Tomonaga-Luttinger Liquid Features in Ballistic Single-Walled Carbon Nanotubes:Conductance and Shot Noise

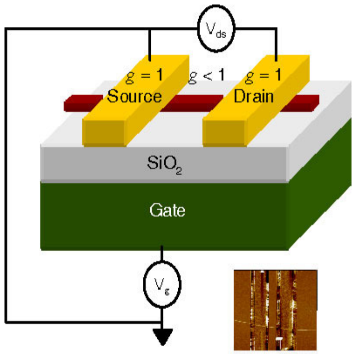
Kim, Recher, Oliver, Yamamoto – Ginzton laboratory, Standford
Kong, H. Dai – Chemistry department, Standford

Abstract:

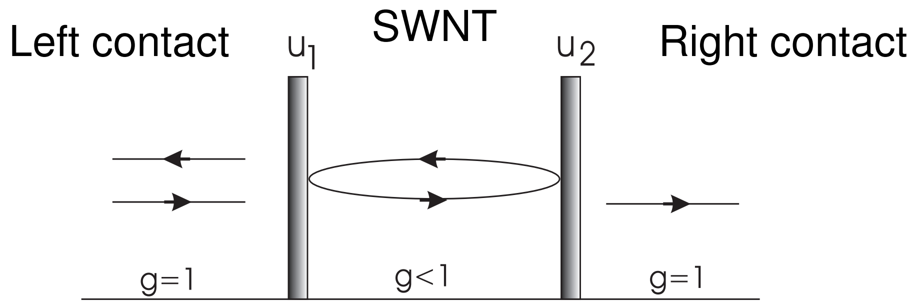
We study the electrical transport properties of well-contacted ballistic single-walled carbon nanotubes in a three-terminal configuration at low temperatures. We observe signatures of strong electron-electron interactions: the conductance exhibits bias-voltage-dependent amplitudes of quantum interference oscillation, and both the current noise and Fano factor manifest bias-voltage-dependent power-law scalings. We analyze our data within the Tomonaga-Luttinger liquid model using the non-equilibrium Keldysh formalism and find qualitative and quantitative agreement between experiment and theory.

Non linear conductance: Fabry-Perot Oscillation

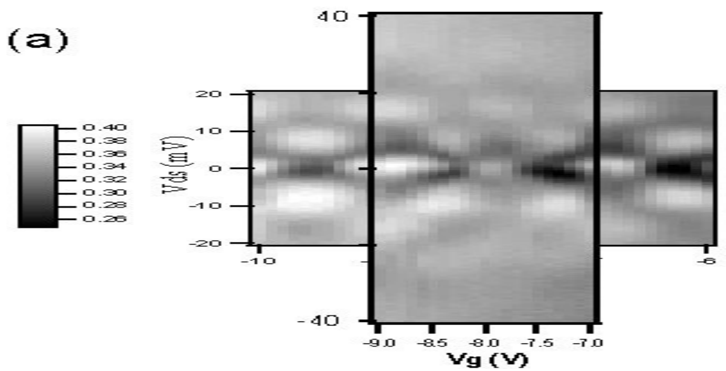
Sample

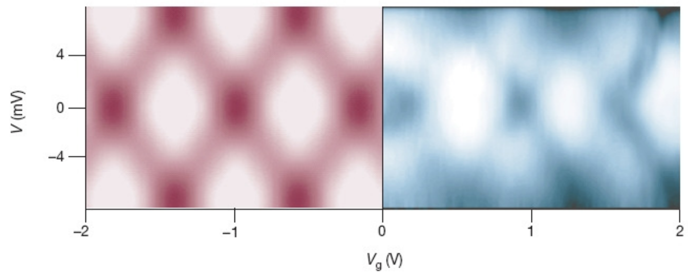


Model



Measurements:





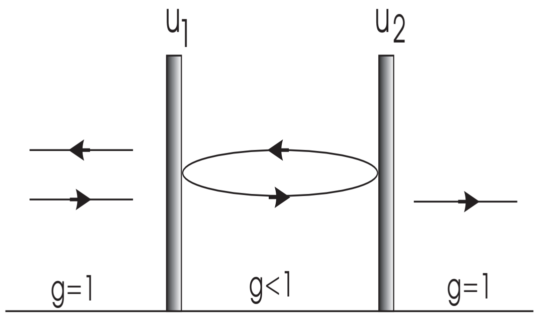
(Liang et al. Nature)

Problem: why the fabry-perot pattern is vanishing at high bias?
This cannot be explained by FL theory, the authors exclude heating effects.

Tomonaga-Luttinger Liquid

Model:
They model the system as TLL with two barriers separating the metal reservoirs from the SWNT and with spatially inhomoegeneous interaction parameter g. the interaction is strong in the SWNT (*0 < g < 1*) and weak in the reservoirs (*g = 1*).

Luttinger liquid:
In a one dimensional system of interacting electrons the Fermi Liquid theory doesn't work!



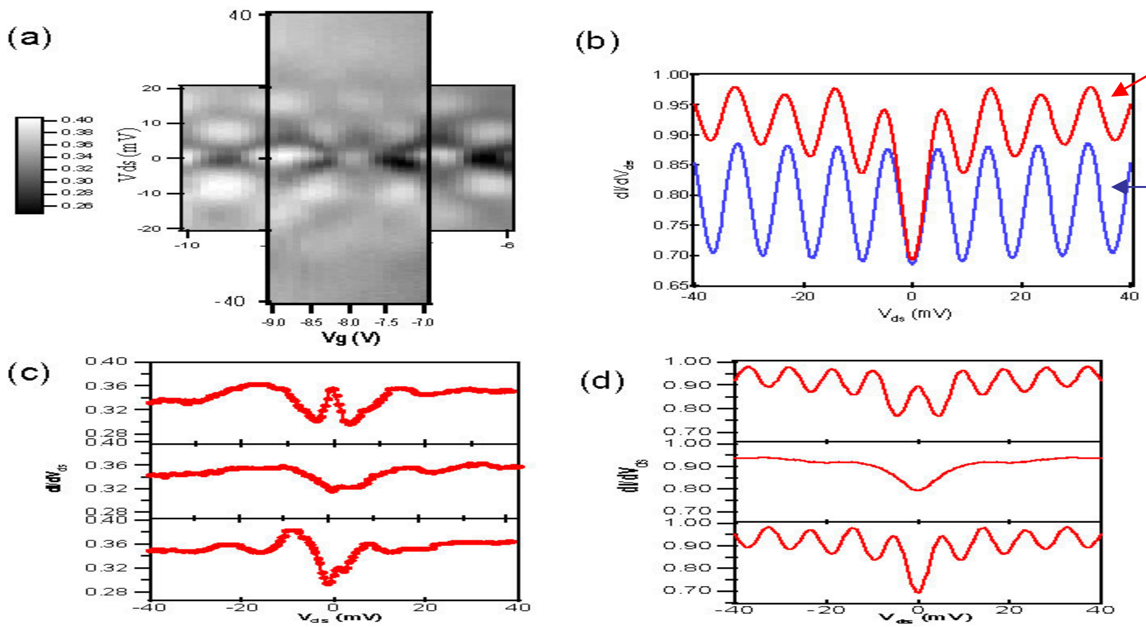
In particular the 4 conducting transverse modes of the SWNT in are transformed to four collective excitations in theTLL theory: one interacting collective mode (a=1, g_a = g) of the total charge and three non-interacting collective modes(a=2-4, g_a = 1) including spin. These modes are partially reflected at the two barriers. The interacting mode further experiences momentum-conserving reflections due to the mismatch of *g* at the interfaces*.

Measurements vs Simulations

They use the Keldish formalism and treat the barrier as perturbation, then the backscattered amplitudes is given by:

$$I_{\mathrm{B}} = \frac{2e}{\pi t_{\mathrm{F}}^2} \sum_{n=1,2} U_{\mathrm{n}} \left| \int_0^\infty dt e^{\mathrm{C_n}(t)} \sin\left(\frac{\mathrm{R_n}(t)}{2}\right) \sin\left(\frac{eV_{\mathrm{ds}}t}{\hbar}\right) \right|$$

Where $\mathbf{t_F = L / v_F}$. it's the non-interacting traveling time. **U1** represent incoherent backscattering at the barriers.
U2 represent the coherent contribution resulting in the FP oscillations.



g = 0.25

g = 1

$U_1 = 0.1$

Period t_F — $Vg = -9, U_2 = -0.1$

Period $2gt_F$ — $Vg = -8.3, U_2 = 0$

Period t_F — $Vg = -7.7, U_2 = 0.1$

To identify LL features uniquely we have to have $eV_{ds} > \mathrm{hbar}/(2g\, t_F)$
The extracted g ~ 0.22 from the measurements.

Shot Noise Measurements

Noise is not only caused by bad experimentalists!:

In particular ***shot noise*** is related to the granularity of the current and contain information about the microscopic mechanism of the conduction process.

In gerneral, the noise p.s. d. is given by :

$$S_{\mathrm{SWNT}}(\omega) \quad = \quad \int dt e^{i\omega t} \langle \{ \delta \hat{I}(t), \delta \hat{I}(0) \} \rangle$$

In case of Poisson statistics the noise power spectral density (noise p.s.d) S:

$S_{possion} = 2eI$ (assuming the current carryed by electrons)

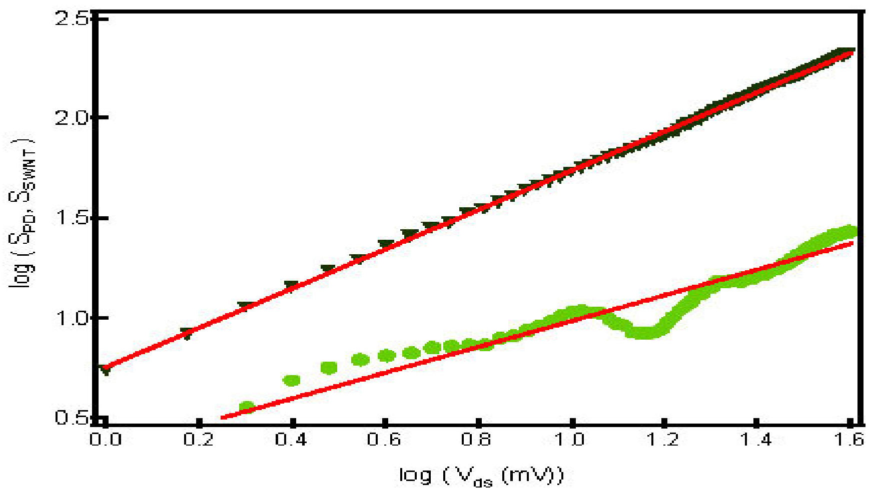
The **Fano Factor** is defined as the ratio of measured noise p.s.d and to the full shot noise value:

$$F = S / 2eI$$

Shot Noise Measurements

Technique:

The measurements were performed by placing two current noise sources in parallel: a SWNT device and a full shot noise generator a weakly coupled lightemitting diode (LED) and photodiode (PD) pair (a full shot noisegenerator) .



They implemented an AC modulation lock-in technique and designed a resonant tank-circuit (f = 15 Mhz) together with a home-built cryogenic low-noise preamplifier 2.2nV/ sqrt (Hz).

The measurements were performed at 4 kelvin

Power spectral density within their Luttinger Liquid model:

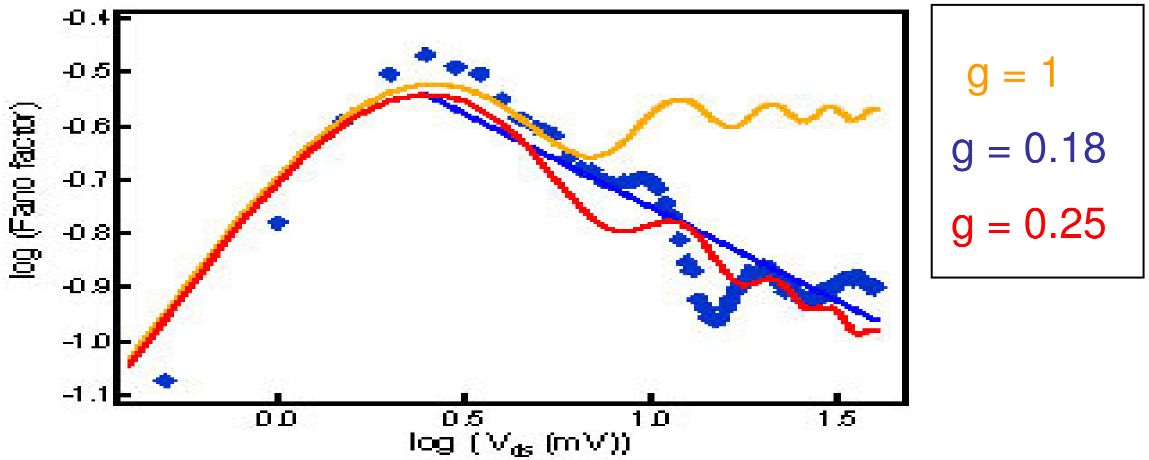
Calculated noise p.s.d :

$$S_{\mathrm{SWNT}}(\omega) \quad = \quad \int dt e^{i\omega t} \langle \{\delta \hat{I}(t), \delta \hat{I}(0)\} \rangle \quad =$$

$$= \quad 2e \coth(eV_{\mathrm{ds}}/2k_{\mathrm{B}}T) I_{\mathrm{B}} + 4k_{\mathrm{B}}T(dI/dV_{\mathrm{ds}} - dI_{\mathrm{B}}/dV_{\mathrm{ds}})$$

where $I_{\mathrm{B}} = \frac{2e}{\pi t_{\mathrm{F}}^2} \sum_{n=1,2} U_{\mathrm{n}} \left| \int_0^\infty dt e^{\mathrm{C_n}(t)} \sin\left(\frac{\mathrm{R_n}(t)}{2}\right) \sin\left(\frac{eV_{\mathrm{ds}}t}{\hbar}\right) \right|$

Measured Fano Factor



First region eVds < KT < h / $4\pi g t_F$
- $F(I) \sim V_{ds}$

Second region eVds > h/4pigt$_F$
- $F(I) \sim (V_{ds})^{alpha}$

•Good agreement with the previous found values of *g*