Electrons in Carbon Nanotubes

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Tube is characterized by $N$ and $M$. 

\[(N, M)\]
From graphite: $v_F = 8 \times 10^5$ ms$^{-1}$
g-factor = 2.0
2-fold valley degeneracy

$E_0 = 1.3$ eV / $d$(nm)
$d \sim 0.7 - 7$ nm

Type I. Metallic tubes
$M-N = 0$  $E_g=0$

Type II. Wide-gap semiconducting tubes
$M-N <> 3p$  $E_g = 2/3 \ E_0$

Type III. Narrow-gap tubes (chiral metals)
$M-N = 3p$  $E_g = 10-20$ meV
State of the art in growth

Synthesis of Ultralong and High Percentage of Semiconducting Single-walled Carbon Nanotubes

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Notes on nanotube device technology

- Metal on tube can give contact transmission ~ 1
- No tuneable contacts yet
- No multiterminal measurements

Gating techniques:
- Doped silicon substrate
- Thin dielectric-metal film added [IBM, Delft]
- Water/electrolyte [Cornell]

\[ E_F \sim -0.3 \text{ eV} \quad \text{(without gate)} = 1 \text{ dopant hole} / 10^3 \text{ C atoms} \]

Mobilities \( \mu > 10^5 \text{ cm}^2/\text{Vs} \) for metallic tubes
\[ > 4 \times 10^4 \text{ cm}^2/\text{Vs} \quad \text{for semiconducting tubes} \]

Transconductance \( g_m > 7 \mu\text{S/nm} \)
Defect-free metallic tube

Metallic tube with defects?

Wide-gap semiconductor

Narrow-gap semiconductor? [Dai group data]

Metallic tube with defects?
Two-terminal resistance of a metallic tube

\[ R = \frac{h}{4te^2} + R_{el-ph} + R_{imp} \]

Contact transmission \( 0 < t < 1 \)

\[ R_{el-ph} + R_{imp} \sim 3k\Omega/\mu m \quad \rightarrow \text{mean free path} \sim 2 \mu m \]
Single-wall tubes as Luttinger liquids

Typical $T$ dependences

$G \sim T^\alpha$

Same power laws found in multiwall tubes [Bachtold et al, PRL 2001]

Coulomb blockade with a dirty 1D L-C transmission looks the same
Where are the correlation gaps? Mott, Peierls, superconducting, ...

Some answers:
Smaller than $kT$
Suppressed by finite size and Coulomb blockade
Hidden by potential nonuniformity

![Diagram showing band crossing point and source-drain setup with $E_F = -0.3$ eV]
Cooling a metallic tube

[Graph showing conductance ($\mu$S) against gate voltage (V) at various temperatures.]

- 285 K
- 129 K
- 40 K
- 16 K
- 8 K
- 1.6 K

Temperature ($T$) in Kelvin, Conductance ($G$) in microsiemens ($\mu$S).
Transport spectroscopy of a quantum dot

$B = 0 \text{ T}$

$T = 100 \text{ mK}$
U = e^2/C_{tot} \sim e^2/\epsilon L \sim 3 \text{ meV} / L [\mu m]

\Delta = \hbar v_F / 4L = 0.5 \text{ meV} / L [\mu m]

\frac{U}{\Delta} \sim 6 \quad \text{in ‘closed’ dots}
Bimodal peak spacing distribution in a selected nanotube dot

\[ G(e^2/h) \]

\[ \Delta N_g (V) \]

\[ V_g (V) \]

\[ index \ n \]

\[ count \]
Pairing and alternating ground state spin

$B = 0$

$B = 6\, T$
Correlated excitation spectra at different electron numbers
Signs of 4-fold shell filling

\[ \delta = \text{K – K'} \text{ subband splitting} \]
Quantum dot

Poor contacts

$G (T = 300 \text{ K})$

$T = 300 \text{ mK}$

$0.3 \frac{e^2}{h}$

Device A

$1.7 \frac{e^2}{h}$

Device B

$3.1 \frac{e^2}{h}$

Device C

$V_g (V)$

Good contacts

quantum dot

quantum wire
Kondo and cotunneling features with half-open contacts

\begin{align*}
V(mV) & \quad 0.0 \quad 0.4 \quad 0.8 \\
V_g(V) & \quad 2.30 \quad 2.35 \quad 2.40 \quad 2.45 \quad 2.50
\end{align*}

\begin{align*}
N \text{ even, } S = 0 \\
N \text{ odd, } S = 1/2
\end{align*}
**Kondo effect in a quantum dot**

For a review, see Kouwenhoven and Glazman
Physics World, January 2001

Odd electron number $N$ ($S=1/2$) only

Repeated spin-flip cotunneling processes $\rightarrow$ correlated electron state in contacts

Transmission through dot $\leftrightarrow$ Kondo scattering rate of magnetic impurity in metal

$$G \sim -\log(T/T_K) \quad \quad \quad T_K \sim (U\Gamma)^{1/2} \exp[-\pi\varepsilon(\varepsilon+U)/\Gamma U]$$

Halfway between Coulomb peaks, at $\varepsilon = -U/2$, for a tube dot,

$$T_K \sim (U\Gamma)^{1/2}\exp[-(\pi/4)U/\Gamma] \quad \quad \quad \Gamma \leq \Delta E \quad \quad \quad U/\Delta E = 6$$

$\sim 50 \text{ K} \times e^{-4.5}$

$\sim 0.5 \text{ K}$
Kondo effect induced by magnetic field

$$B \left( \frac{e^2}{h} \right)$$

$$G(B)$$

$$V_g = -0.322 \text{ V}$$

$$V_g = -0.296 \text{ V}$$

Odd $N$

Even $N$

$$\Delta_t$$

$$\Delta_s$$
Inelastic cotunneling – or more?

Is there some Kondo nature to these nonequilibrium features?
A Quantum Dot in the Kondo Regime Coupled to Superconductors

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(Dated: August 13, 2002)

normal leads

Apply small $B$-field

superconducting with $\Delta = 1$ K

Multiple Andreev reflection

\[ E[\{N_{\mu\sigma}\}] = \sum_{\mu,\sigma,l} \epsilon_{l\mu}[\phi]n_{l\mu\sigma} - h \sum_{\mu} (N_{\mu\uparrow} - N_{\mu\downarrow}) + \frac{1}{2} U_c \left[ \sum_{\mu,\sigma} N_{\mu\sigma} - 2N_{\text{ion}} - N_0 \right]^2 + \delta U \sum_{\mu,l} n_{l\mu\uparrow}n_{l\mu\downarrow} + J \sum_{\mu,\mu'} N_{\mu\uparrow}N_{\mu\downarrow}, \]

**Predictions: for a (10,10) [or (5,5)] tube**

\[ 3.94[5.04] > U_c/\Delta > 1.14[1.34], \]
\[ \delta U/\Delta = 0.11[0.22], \quad J/\Delta \geq 0.22[0.44] \]

In the Kondo regime, Liang et al find experimentally

\[ J/\Delta \sim 0.1 - 0.2 \]

but \[ U/\Delta \sim 0.15 - 0.3 \]

compared with \( U/\Delta \sim 5 \) in closed dots!

A dramatic difference is seen between closed and open dots, involving major changes in the spectrum with a small change in contact quality.
Some noteworthy aspects of nanotube quantum dots

• 1D level structure, but complexities not understood
• Zeeman tuning in $B$-field - negligible orbital couplings
• High $T_K$ for large $N$. $T_K \sim < (U\Delta)^{1/2} \exp[-(\pi/4)U/\Delta]$ 
• Nonequilibrium and multilevel Kondo effects
• Lead material can be changed – eg, superconductor
• Dramatic closed $\rightarrow$ open transition