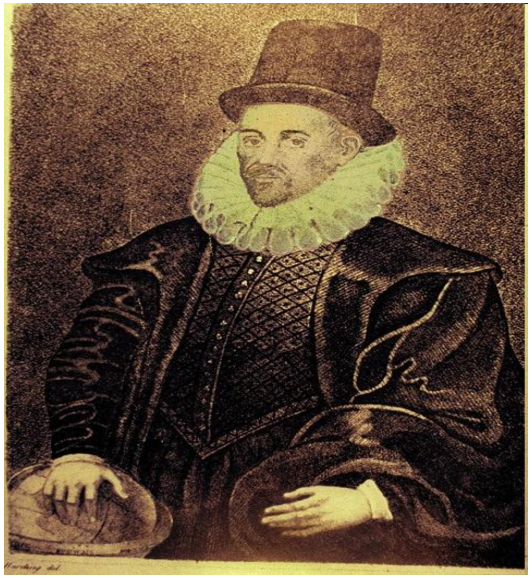
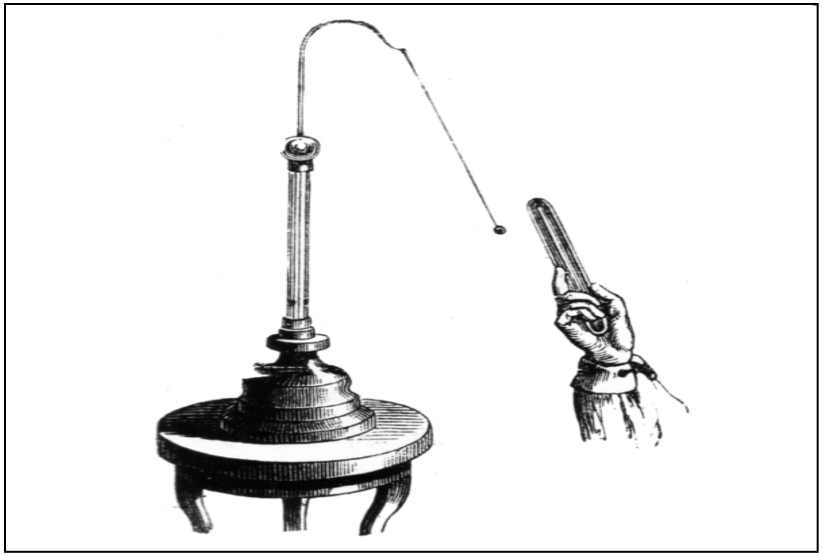
Electro-Mechanical Properties of Solids

Autumn College on Non-Equilibrium Systems, Buenos Aires, 2 – 13 May, 2011

Early Electro-Mechanics : Charge Metrology





William Gilbert
Born on May 24, 1544, in Colchester, England
Died on Dec. 10, 1603, in London

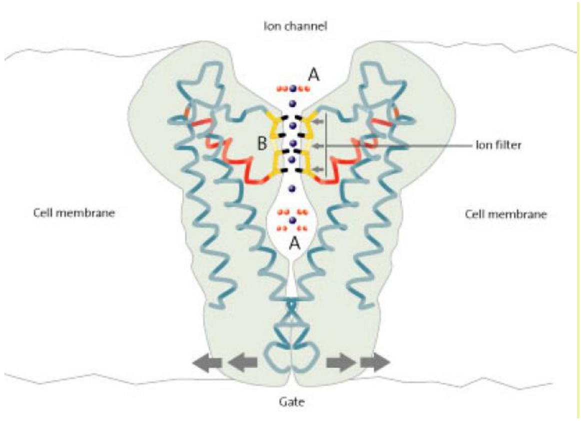
The **electroscope** was an early scientific instrument used to detect the presence and magnitude of electric charge on a body

Downsizing of Electro-Mechanical Devices

Macroscopic Electromechanical Device

Micro-Electromechanical Accelerometer (Airbag Sensor)

A small integrated circuit with integrated micro mechanical elements, which *move in response to rapid deceleration*. This motion causes a *change in capacitance*, which is detected by the electronics on the chip that then sends a signal to fire the airbag.



Nano-Electromechanical Machinery in the Living Cell

Ion channels make it possible for cells to generate and transmit electrical signals, and are the basic molecular building blocks in the nervous system. Rapid transport, ion selectivity, and electrically controlled channel gating are central to their functionality.

*

Heating and Cooling of NEMS Caused by Transport of a Single Electrons.

Robert Shekhter[1]

In collaboration with

L.Gorelik[2], M.Jonson[1,3], F.Santandrea,

[1]University of Gothenburg / [2]Chalmers Univ. of Technology / [3]Heriot-Watt University

- *NEM-SET Devices*
- *Energy transfer in NEM electric weak links*
- *Cooling of NEM resonator by thermally activated CB transport*
- *Electron-vibron interaction in a sduspended nanotube-based SET transistor*
- *Conclusions*

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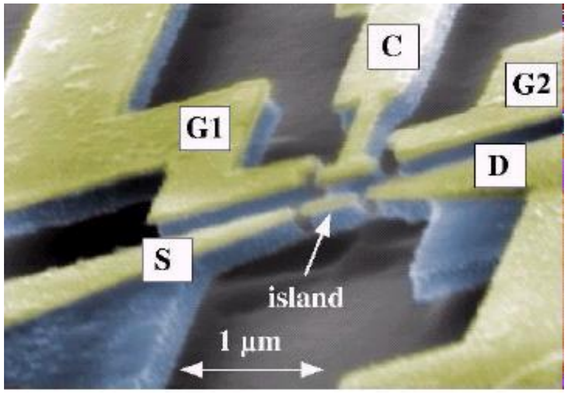
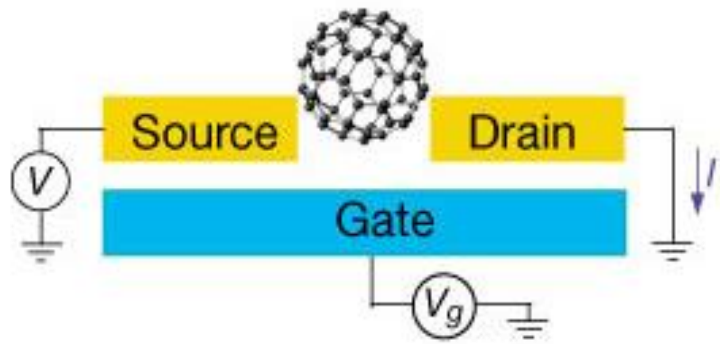
Nanoelectromechanical Devices

Quantum ”bell”



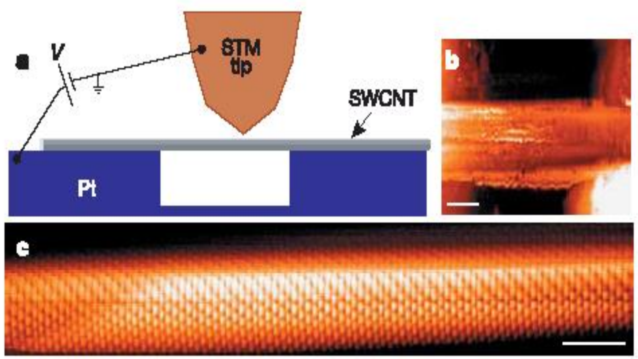
A. Erbe *et al*., PRL **87**, 96106 (2001);

Single-C_{60} transistor

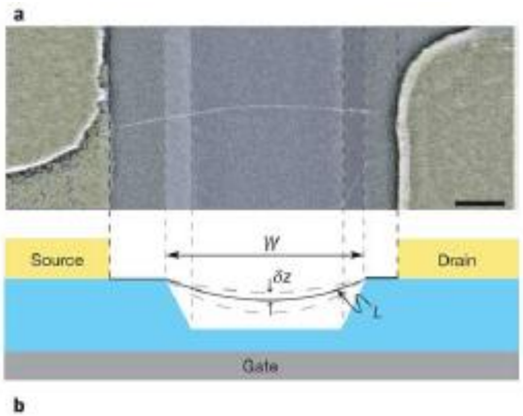


H. Park *et al*., Nature **407**, 57 (2000)

CNT-based nanoelectromechanical devices

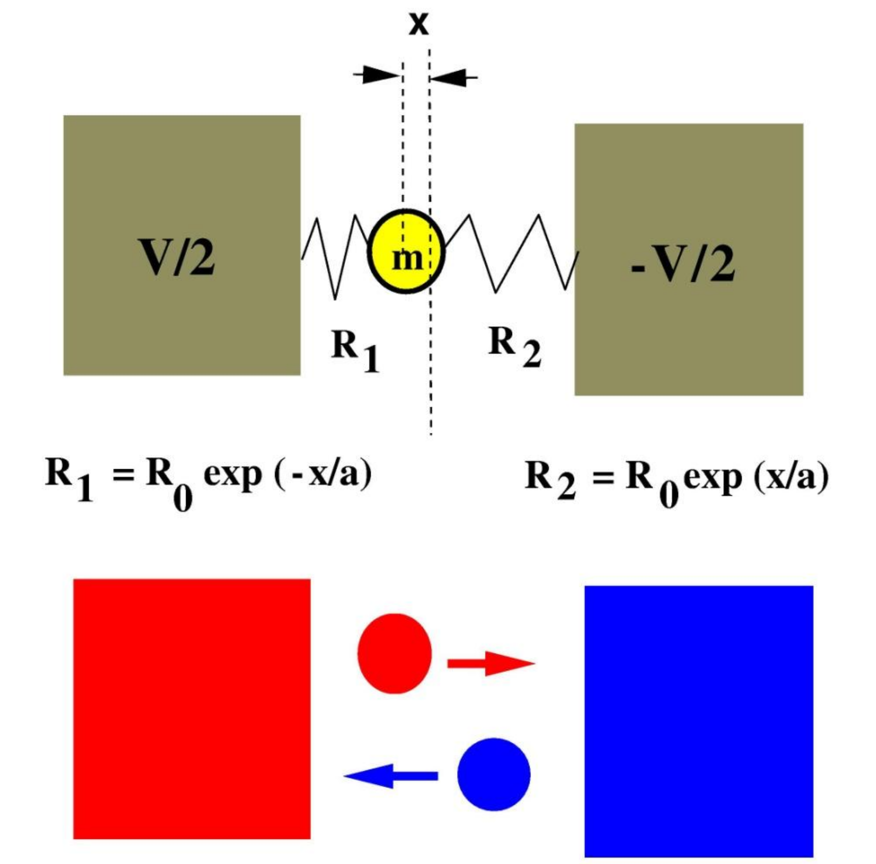


B. J. LeRoy et al., Nature **432**, 371 (2004)



V. Sazonova et al., Nature **431**, 284 (2004)

Shuttle NEM nstability

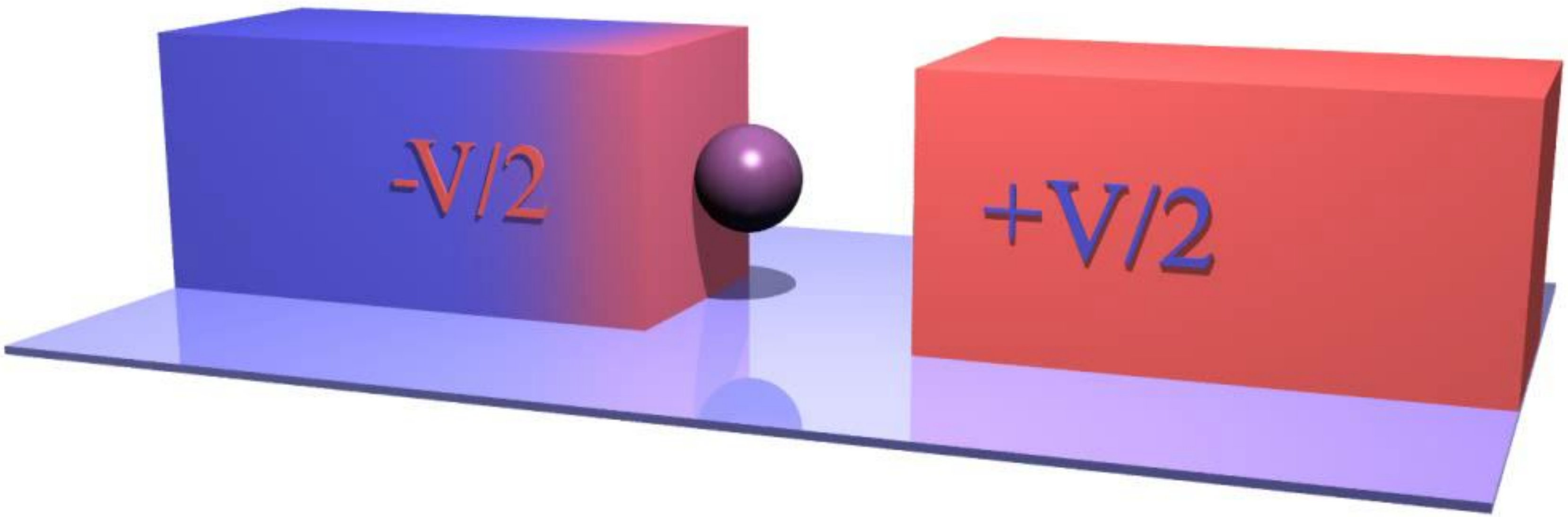


Velocity direction is correlated with the charge sign

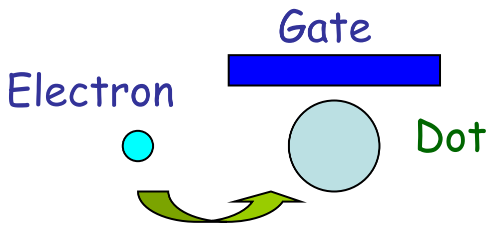
If W exceeds the dissipated power an instability occurs

Gorelik et al., PRL, **80**, 4256(1998)

Electronic Shuttle Device



Coulomb blockade

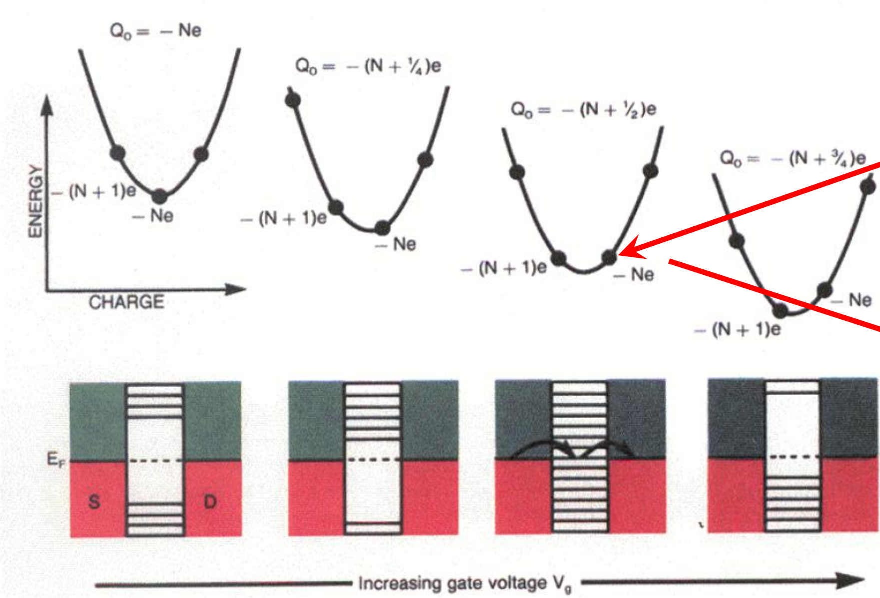


Repulsion at the dot

Cost $$E = QV_g + \frac{Q^2}{2C}$$

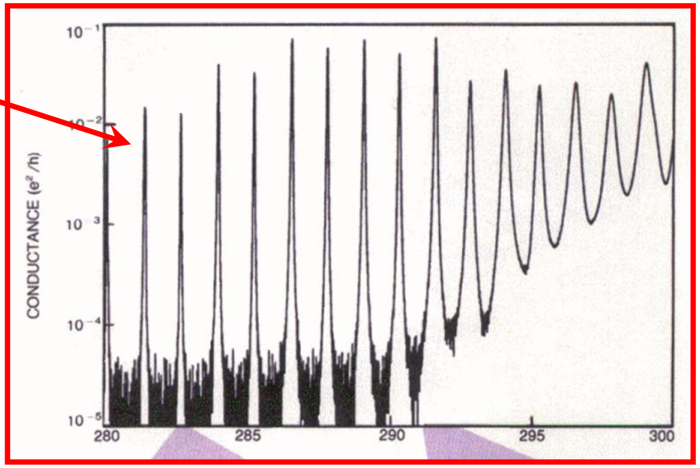
Attraction to the gate

$$Q = -Ne$$



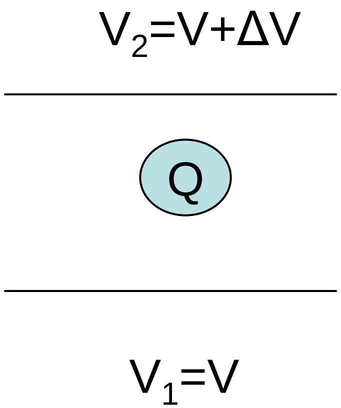
At $$V_g = -\left(N + \frac{1}{2}\right)\frac{e}{C}$$

the energy cost vanishes !



Single-electron transistor (SET)

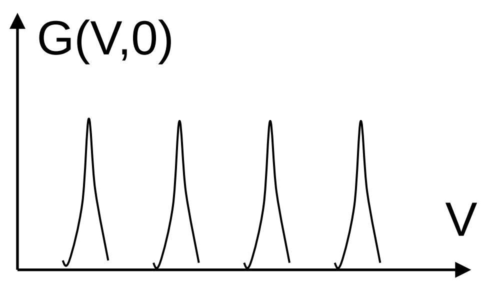
CB of Single Electron Tunneling

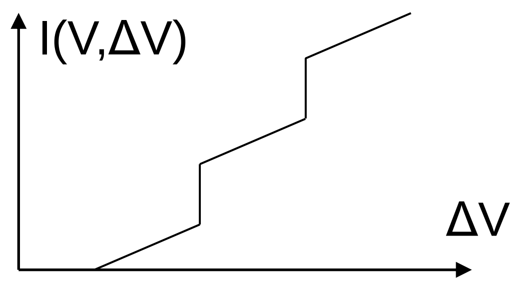


Coulomb oscillations of G(V)=dI(V,ΔV)/dΔV;

”Coulomb staircase”

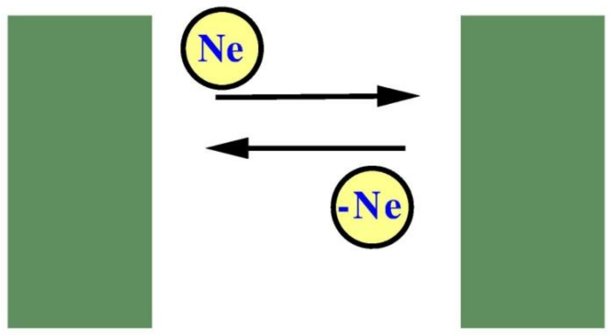
”gate effect”

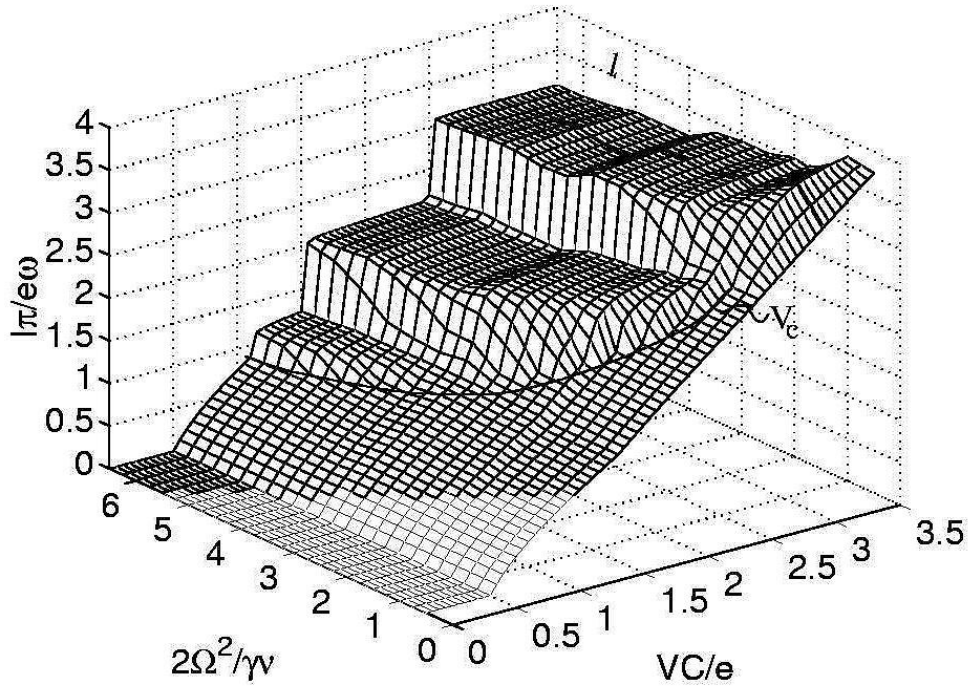




R.I. Shekhter, Sov. Phys.JETP 36, 747-750 (1973)
I.O. Kulik and R.I. Shekhter, Sov. Phys. JETP 41, 308-316 (1975)

Shuttling of Single Electronic Charge





Quantum Nanoelectromechanics of Shuttle Systems

$$\boxed{\delta X \delta P \cong \hbar}$$

$$\boxed{\delta X \cong 2X_0 \equiv \sqrt{\frac{2\hbar}{M\omega}}}$$

If $\dfrac{R(X+\delta X)}{R(X)} >> 1$ then quantum fluctuations of the grain significantly affect nanoelectromechanics.

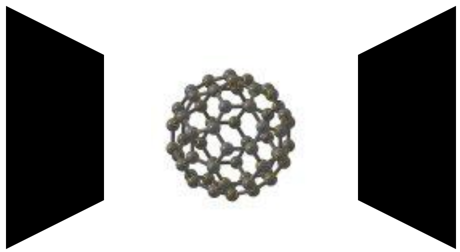
Conditions for Quantum Shuttling

$$\frac{2X_0}{\lambda} \gtrsim 1$$

λ – Tunneling length

$$X_0 \equiv \sqrt{\frac{\hbar}{2M\omega}}$$

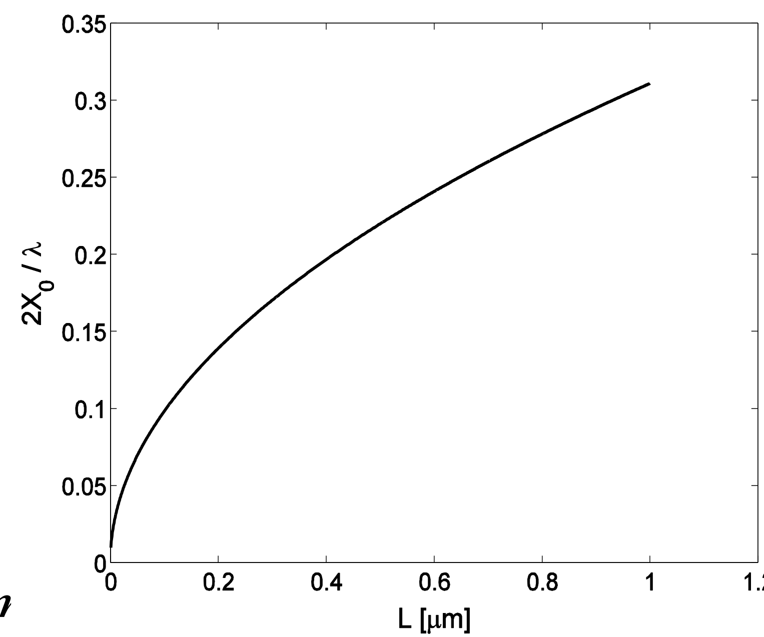
1. Fullerene based SET



$$\omega \cong 1\,\mathrm{THz}$$

$$\frac{X_0}{\lambda} \cong 0.1$$

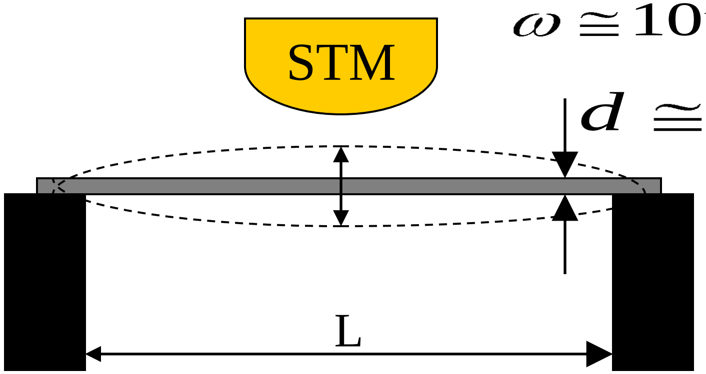
Quasiclassical shuttle vibrations.



2. Suspended CNT

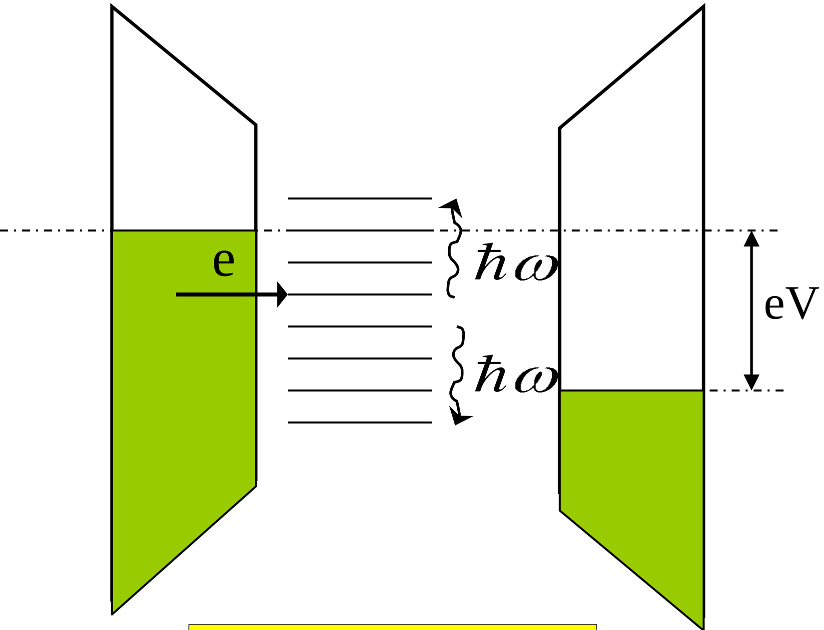
$$\omega \cong 10^{14}\ \mathrm{Hz}\left(\frac{d}{L}\right)^2$$

$$d \cong 1\,\mathrm{nm}$$



$\omega \cong 10^8$ - 10^9 Hz for SWNT with $L \cong 1\mu m$

Quantum Shuttle Instability



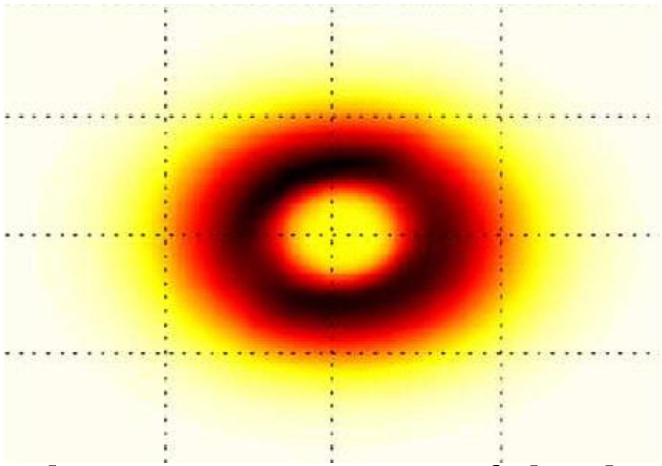
$$T << \hbar\omega$$

$$\gamma < \gamma_{\mathrm{thr}} \equiv \Gamma \frac{d}{\lambda}$$

$$d = \frac{eE}{2k}$$

d-hift in oscillator position caused by charging it by a single electron charge

Quantum vibrations, generated by tunneling electrons, remain undamped and accumulate in a **coherent "condensate"** of phonons, which is classical shuttle oscillations.



Phase space trajectory of shuttling.
From Ref. (3)

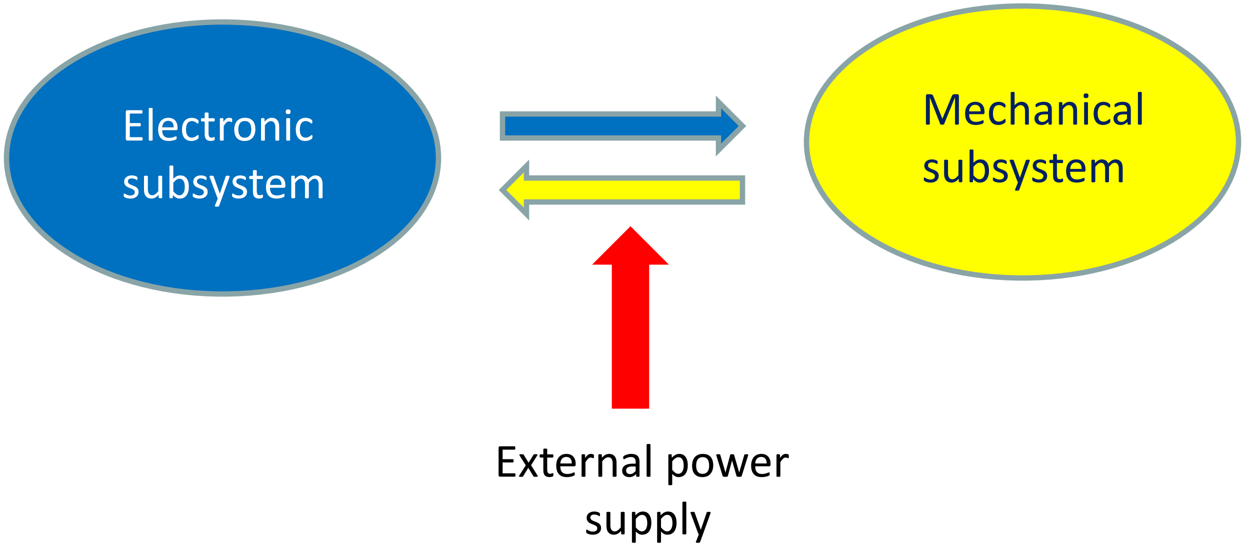
References:

(1) D. Fedorets *et al.* Phys. Rev. Lett. 92, 166801 (2004)

(2) D. Fedorets, Phys. Rev. B **68**, 033106 (2003)

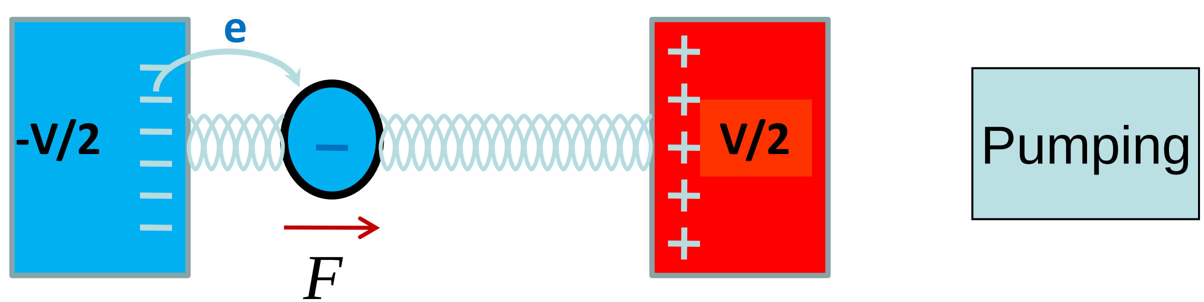
(3) T. Novotny *et al.* Phys. Rev. Lett. **90** 256801 (2003)

Energy Transfer in NEM Systems



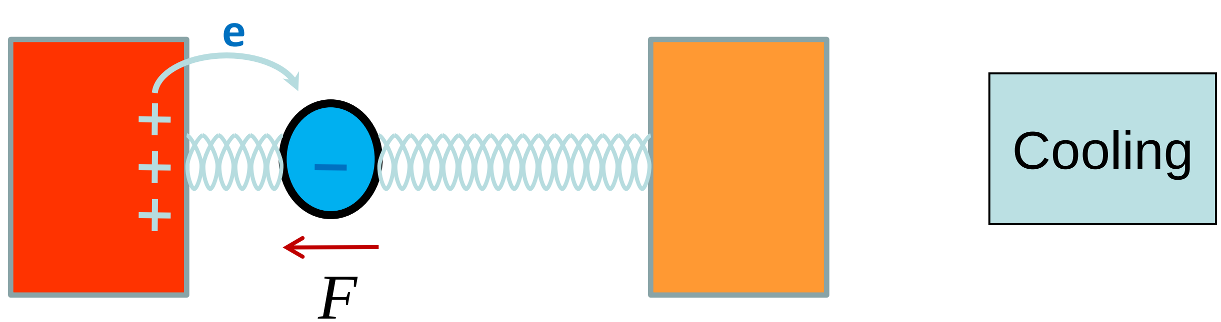
”Pumping” versus ”Cooling” in NEM-SET Device

$|V| > V_c$



$|V| < V_c$

Thermally activated transport

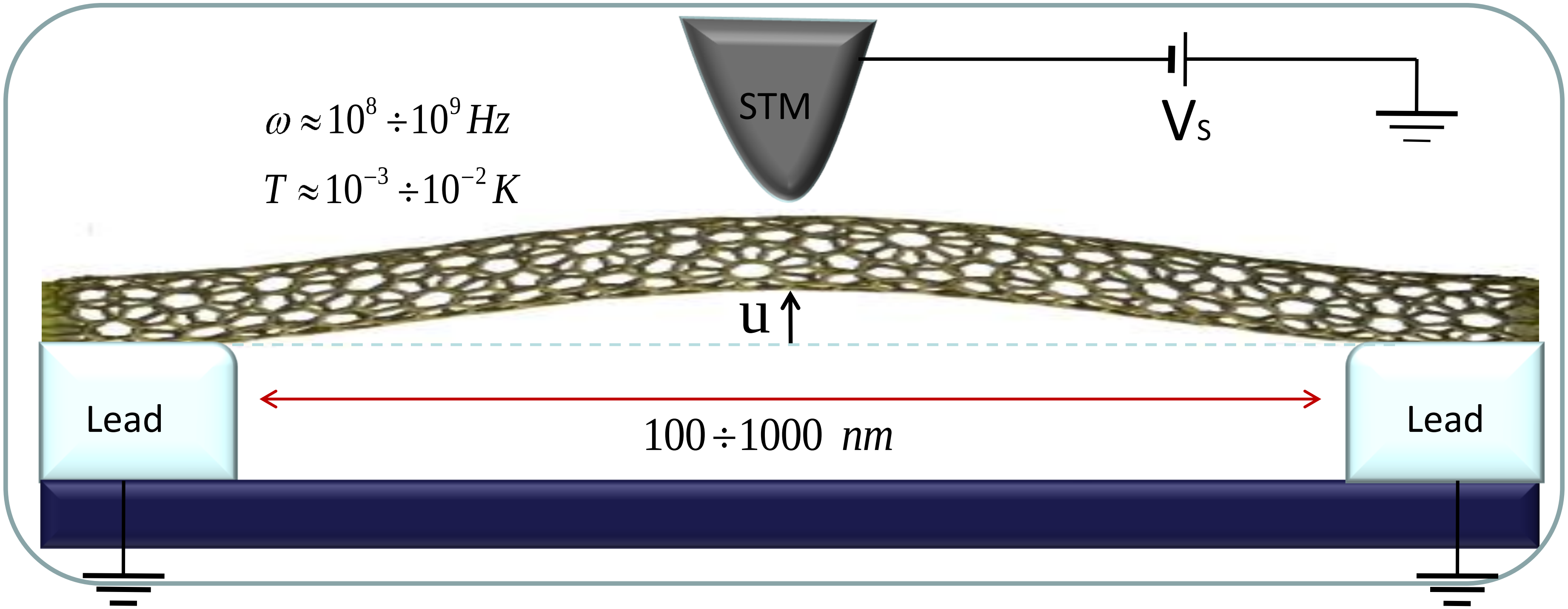


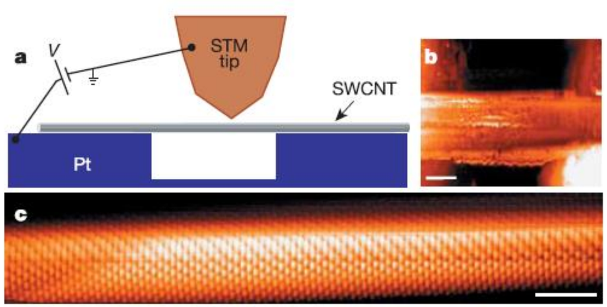
Would the above ”classical” classification survive in the quantum limit?

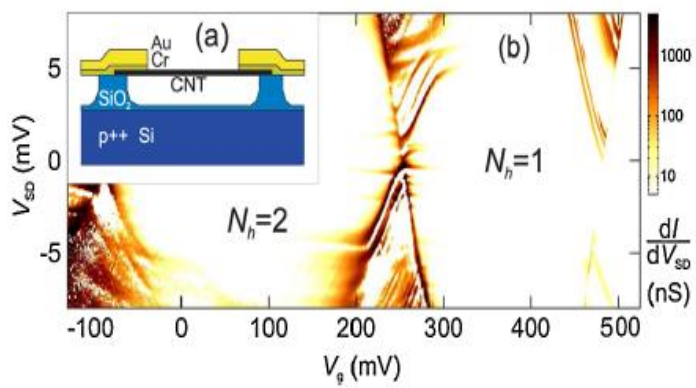
Ground State Cooling in Suspended Nanotube-Based SET Device

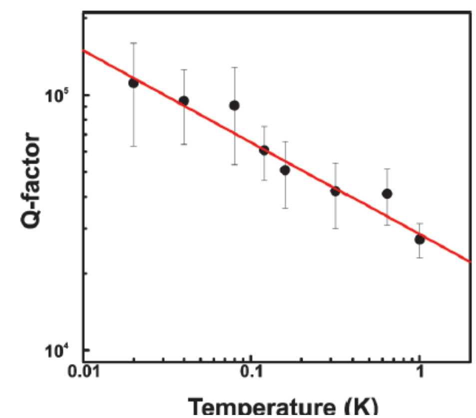
F. Santandrea, L.Y. Gorelik, R.I. Shekhter and M. Jonson:
Cooling of nanomechanical resonator by thermally activated single-electron transport,
arXiv:1012.3004 (2010); PRL, 2011 (in press)

NEM Resonator as a Coulomb Blockade Device







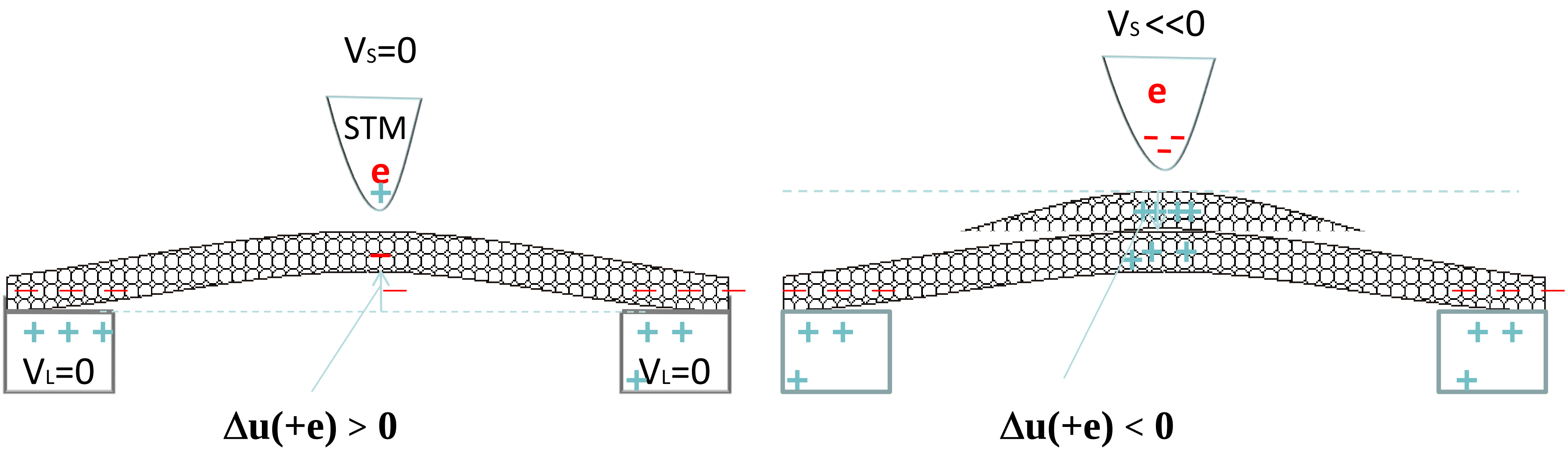


B.J.LeRoy, et al. Nature, **432,** 371 (2004)

Huttel AK, et al. PHYS. REV. LETT. **102,** 225501, (2009)

Huttel AK, et al. Nano letters **9,** 2547, (2009)

Polaronic Coupling



$$\hat{H}_p = \kappa \Delta u(V_S) \cdot \hat{u} \cdot \hat{N},$$

$\hat{N}$ is number of extra electron on the nanotube $N = 0,1$

κ is elastic constant

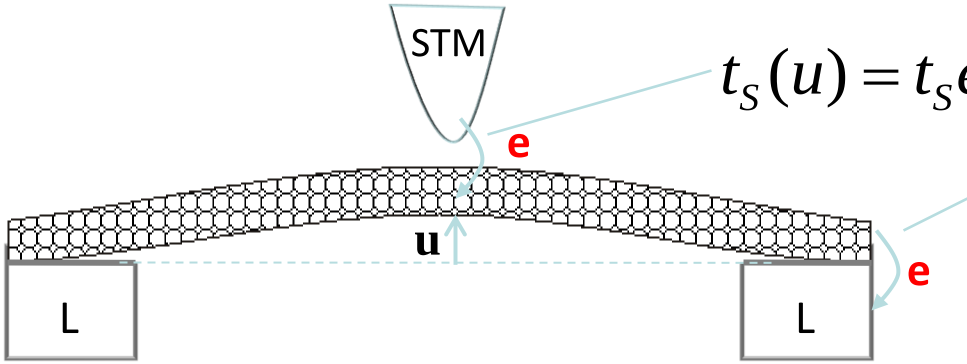
$$\Delta u \propto \Delta F = -\frac{\partial \Delta U(u)}{\partial u}$$

$$\Delta U \equiv U_e - U_0 = -\frac{eC_L}{(C_S(u) + C_L)}\left[|V_s| - \frac{e}{2C_L}\right]$$

$$\boxed{\Delta u(V_S) \propto -\frac{\partial C_s(u)}{\partial u}(|V_S| - V_c)}$$

C_S, C_L are capacitances between nanotube and STM, leads electrodesandis

Tunneling Coupling



$$t_S(u) = t_S e^{u/\lambda}$$

overlapping integral depends on the distance between nanotube and STM

t_L

Hamiltonian

$$H_e + \frac{\hat P_u^2}{2m} + \frac{\kappa \hat u^2}{2} + \sum_{k,k'} t_S e^{\hat u/\lambda} c_k^+ a_{k',S} + \sum_{k,k'} t_L a_{k,L}^+ c_{k'} + h.c.$$

$$e^{-i\hat N \Delta u \hat P_u} \quad H_e + \frac{\hat P_u^2}{2m} + \frac{\kappa \hat u^2}{2} + \kappa \Delta u \cdot \hat u \hat N + \sum_{k,k'} t_S e^{-\hat u/\lambda + i\Delta u \hat P} c_k^+ a_{k',S} + \sum_{k,k'} t_L e^{+i\Delta u \hat P} a_{k,L}^+ c_{k'} + h.c. \quad e^{i\hat N \Delta u \hat P_u}$$

$\hat u = u_0 (b^+ + b)/\sqrt{2}$, $\hat P_u = i\hbar u_0^{-1} (b^+ - b)/\sqrt{2}$ $\quad u_0 = \sqrt{\hbar / m\omega}$ - zero-point amplitude

$$H_e + \hbar\omega b^+ b + \sum_{k,k'} t_S \left[1 + \left(\frac{u_0}{\lambda} - \frac{\Delta u}{u_0} \right) b^+ + \left(\frac{u_0}{\lambda} + \frac{\Delta u}{u_0} \right) b \right] c_k^+ a_{k',S}$$

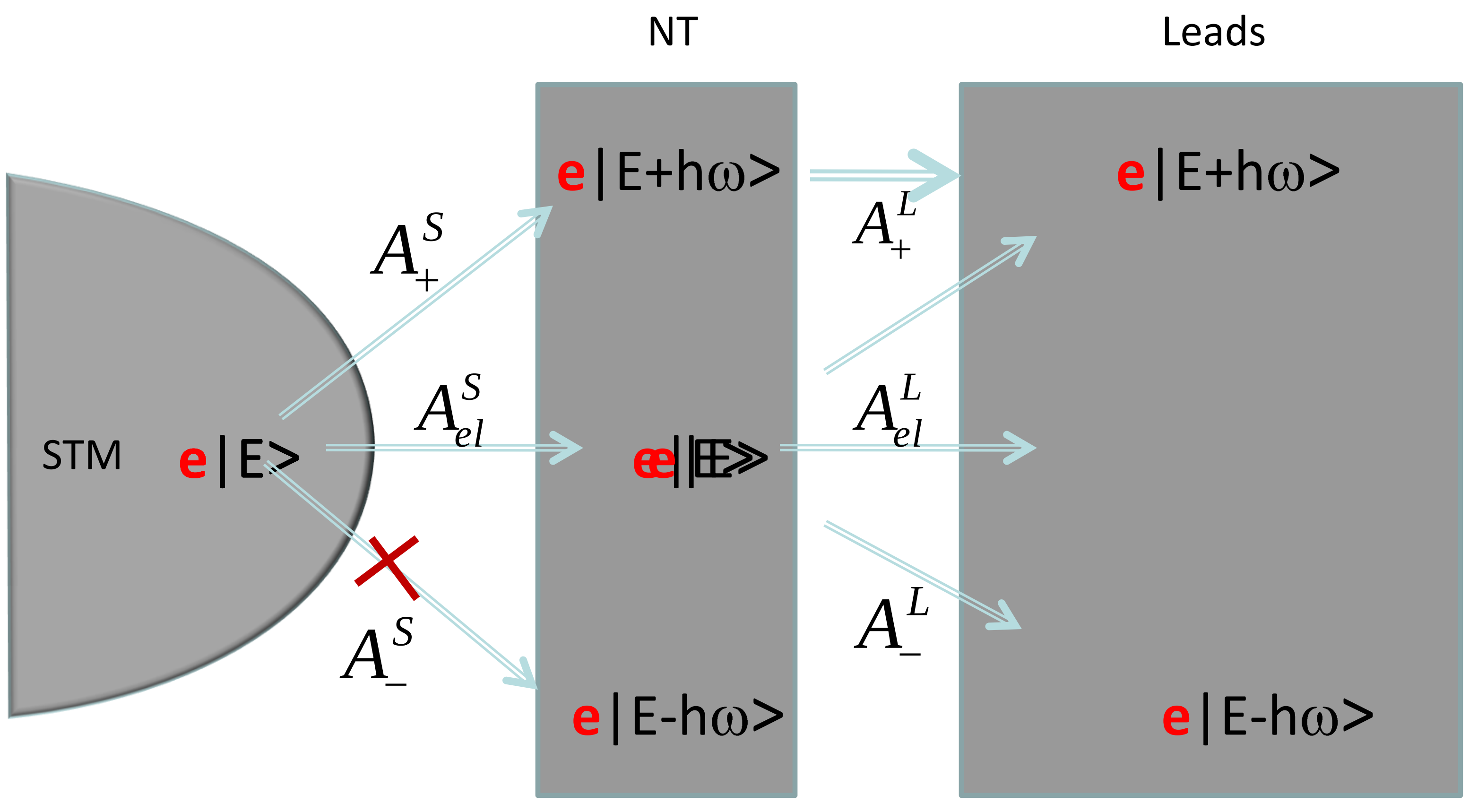
$$+ \sum_{k,k'} t_L \left[1 + \frac{\Delta u}{u_0} b^+ - \frac{\Delta u}{u_0} b \right] a_{k,L}^+ c_{k'} + h.c.$$

Inelastic Electronic Tunneling

$$\sum_{k,k'} t_S\left[1+\left(\frac{u_0}{\lambda}-\frac{\Delta u}{u_0}\right)b^+ +\left(\frac{u_0}{\lambda}+\frac{\Delta u}{u_0}\right)b\right]c_k^+ a_{k',S} + \sum_{k,k'} t_L\left[1+\frac{\Delta u}{u_0}b^+ - \frac{\Delta u}{u_0}b\right]a_{k,L}^+ c_{k'} + h.c.$$

$$A_{el}^{S(L)} = t_{S(L)}, \qquad A_{\pm}^{S} = A_t^S \pm A_p^S \qquad A_{\pm}^{L} = \pm A_p^L$$

$$A_t^S = t_S u_0/\lambda \qquad A_p^S = t_S \Delta u(V_S)/u_0 \qquad A_p^L = t_S \Delta u(V_S)/u_0$$



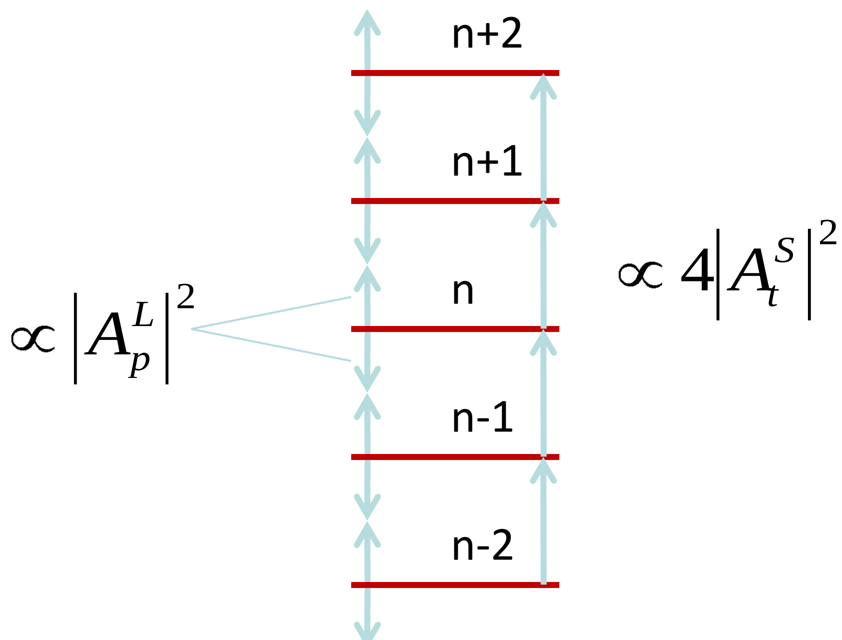
Pumping and Cooling of the Mechanical Vibrations

$$\boxed{t_L >> t_S}$$

Electronic inelastic transitions generates transition between vibronic states

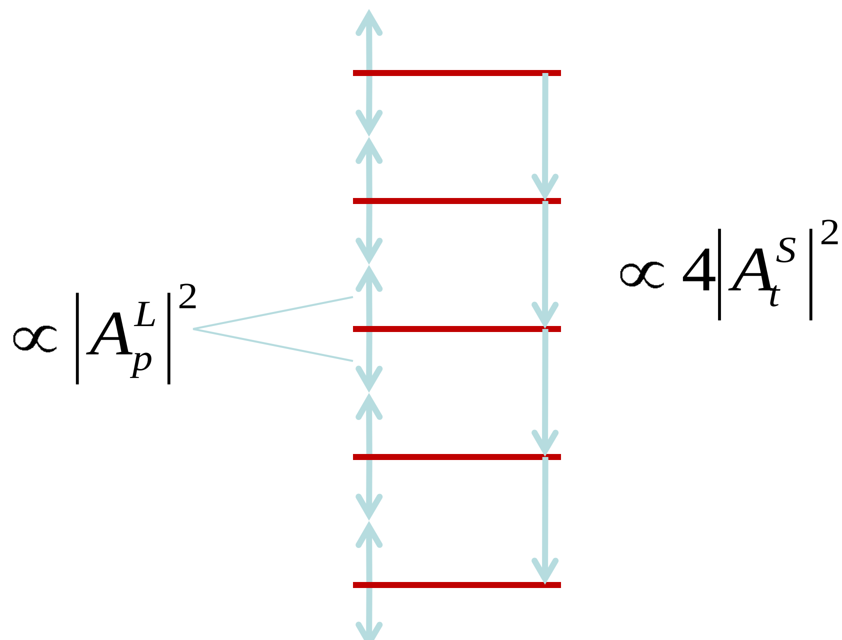
Pumping

$$A_p^S = -A_t^S > 0 \; (V_S > V_c) \Rightarrow A_+^S = 0$$



Cooling

$$A_p^S = A_t^S < 0 \; (V_S < V_c) \Rightarrow A_-^S = 0$$



Pumping Energy out of the Vibronic System

$\Gamma_{+(-)}$: Rate for electron tunneling events accompanied by vibron emission (absorption)

ρ_n : Probability for the nanotube to be in the Fock state occupied by *n* vibrons

$$\Gamma_- \rho_{n+1} + \Gamma_+ \rho_{n-1} - \left(\Gamma_+ + \Gamma_-\right)\rho_n = L_\gamma\left[\rho_n\right]$$

$$L_\gamma\left[\rho_n\right] \equiv \gamma\left(n+1\right)\left[\left(n_{th}+1\right)\rho_{n+1} - n_{th}\rho_n\right] - \gamma n\left[\left(n_{th}+1\right)\rho_n - n_{th}\rho_{n-1}\right]$$

$$\gamma \equiv \omega / Q; \qquad n_{th} = 1/\left(e^{\hbar\omega/kT} - 1\right)$$

Here L_γ is the Lindblad operator

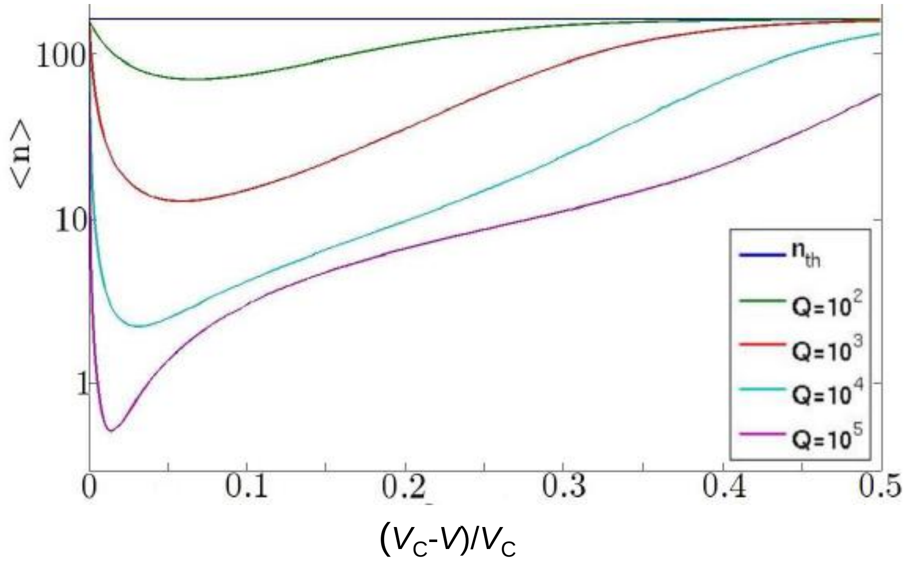
Stationary Distribution of Vibrons

$$p_n = (1-r)r^n\,,$$

$$r = \frac{\varepsilon_p^2 + (\varepsilon_t - \varepsilon_p)^2 + (\gamma/\Gamma_S)n_{\rm th}}{\varepsilon_p^2 + (\varepsilon_t + \varepsilon_p)^2 + (\gamma/\Gamma_S)(n_{\rm th}+1)}$$

$$\varepsilon_p = \frac{|\eta(V_C - V)|}{2V_C}$$

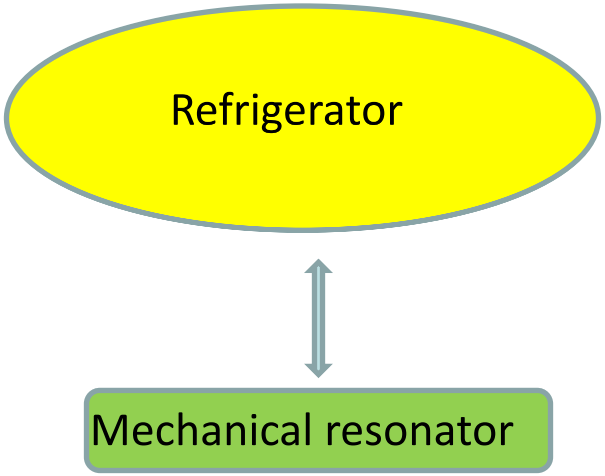
$$\varepsilon_t = \frac{X_0}{\lambda\sqrt{2}}$$

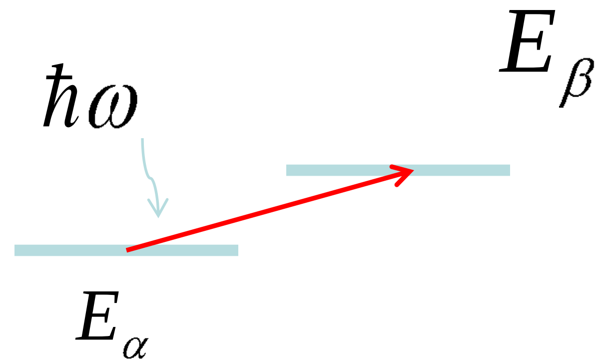


$$\langle n\rangle = \sum_m m\rho_m = \frac{r}{1-r} \approx 0.2 \quad \text{for} \quad \gamma << \Gamma_\pm$$

The average number <n> of vibrons is plotted against the difference between the Coulomb blockade threshold voltage V_c and the bias voltage V. Each curve corresponds to a different quality factor Q of the oscillator, while the straight line gives the thermal average number of vibrons at 1 kelvin.

Thermal Transport Controlled by Quantum Interferrence





$$P(in, N \to f, N \pm 1) \propto \sum_{\alpha,\beta} \left| \langle \alpha, N | T_{\mathrm{int}} | \beta, N \pm 1 \rangle \right|^2 \delta(E_\beta - E_\alpha \pm \hbar\omega)$$

N-number of vibrons

Conclusions

1. The direction of energy transfer between the electronic and mechanical parts of a NEM device can be controlled externally.

2. Energy pumping into the mechanical subsystem of a NEM-SET device can be reversed if the driving voltage is reduced to below the CB threshold.

3. The above statement valid in both classical and quantum regimes of NEM operations.