Tunneling in suspended carbon nanotubes assisted by longitudinal phonons

S. Sapmaz, P. Jarrillo-Herrero, Ya. M. Blanter,
C. Dekker, and H. S. J. Van der Zant

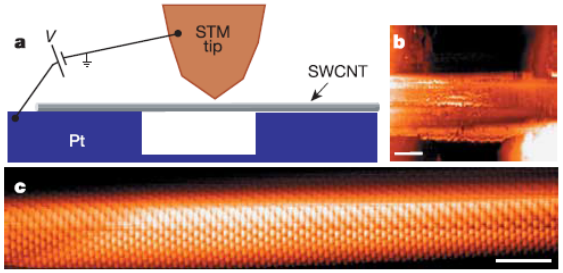
Cond-mat/0508270

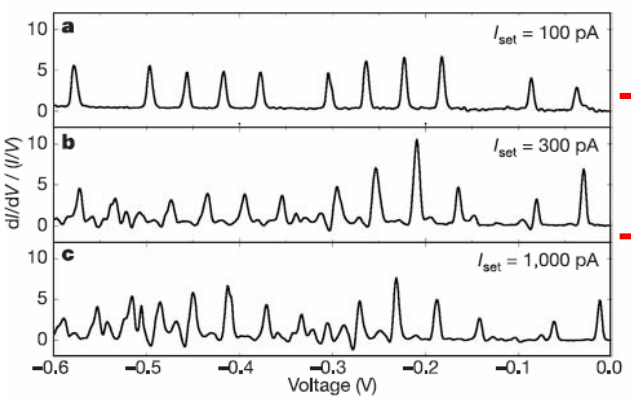
Current-voltage characteristics of suspended single-wall carbon nanotube quantum dots show a series of steps equally spaced in voltage. The energy scale of this harmonic, low-energy excitation spectrum is consistent with that of the longitudinal low-k phonon mode (stretching mode) in the nanotube. Agreement is found with a Franck-Condon-based model in which the phonon-assisted tunneling process is modeled as a coupling of electronic levels to underdamped quantum harmonic oscillators. Comparison with this model indicates a rather strong electron-phonon coupling factor of order unity.

Vibrational effects at the molecular scale

Electrical generation and absorption of phonons in CNTs

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



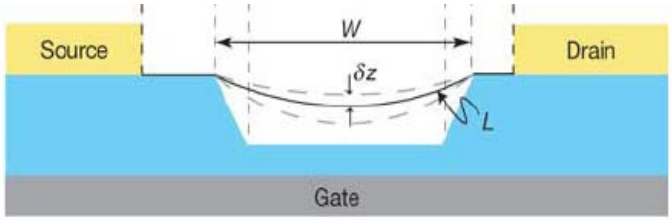


→ Coulomb peaks

→ Coulomb+phonon satellites

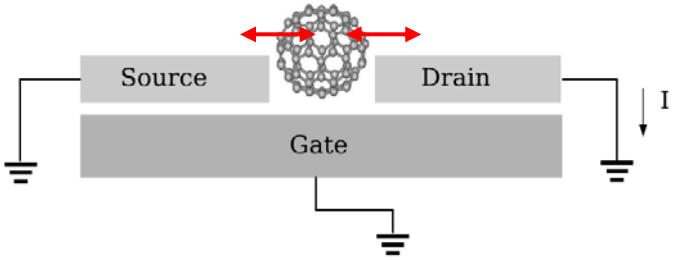
A tunable carbon nanotube electromechanical oscillator

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



C60 shuttle

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



Device fabrication

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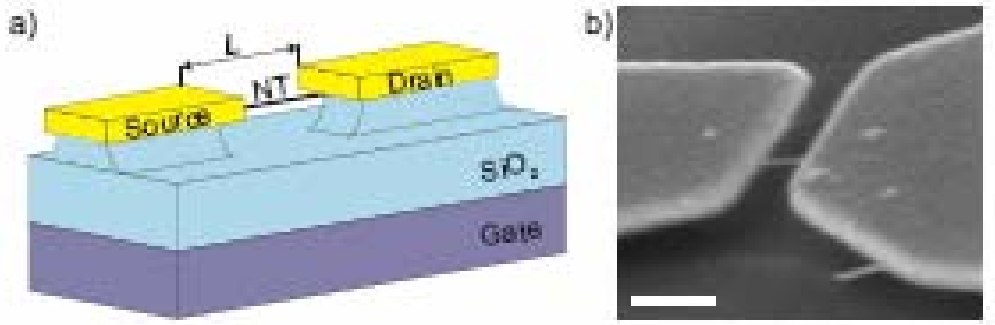
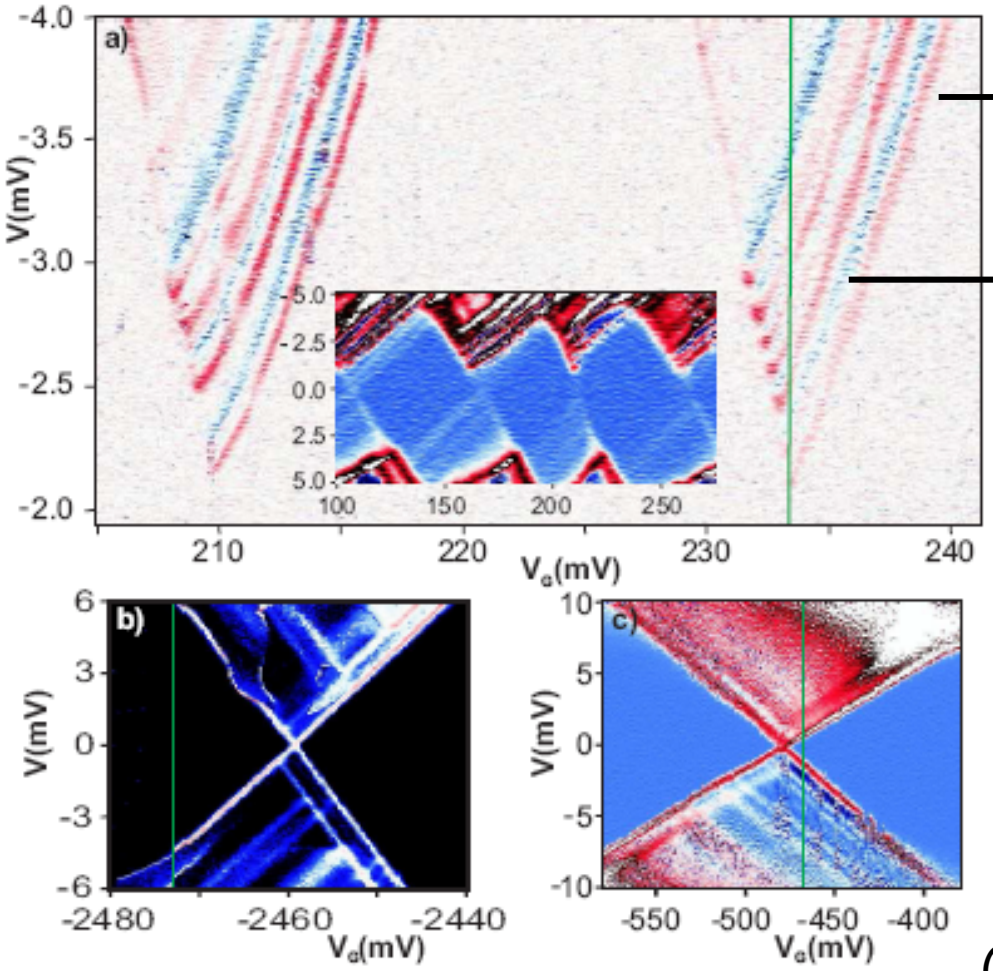


SEM micropgraph

- Individual CNTs produced by laser ablation and CVD
- CNTs on Si/SiO_2 substrate via AFM
- Electrodes via e-beam litography + thermal evaporation of Cr/Au
- Remove underlying SiO2 via buffered HF

Stability diagrams



(a) L=1.2 μm, T=10 mK (inset 300 mK)
(b) L=420 nm, T=300 mK
(c) L=140 nm, T=300 mK
d~1-1.4 nm

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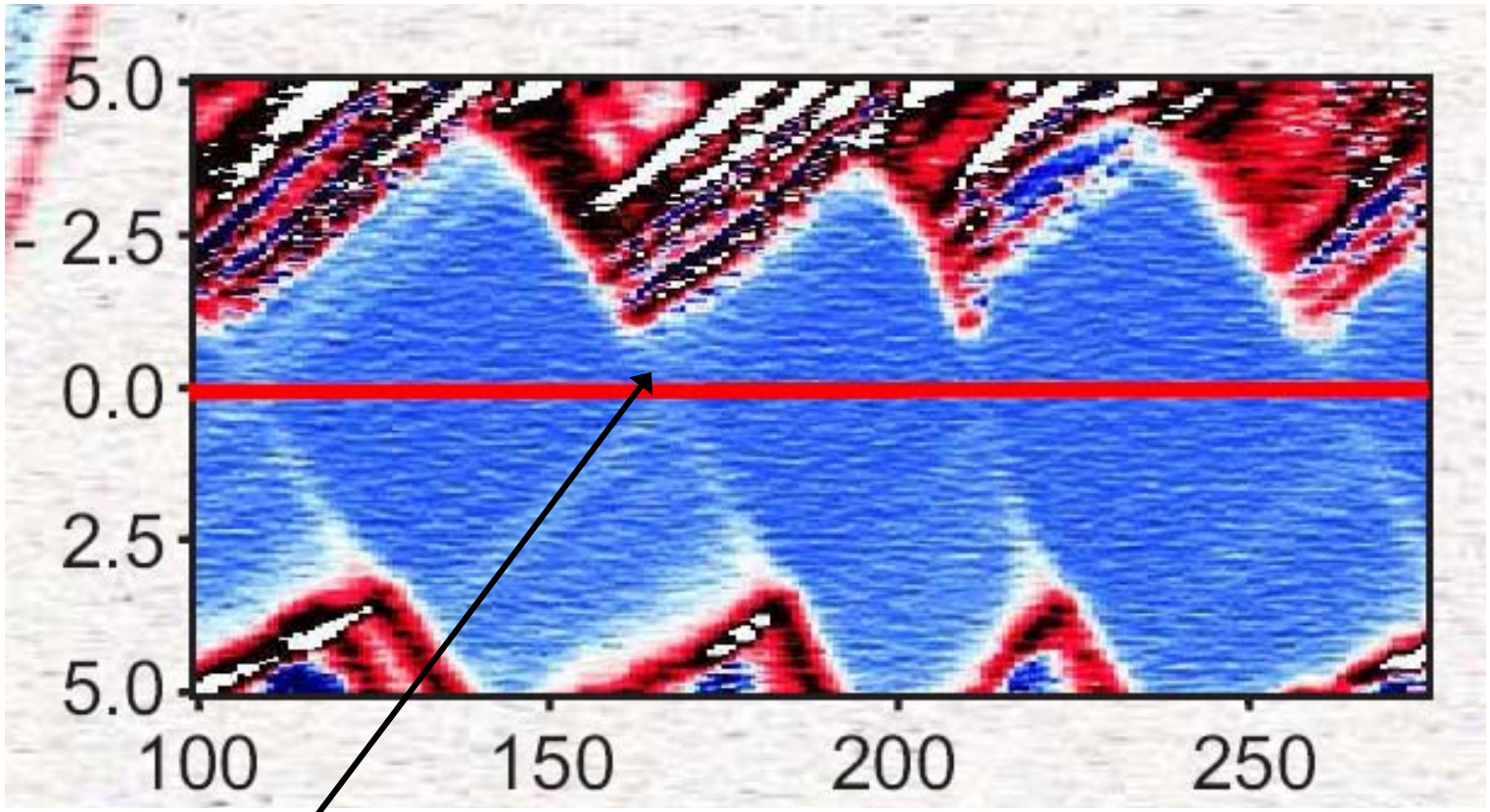
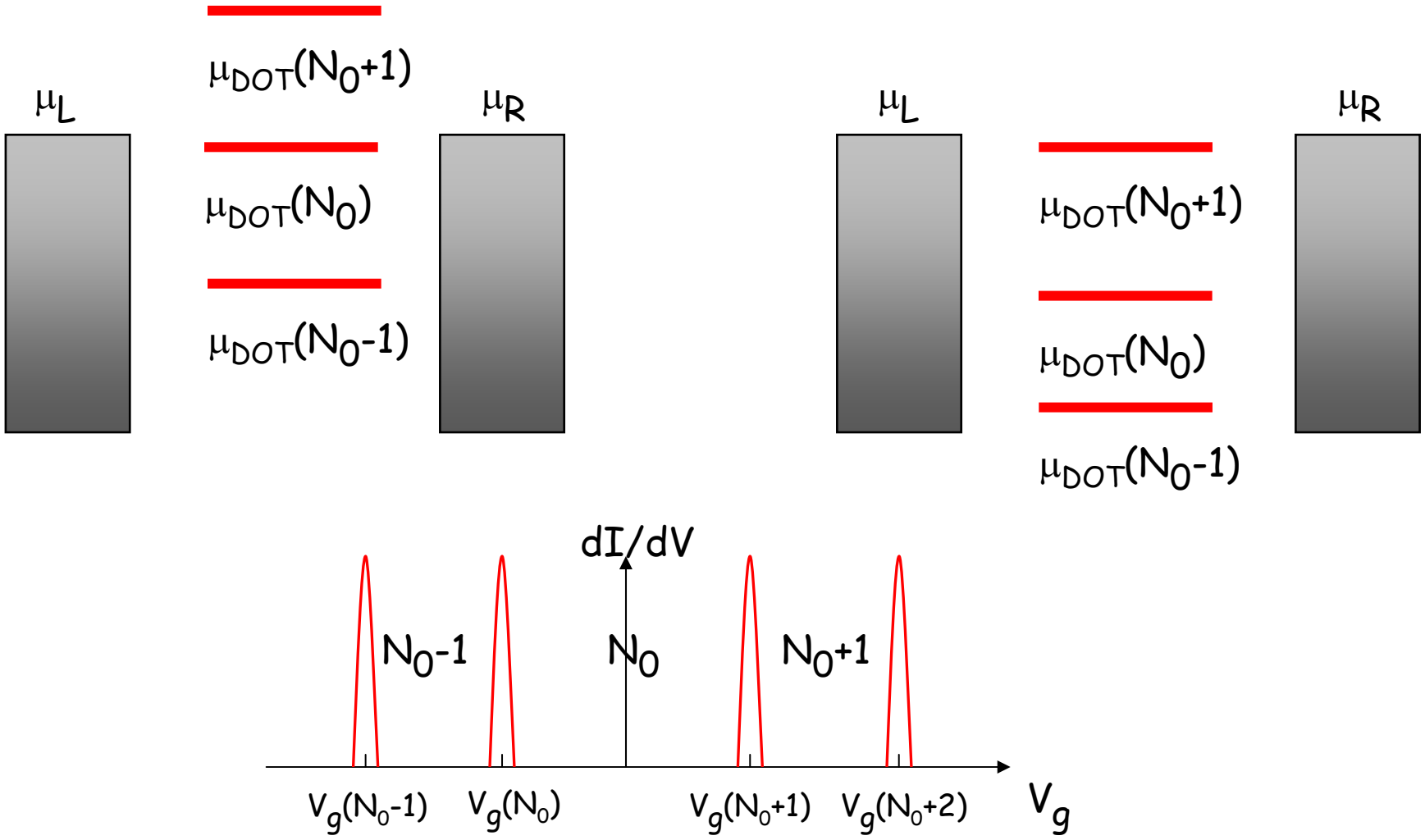
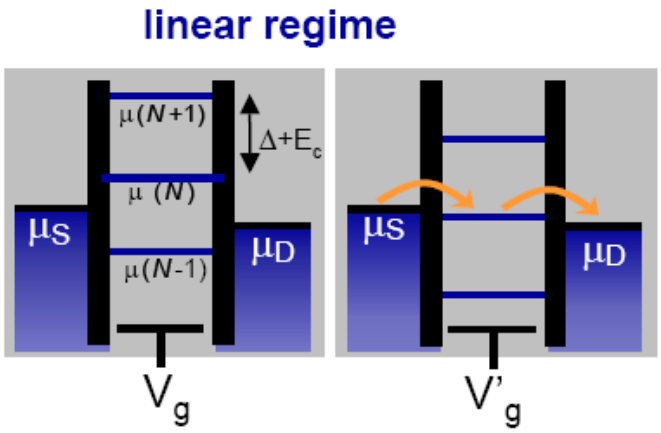


current suppression cannot be counteracted
by changing the gate voltage
Franck-Condon blockade?

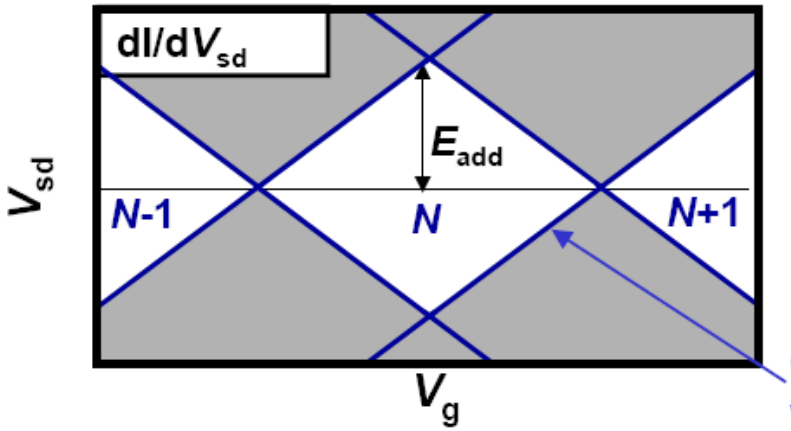
Coulomb blockade in quantum dots



stability diagram and Coulomb diamonds

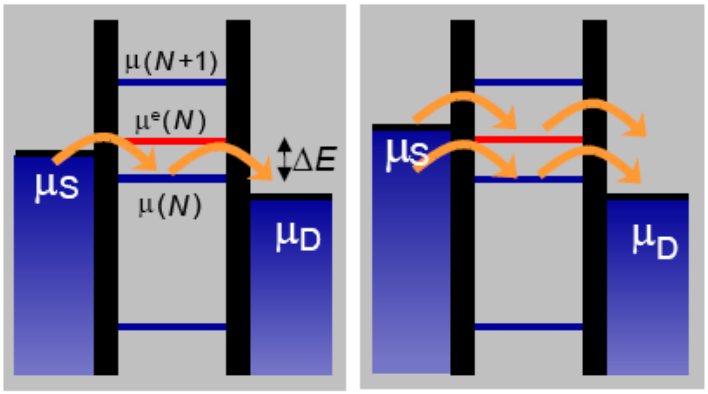


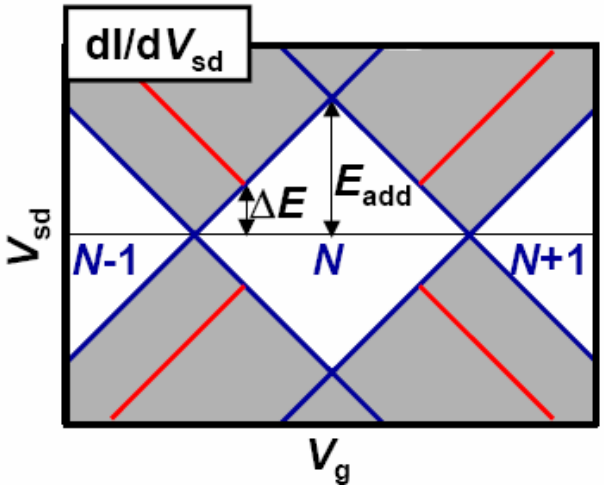
- two 'knobs': V_{SD} and V_{gate}
- state contributes to transport if $\mu_s > \mu(N) > \mu_d$



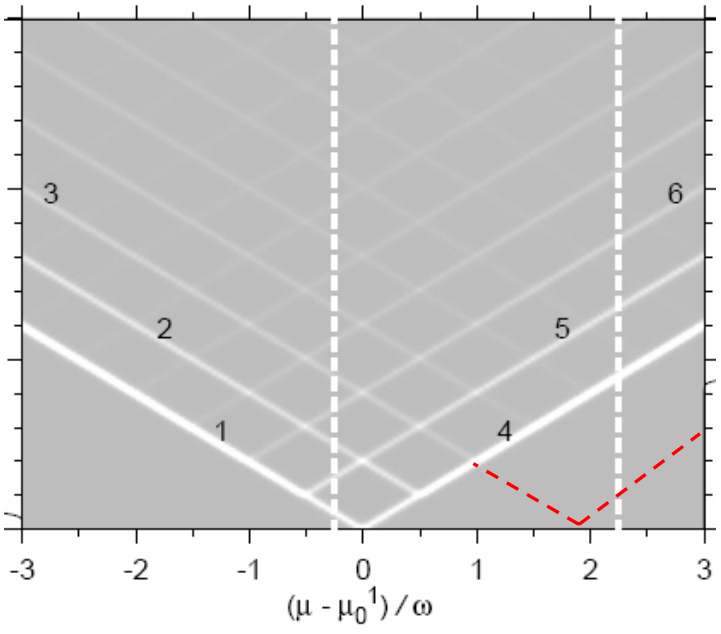
from: Herre van der Zant's talk

level spectroscopy



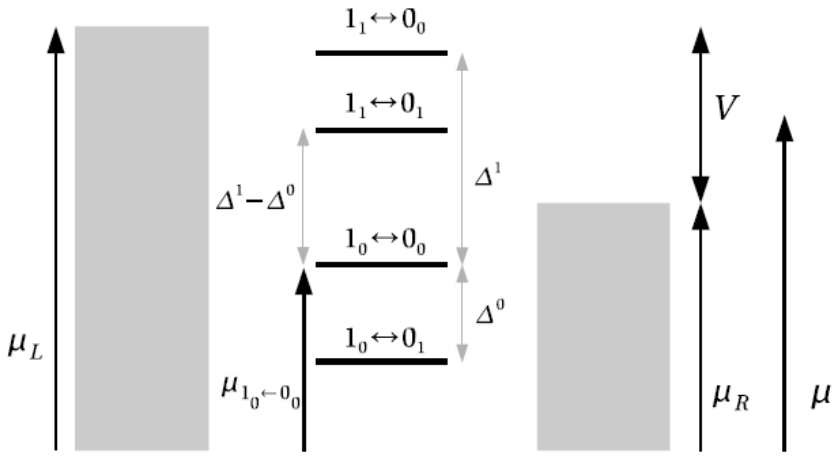


- excited states result in extra lines in stability diagram (red)
- excited states can be electronic, vibrational, or spin related



Side bands related to excitations
2 excited states for N=0 and 1

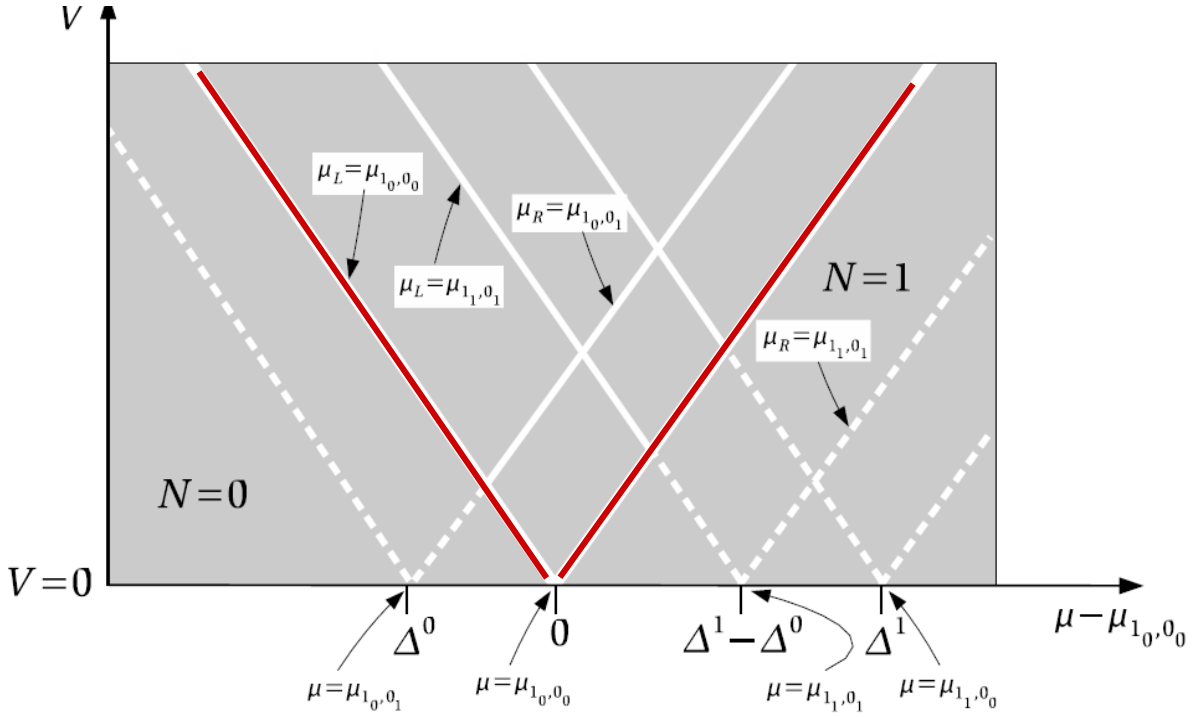
K. Nowack, Diploma (2004)



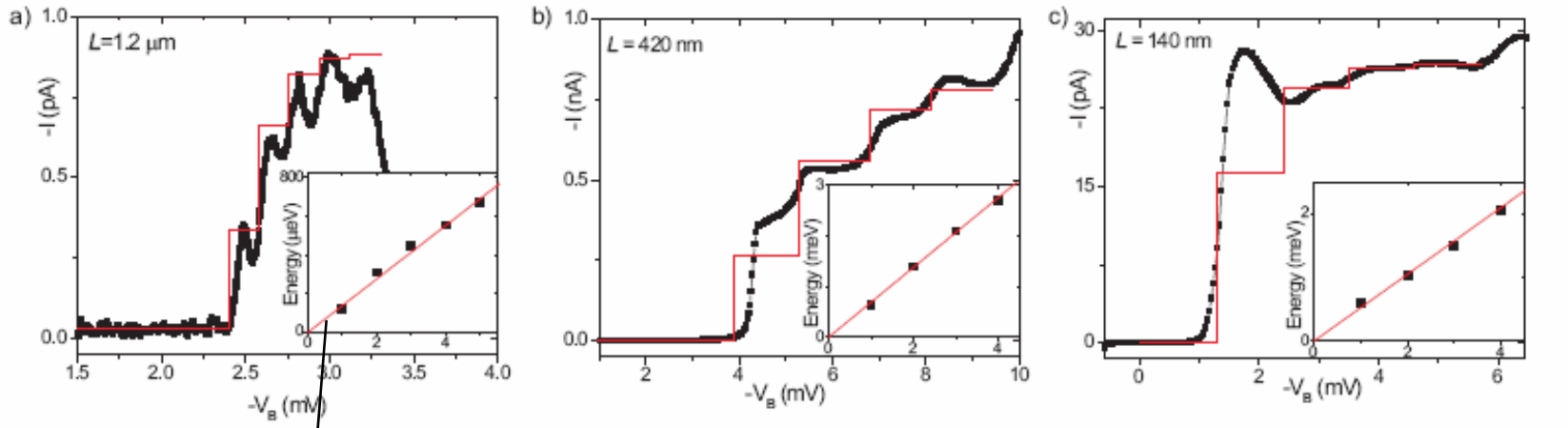
1_m <-> 0_n : addition energy from n-th excited state with 0 charge to m-th excited state with 1 electron

$\Delta^N = E^N_1 - E^N_0$ N=0,1

= level spacing



Main point: Energy spacing of excitation lines is a harmonic spectrum with fundamental energy $\hbar\Omega$ betw. 140 μeV and 530 μeV << mean electronic level spacing $\Delta \sim hv_F/2L$

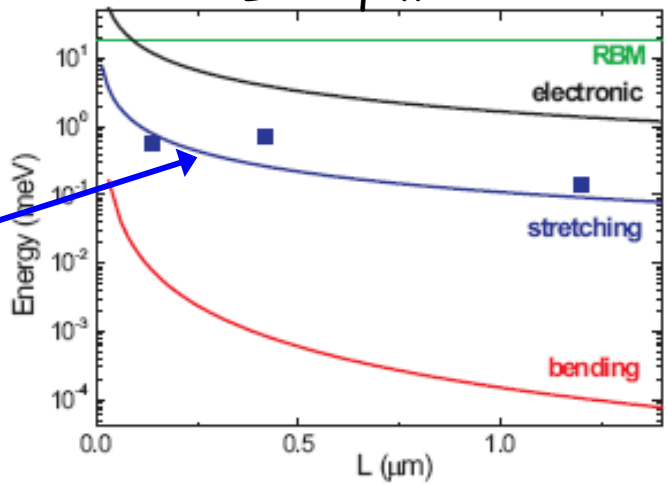


$E \sim \hbar\Omega\, n$ → Vibrational mode coupled to the tunneling charge

n= number of excited vibrational quanta

Which mode ???

Low-q modes



$$E = (nh/L)\sqrt{Y/\rho_m},$$

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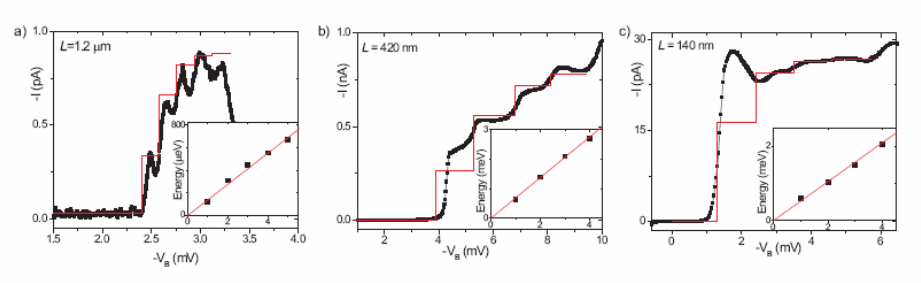

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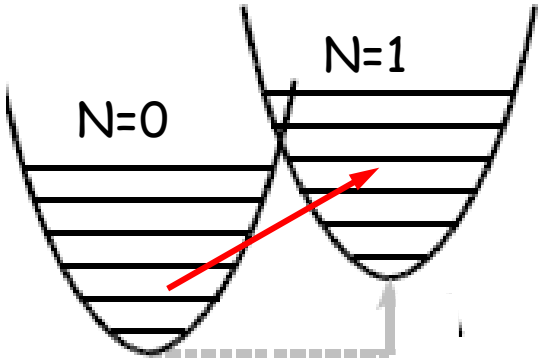


~g

Franck-Condon (FC) model:

Electronic states coupled to a local vibrational mode

$H = \varepsilon_d\, d^+d + H_{Coul} + (\Omega/2)\,(P^2 + Q^2) + g\,Q\,d^+d$

$= \varepsilon_d\, d^+d + H_{Coul} + (\Omega/2)\,(P^2 + [Q + \sqrt{2}\,(g/\Omega)\,d^+d]^2) - (\ldots)$

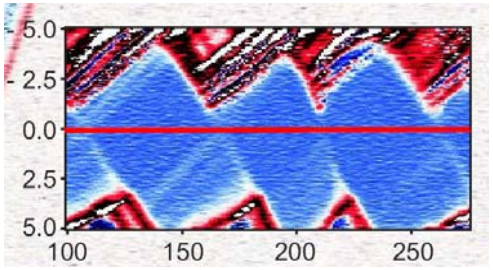
transition rates ~FC factors
nuclear geometry change upon charging

$$F^i_{q\tilde{q}} = \left| \int \Psi_q(Q)^* \Psi_{\tilde{q}}(Q + \sqrt{2}\,g)\,\mathrm{d}Q \right|^2$$

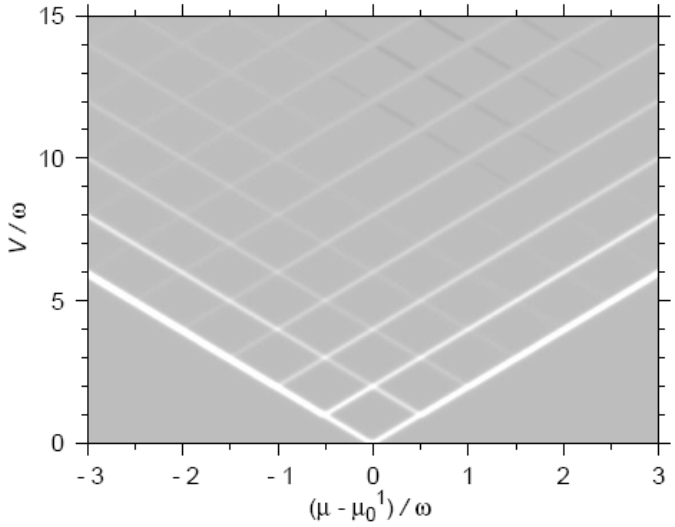
Current steps related to g

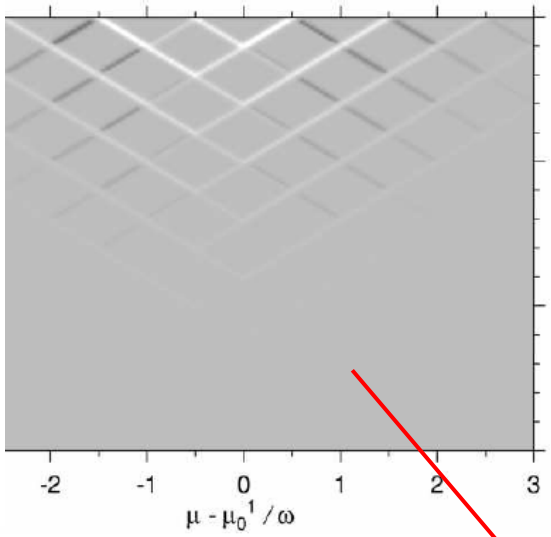
Estimates: g ~ 0.95, 1.1 and 0.5

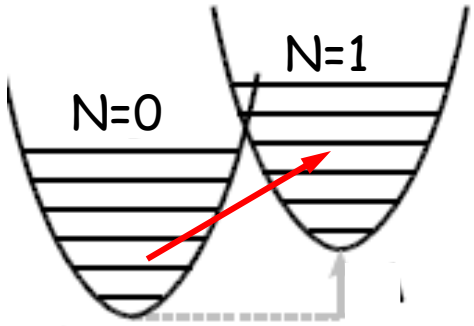
Franck-Condon blockade for strong electron-vibron coupling



Nowack/Wegewijs, cond-mat/0506552
Koch/von Oppen, PRL 94, 206804 (2004)





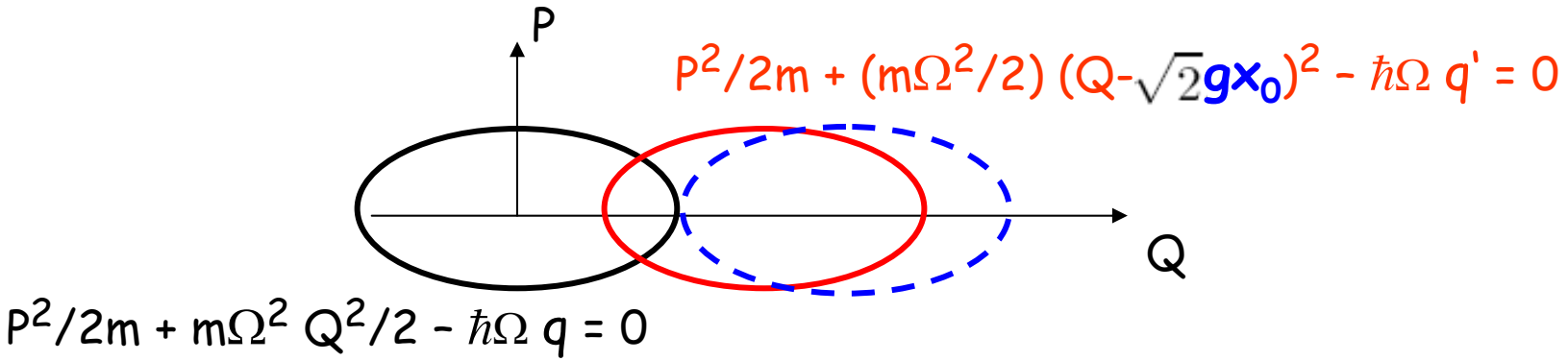


$g \ll 1$

$g \gg 1$

Exponential suppression of the current at low voltages

Quasi-classical perspective



Transitions are ONLY allowed if their classical counterparts are also allowed
→ if phase space trajectories of the oscillators do intersect or are tangential !

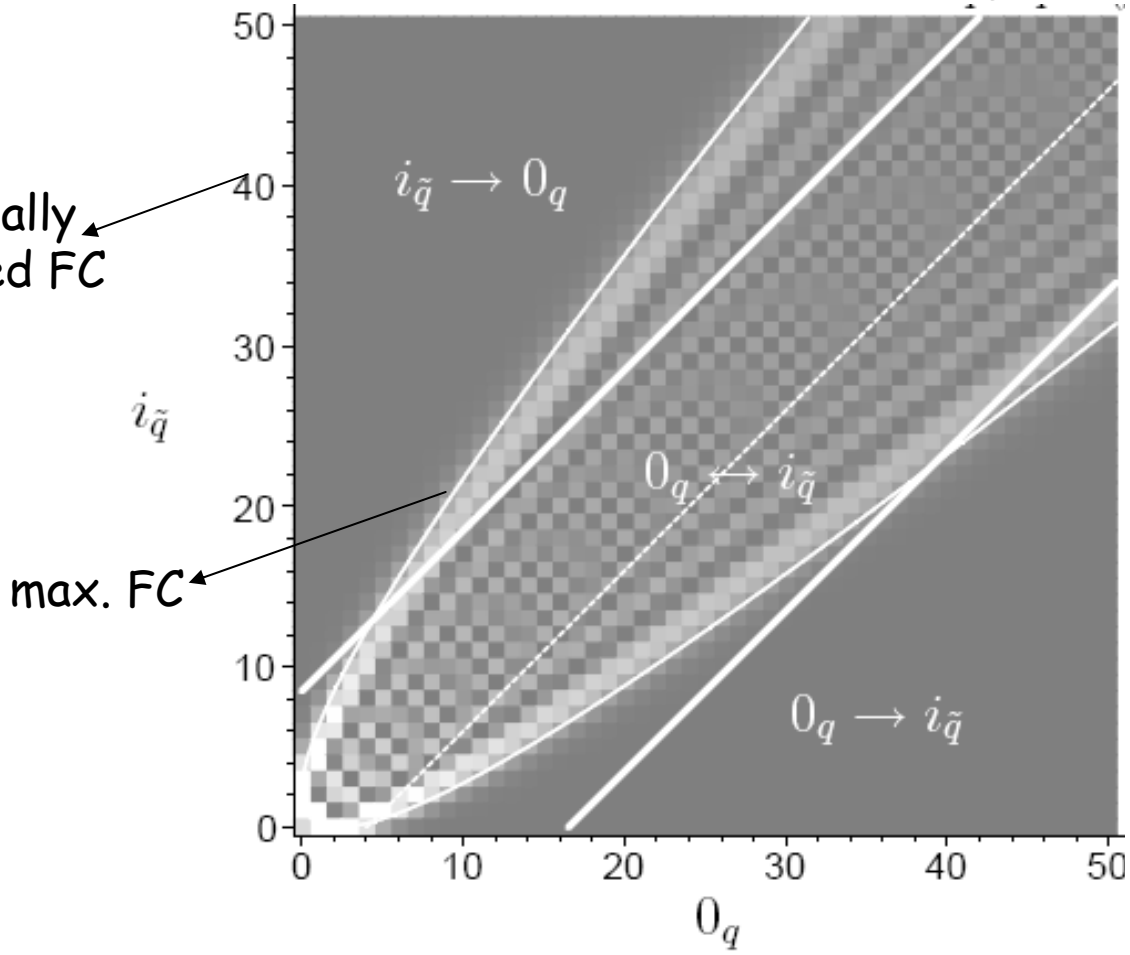
Condition ($P^2 \geq 0$!)

$$q+q' \geq (q-q')^2/2g^2 + g^2/2$$ Franck-Condon parabola

Nowack/Wegewijs, cond-mat/0506552

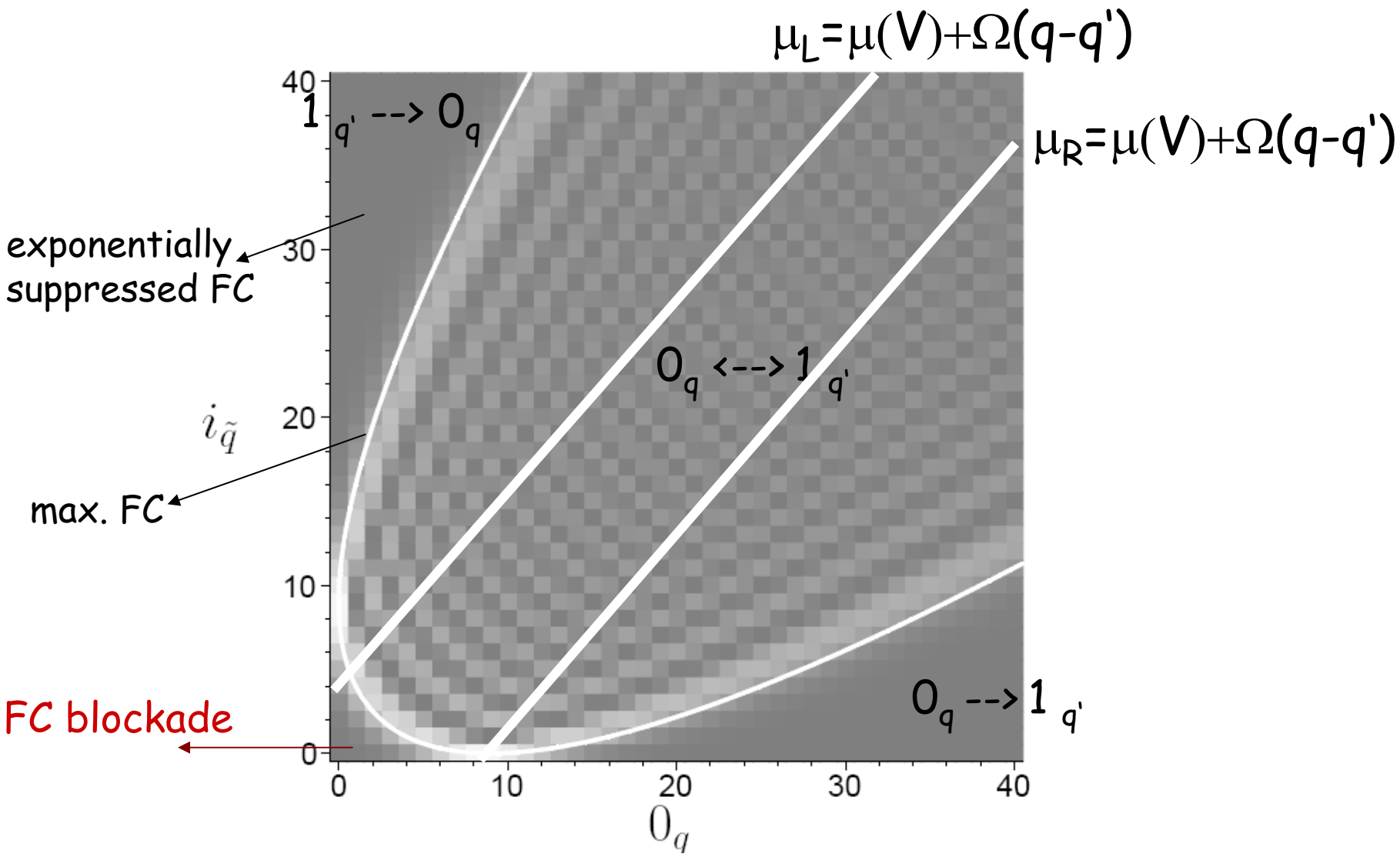
Weak charge-vibron coupling $g \ll 1$

$\mu_L = \mu(V) + \Omega(q - q')$



$\mu_R = \mu(V) + \Omega(q - q')$

Strong charge-vibron coupling $g \gg 1$



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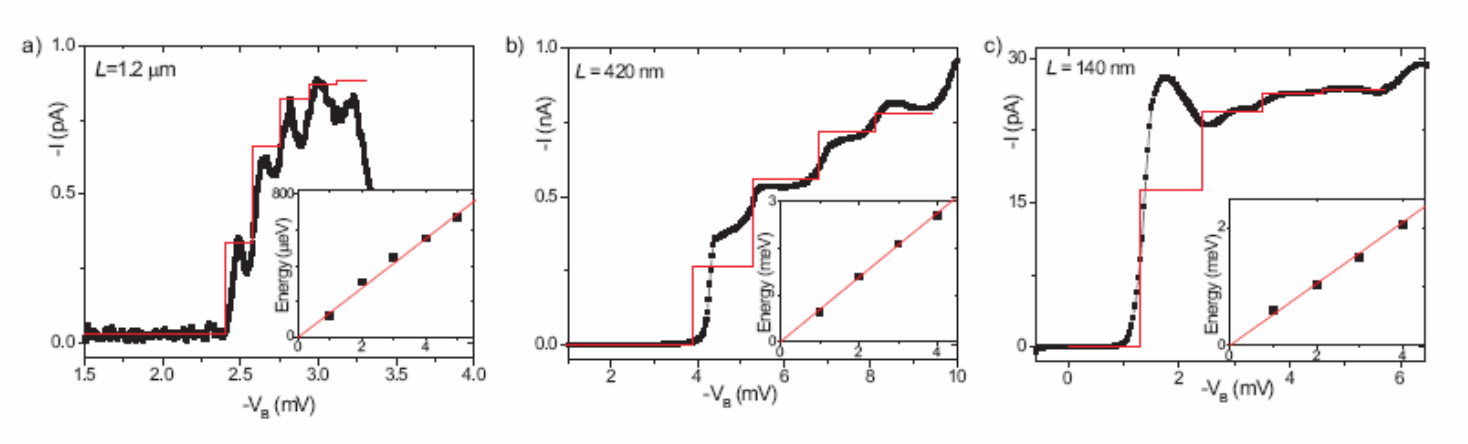
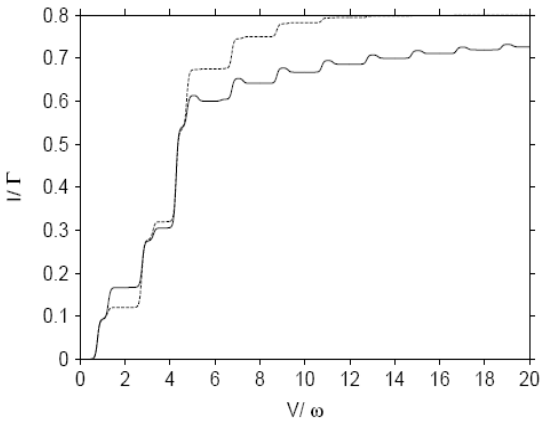


Not clear: NDC alternating with PDC
Asymmetric vibron-charge coupling ?
Nowack/Wegewijs, cond-mat/0506552

Further, fit is not perfect->
nonequilibrium phonons ?
asymmetric coupling to leads ?



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Why electron-vibron coupling so large, g~ 1 ?

In graphite g is small but ....
inhomogeneous electron charge distribution ?

Interaction with polarization charge:

$$W = -\int dx dx' \rho(x) K(x-x') \frac{\partial P}{\partial x'}. \qquad P(x) \approx e\rho_0 z(x)$$

$z(x)=A_n \sin(\pi n x/L)$

→ Force $F = \frac{e\rho_0 \pi n}{L} \int_0^L dx\ \rho(x) \cos\frac{\pi n x}{L}.$ → ρ(x)=const -> F=0 !

Assume now $\rho(x)=e\,\delta(x-L/2)$ → $F_l = (-1)^l e^2 \rho_0 2\pi l/L$
only even harmonics n=2l

This is an extreme case, in general it is enough if ρ(x) is not constant

Thanks to Andrea Donarini

The End