\right)\varepsilon_i}$$





Anisotropic Optical Conductivity (Effective Medium Maxwell–Garnett Theory)





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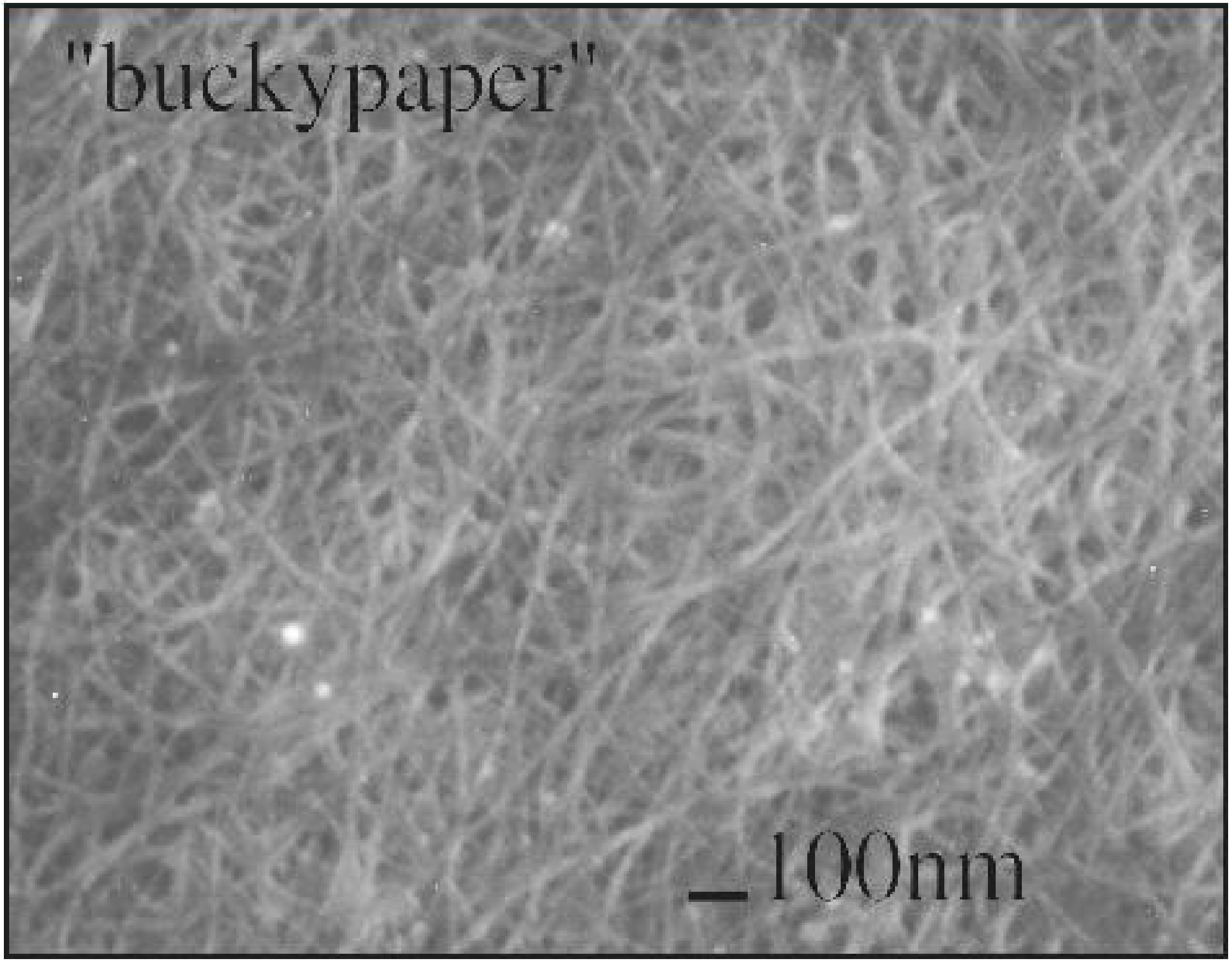
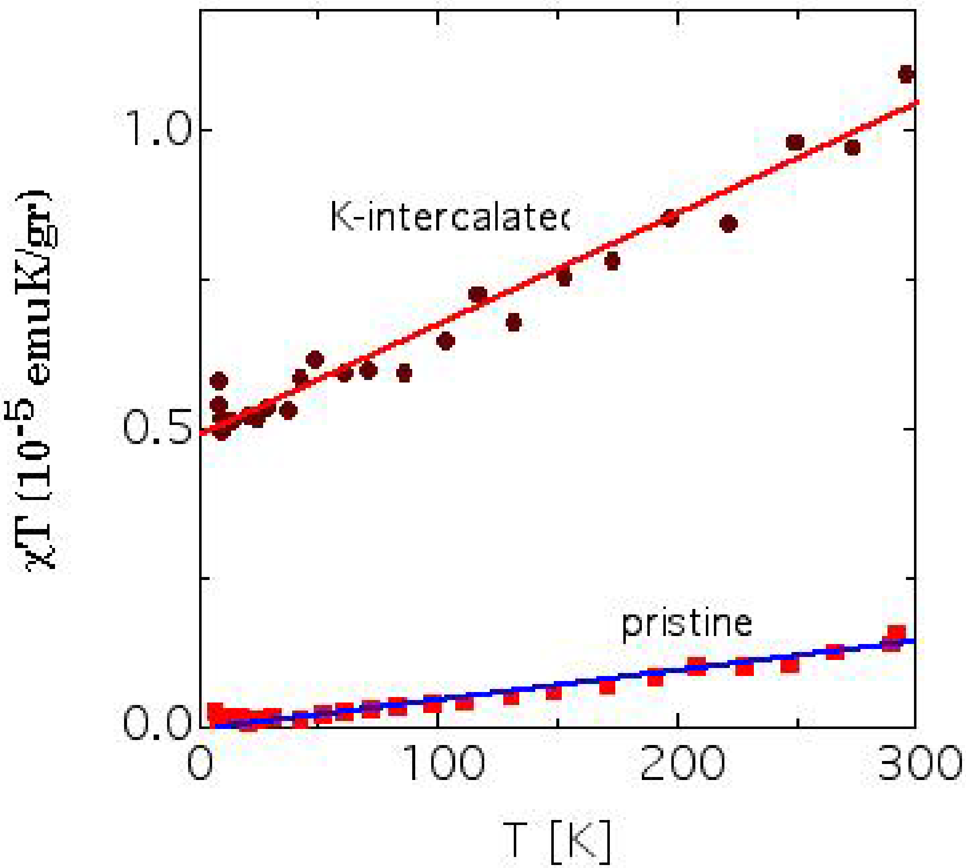
Bommeli et al., Solid State Commun. 99, 513 (1996)

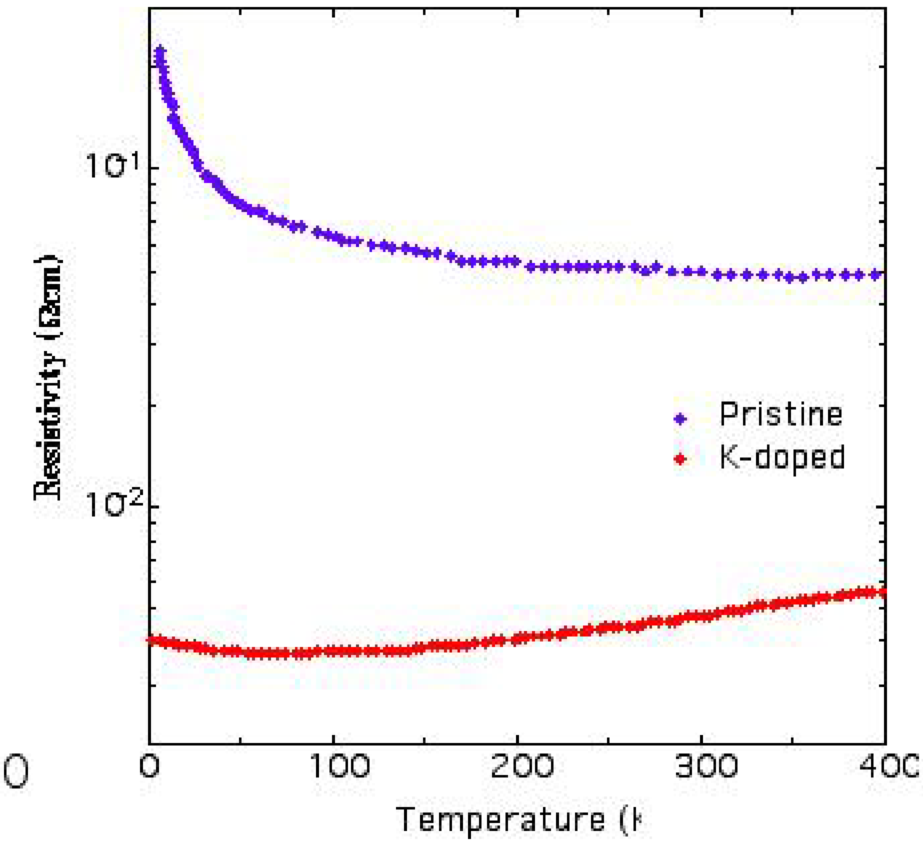
Single-Walled Carbon Nanotubes: Bucky-Paper



Ruzicka et al., Phys. Rev. B61, R2468 (2000)

Carbon Nanotubes: Pristine vs. Alkali Doping





Chauvet et al., Phys. Rev. B53, 13996 (1996)
Ruzicka et al., Phys. Rev. B61, R2468 (2000)

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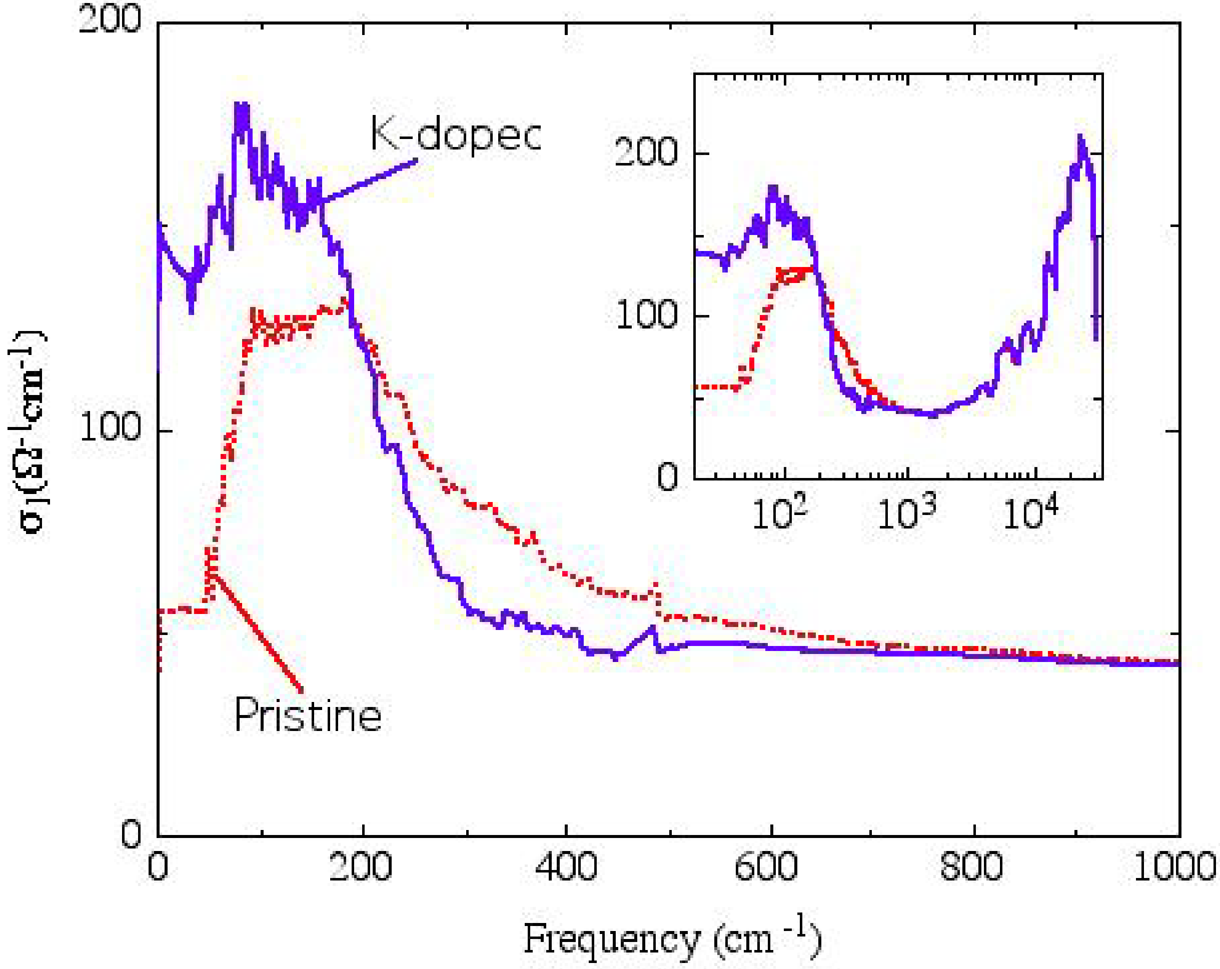
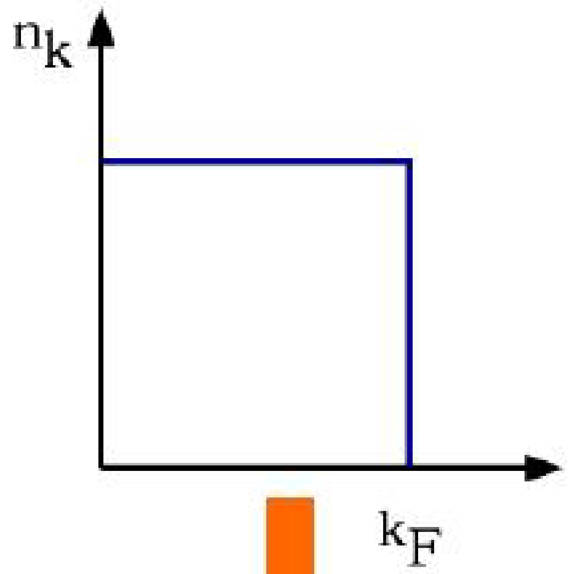
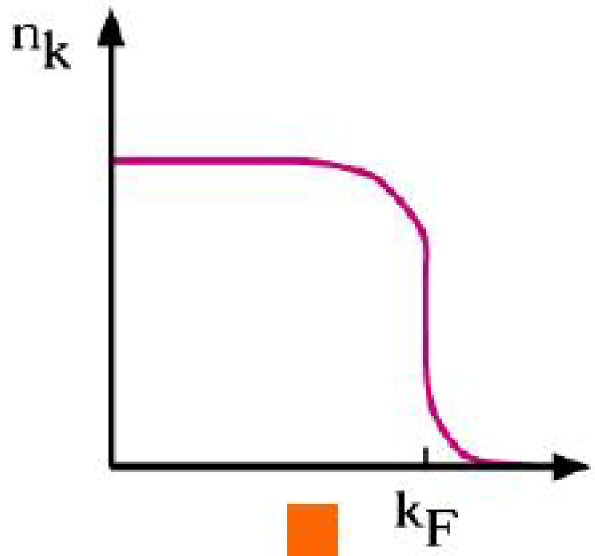
Optical Conductivity of SWNT (Bucky-Paper)

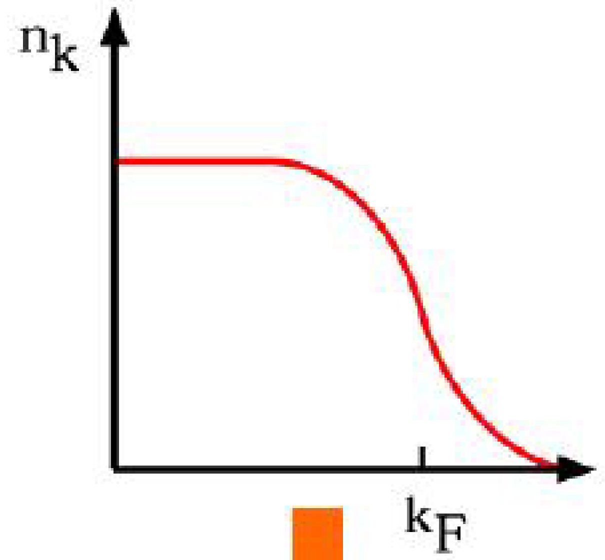


Ruzicka et al., Phys. Rev. B61, R2468 (2000)

Fermi versus Tomonaga Luttinger Liquid





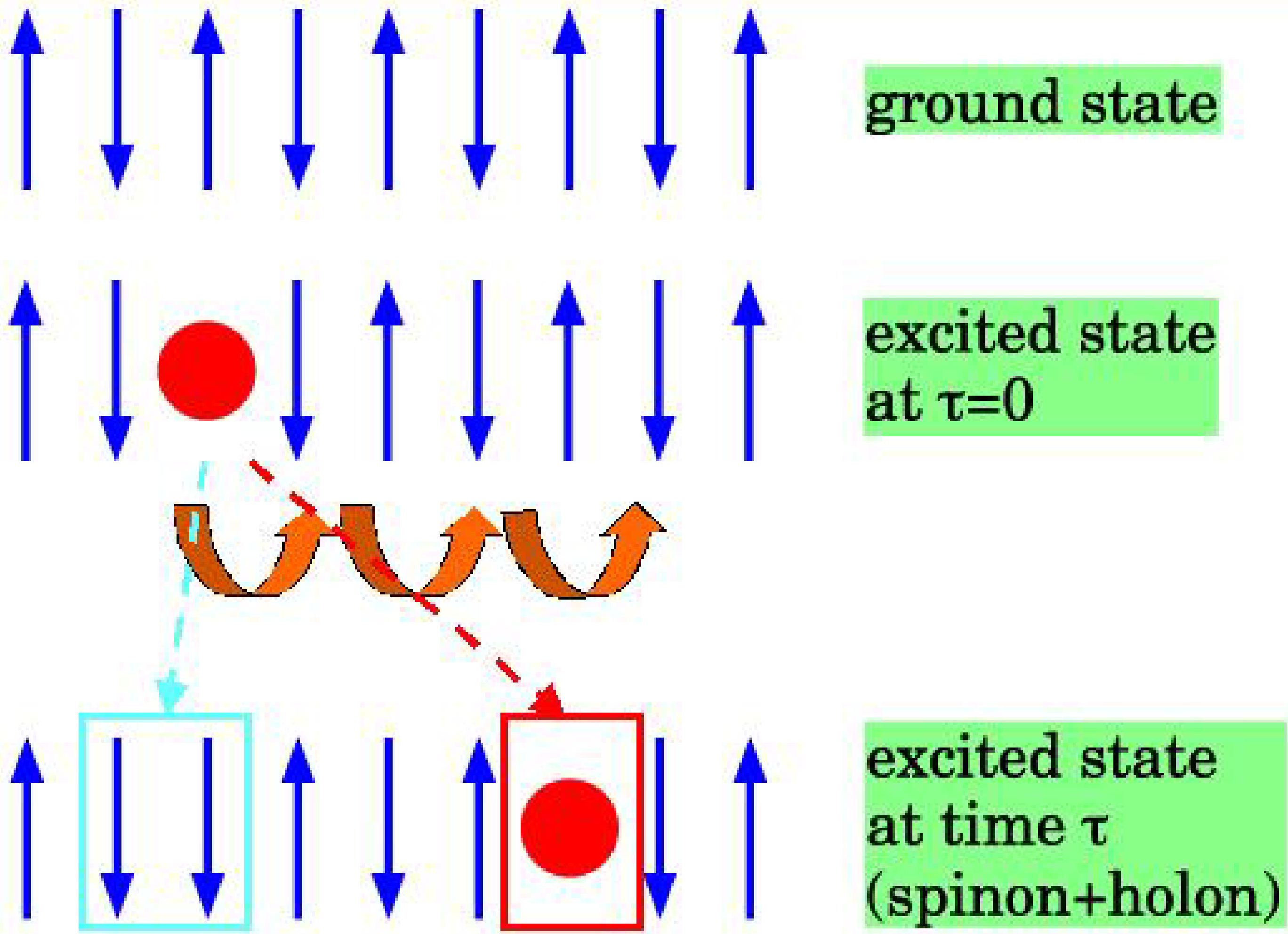


non-interacting electron gas

interacting electron gas

marginal (Luttinger) liquid

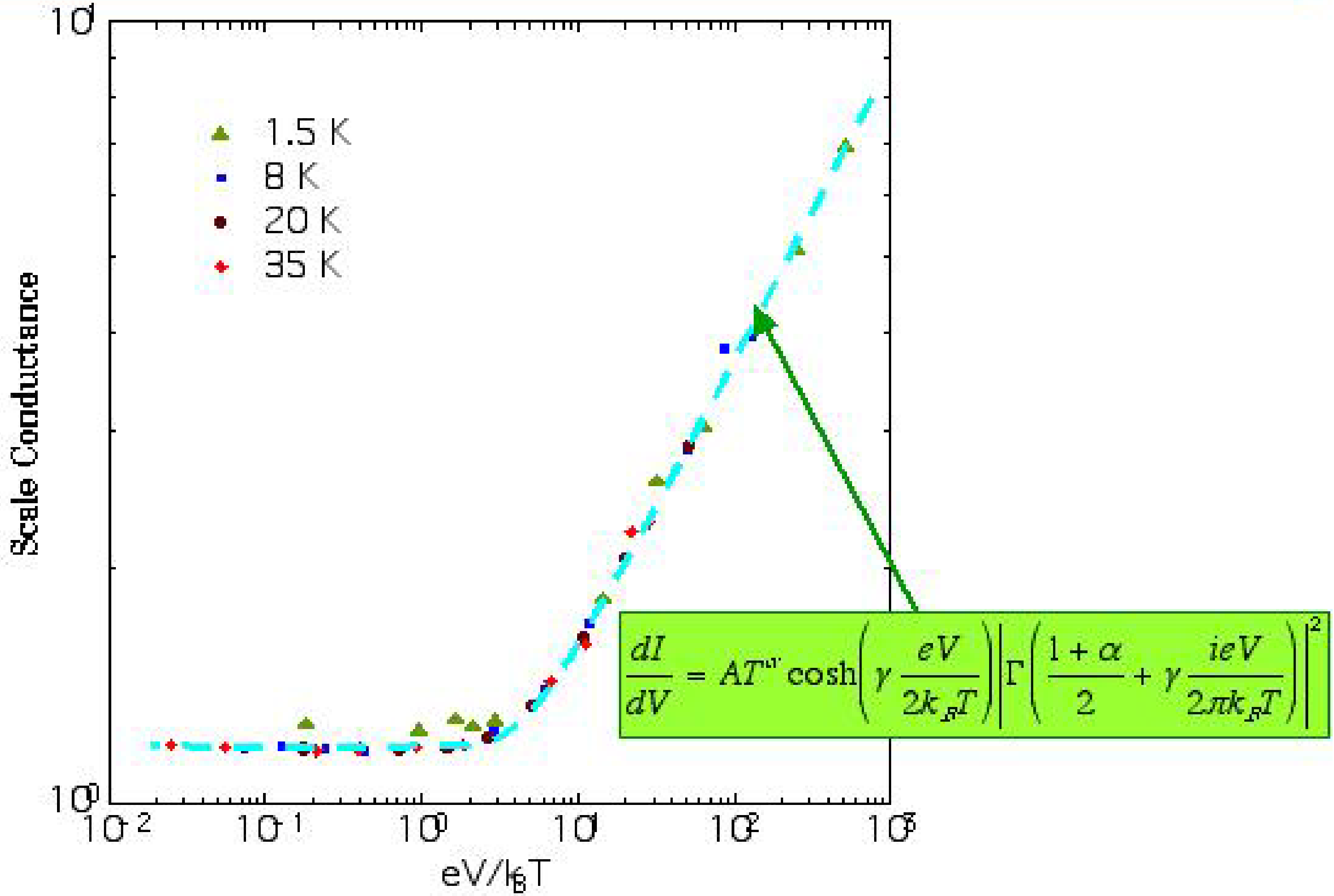
Spin–Charge Separation



Jerome, NATO–School Les Houches (1999)

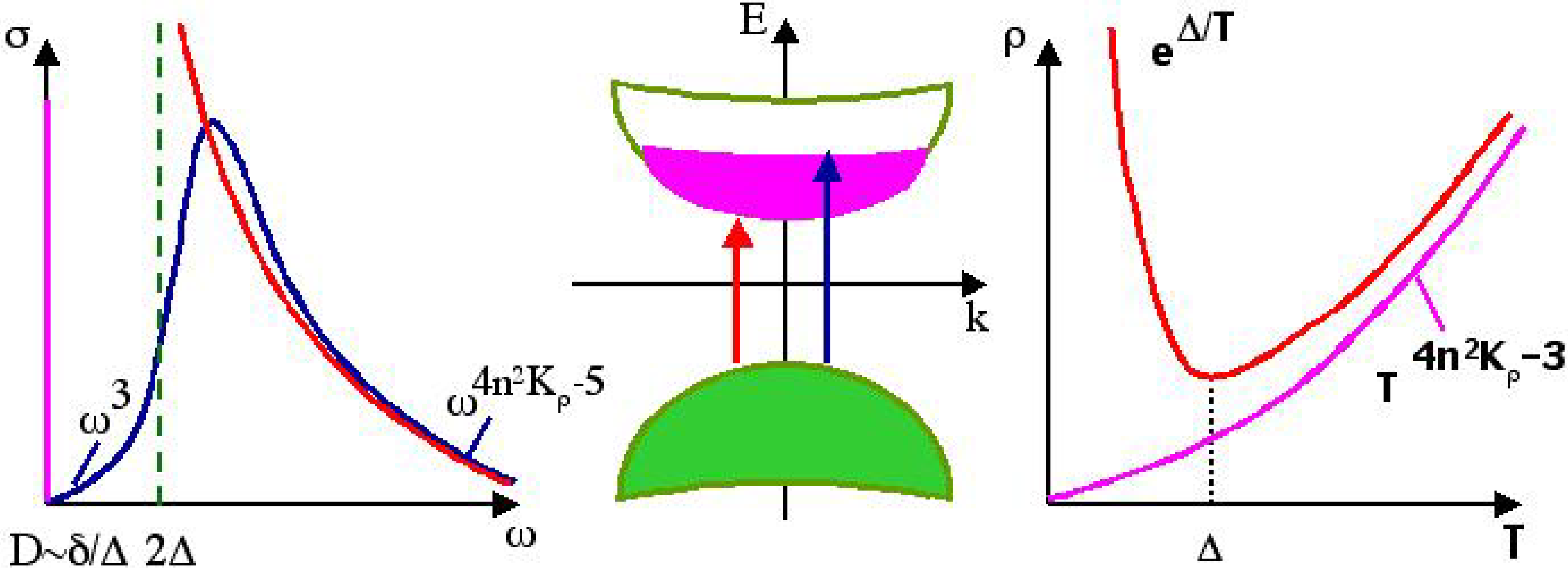
Electrons in One Dimension: Like Cars in Traffic Jam

Luttinger Liquid Behavior in Carbon Nanotubes



Bockrath et al., Nature 397, 598 (1999)

Dynamics and Transport for the Mott–Hubbard Model in One-Dimension



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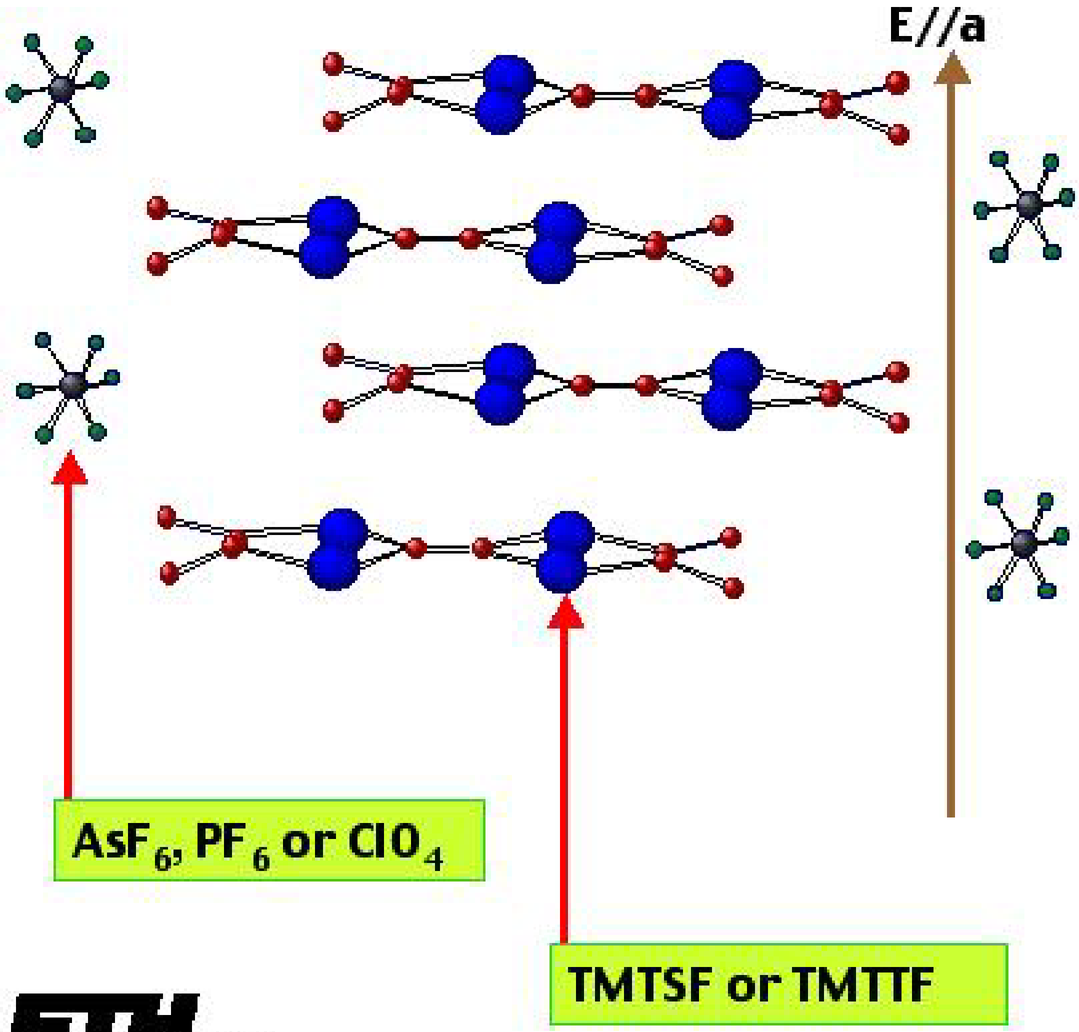
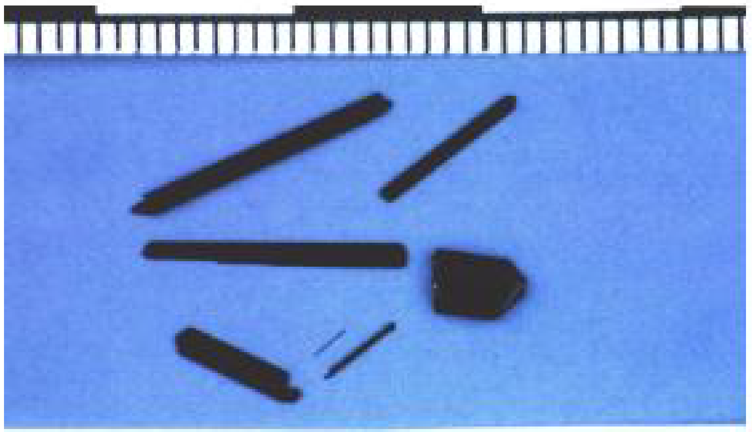
Giamarchi, Physica B230–232, 975 (1997)

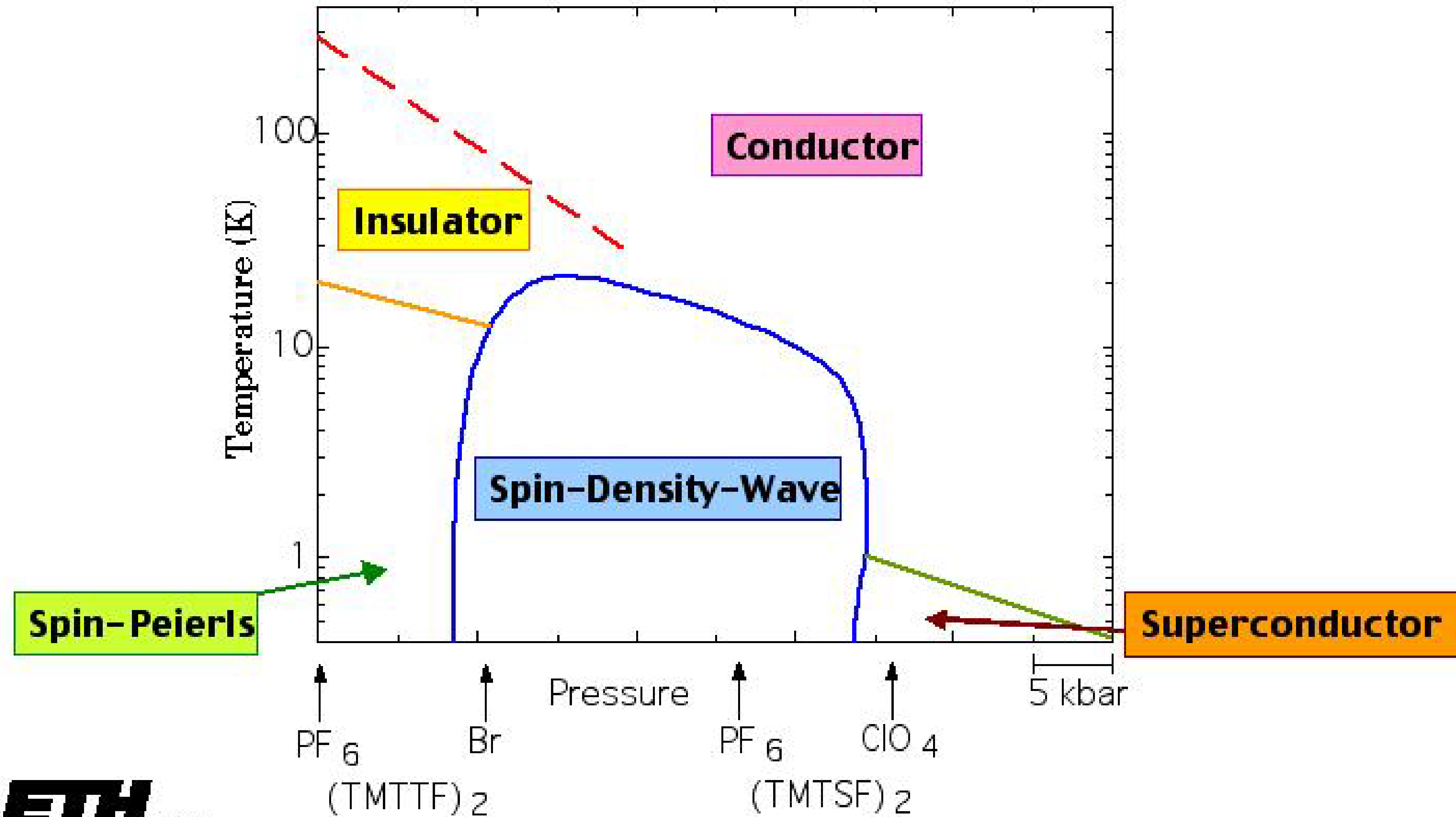
Crystal Structure of the Bechgaard Salts



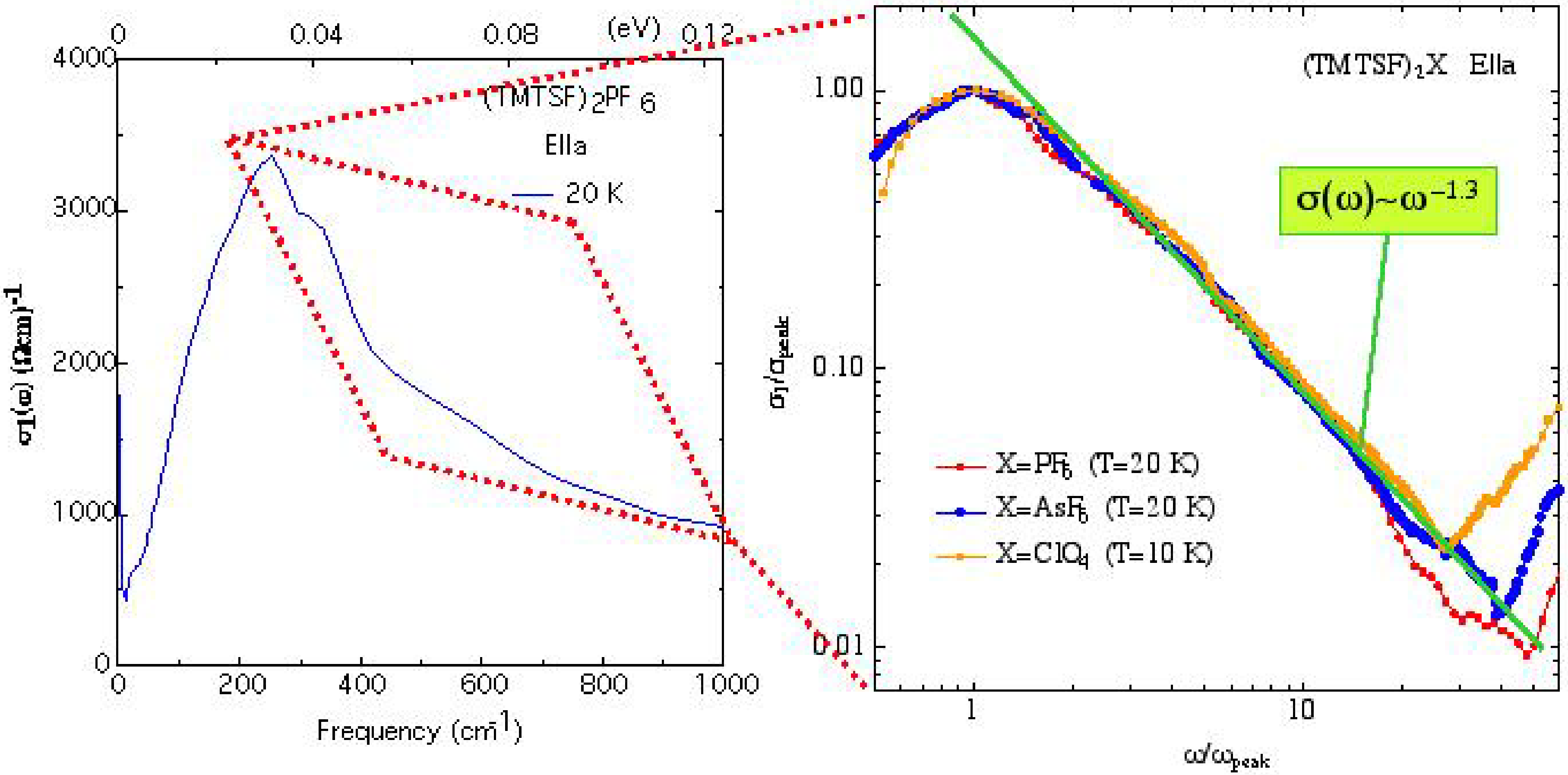


$(TMTSF)_2PF_6$

Phase Diagram of the Bechgaard Salts

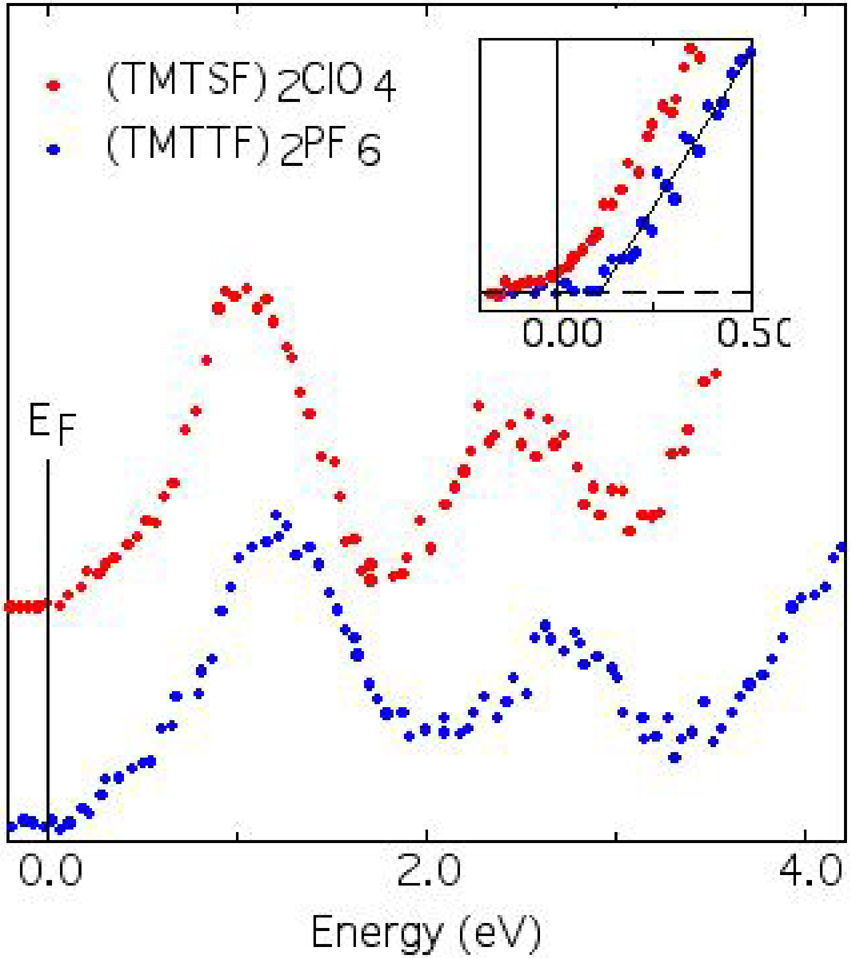


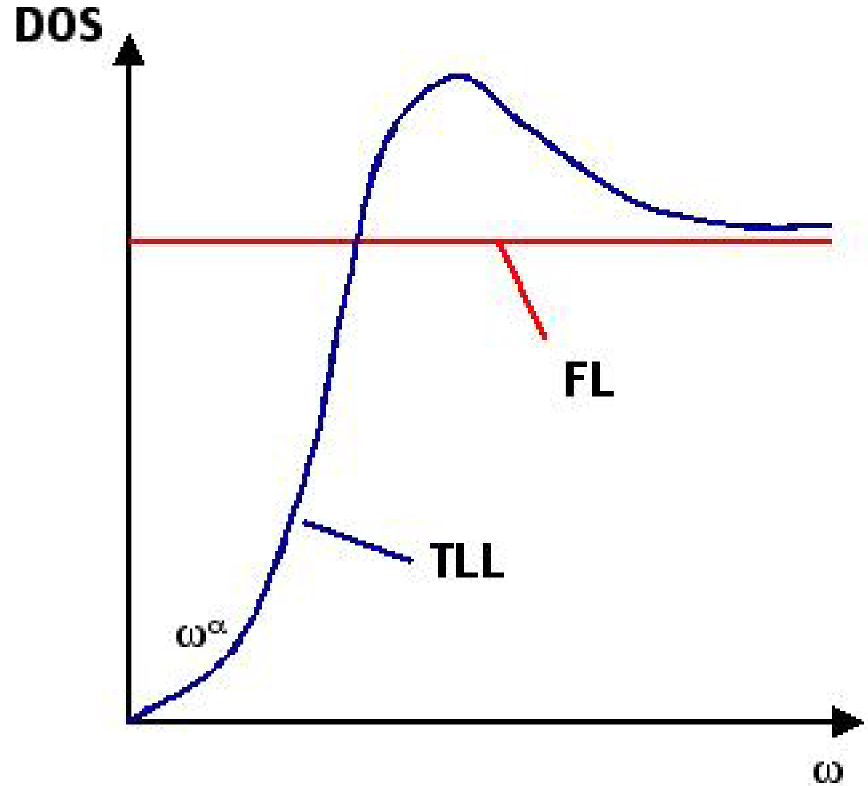
Power Law Frequency Dependence in the Optical Conductivity of TMTSF Salts



Vescoli et al., Science 281, 1181 (1998)

Photoemission Spectra of Bechgaard Salts





Zwick et al., Phys. Rev. Lett. 79, 3982 (1997)

What is next?

DNA: a New Challenging One-Dimensional System

- DNA can be viewed as one-dimensional molecular wire and as building blocks of electronic circuits.
- Electron transfer involving DNA is thought to be important in radiation damage and repair, in biosynthesis as well as in our understanding of carcinogenesis and mutagenesis.
- The question whether DNA is able to transport electrons is attracting a lot of interest.
- dc-transport results are so far puzzling, ranging from insulating to conducting, even with proximity-induced superconductivity.

➡ Optics will be relevant as contact-less technique.

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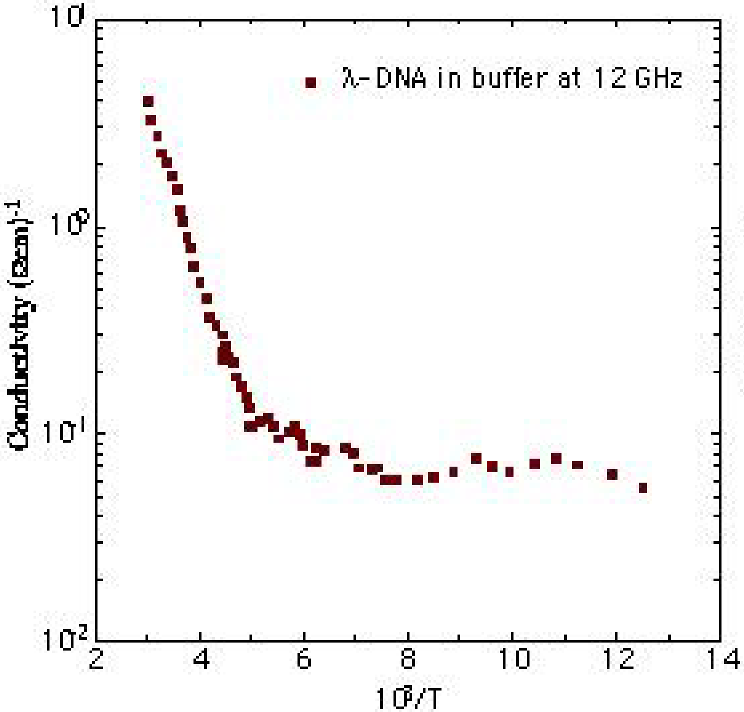
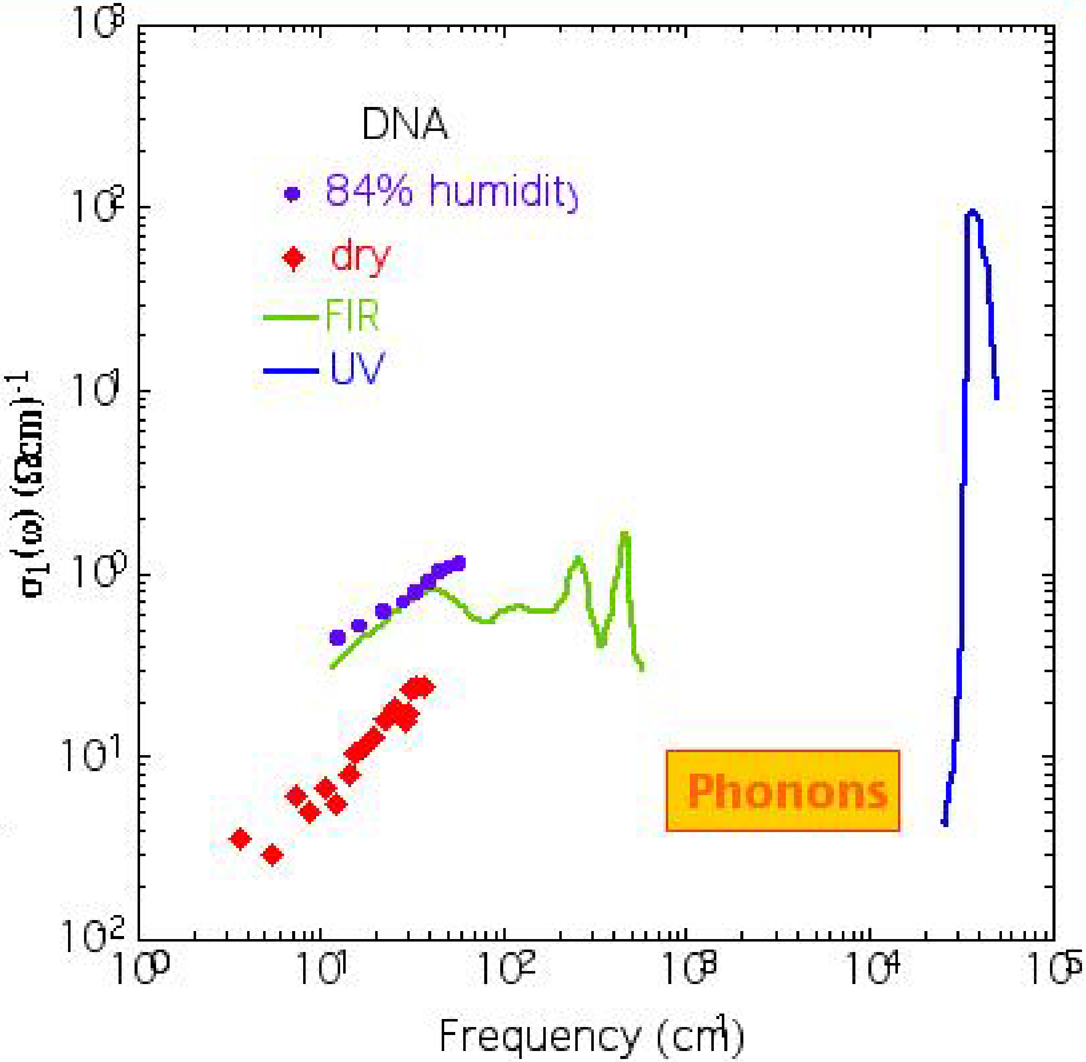
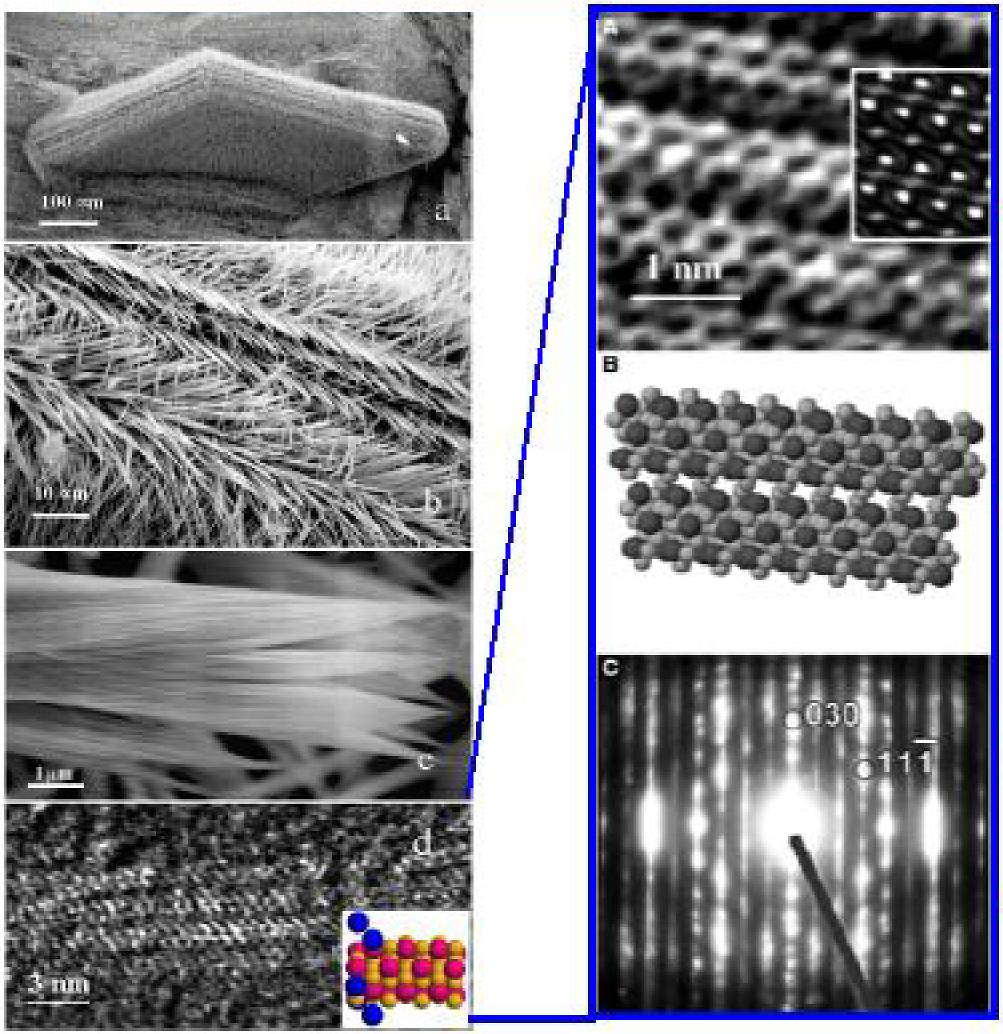
Optics in DNA: a Wide Band–Gap Insulator





(Gruner et al., private communication)

Single-Walled MoS_2 Nanotubes



- Sub-nanometer diameter (<1 nm).
- The tubes group into bundles of identical molecules, varying only in length.
- The structure corresponds to a (3,3) armchair nanotube with the [100] basal direction parallel to the tube axis.
- They offer a promising chalcogenide-based alternative to carbon nanotube technology.

Remskar et al., Science 292, 479 (2001)

Conclusions

- Characteristic energy scales
  - Superconducting and spin-density-wave gap
  - Scattering rate and plasma frequency of charge carrier
- Intrinsic parameters about the strength of interactions
  - Electron-electron and/or electron-phonon interaction
- Electronic interband transitions and phonon modes spectrum

➡ Tuning of different (correlated) states by external parameters (magnetic field and pressure)

➡ Dimensionality crossover (one- versus two-dimensional systems)

Acknowledgements

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Thank You for Your Attention

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