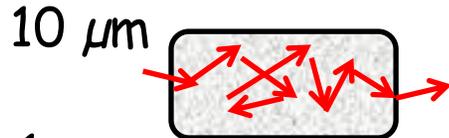
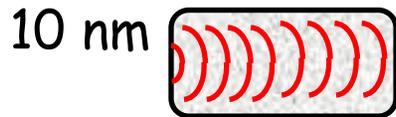
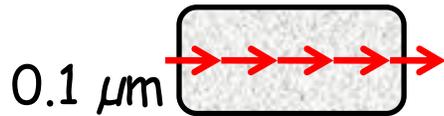


Nanoelectronics

0.1 mm Macroscopic dimensions



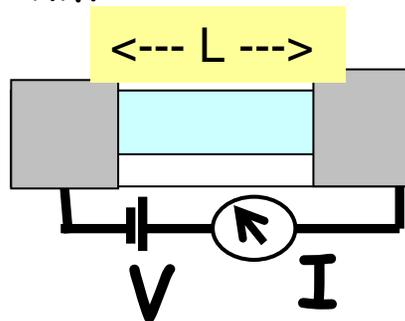
1 μm



1 nm

Atomic dimensions

0.1 nm



NCN

<http://www.nanohub.org/courses/cqt>

and the
meaning of resistance

1a,b: What and where is
the resistance?

2a,b: Quantum transport

3a,b: Spins and magnets

4a,b: Maxwell's demon

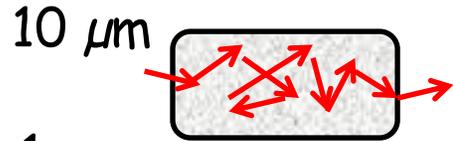
5a,b: Correlations and entanglement

Supriyo Datta

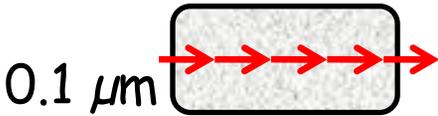
PURDUE
UNIVERSITY

Nanoelectronics and the meaning of resistance

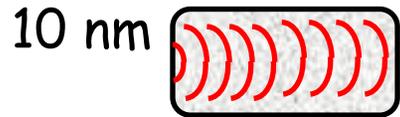
0.1 mm Macroscopic dimensions



10 μm



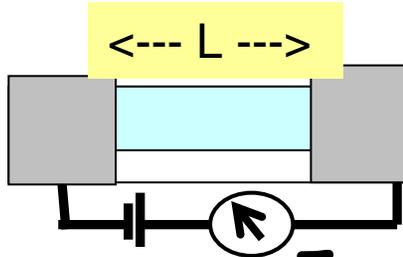
0.1 μm



10 nm

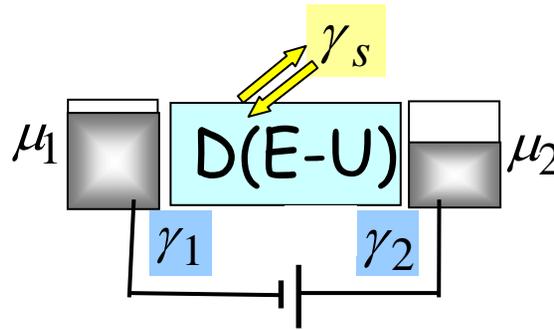
1 nm Atomic dimensions

0.1 nm



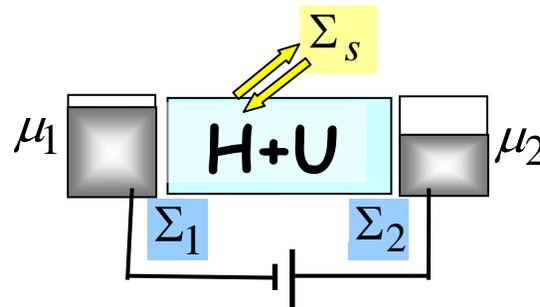
NCN V I

Lectures 1a,b:
Simple model



Lectures 3a,b:
Include spin

Lectures 4a,b:
Energy exchange
and the second law



Lectures 5a,b:
Beyond mean field
theory

Lectures 2a,b:
Microscopic model

$$R = V/I, G = I/V$$

$$1 \mu\text{m} = .001 \text{ mm}$$

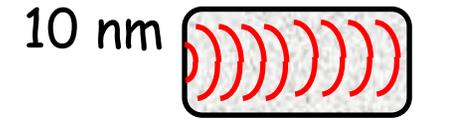
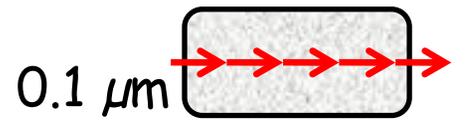
$$1 \text{ nm} = .001 \mu\text{m}$$



0.1 mm **Macroscopic dimensions**

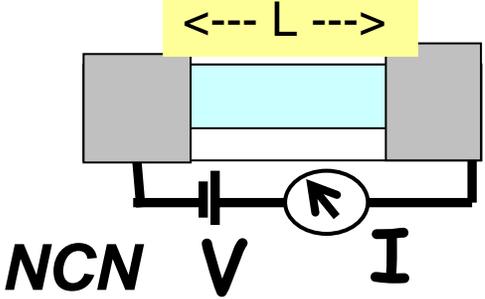


1 μm

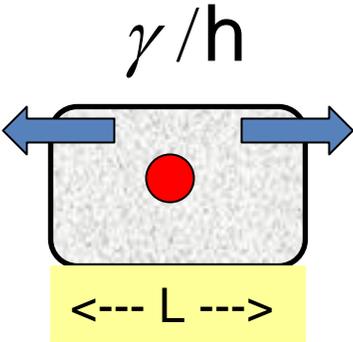


1 nm **Atomic dimensions**

0.1 nm



$$D \sim A L$$



$$G = \sigma A / L$$

$$\frac{\gamma}{\hbar} \sim \frac{2D}{L^2} \rightarrow D\gamma \sim A/L$$

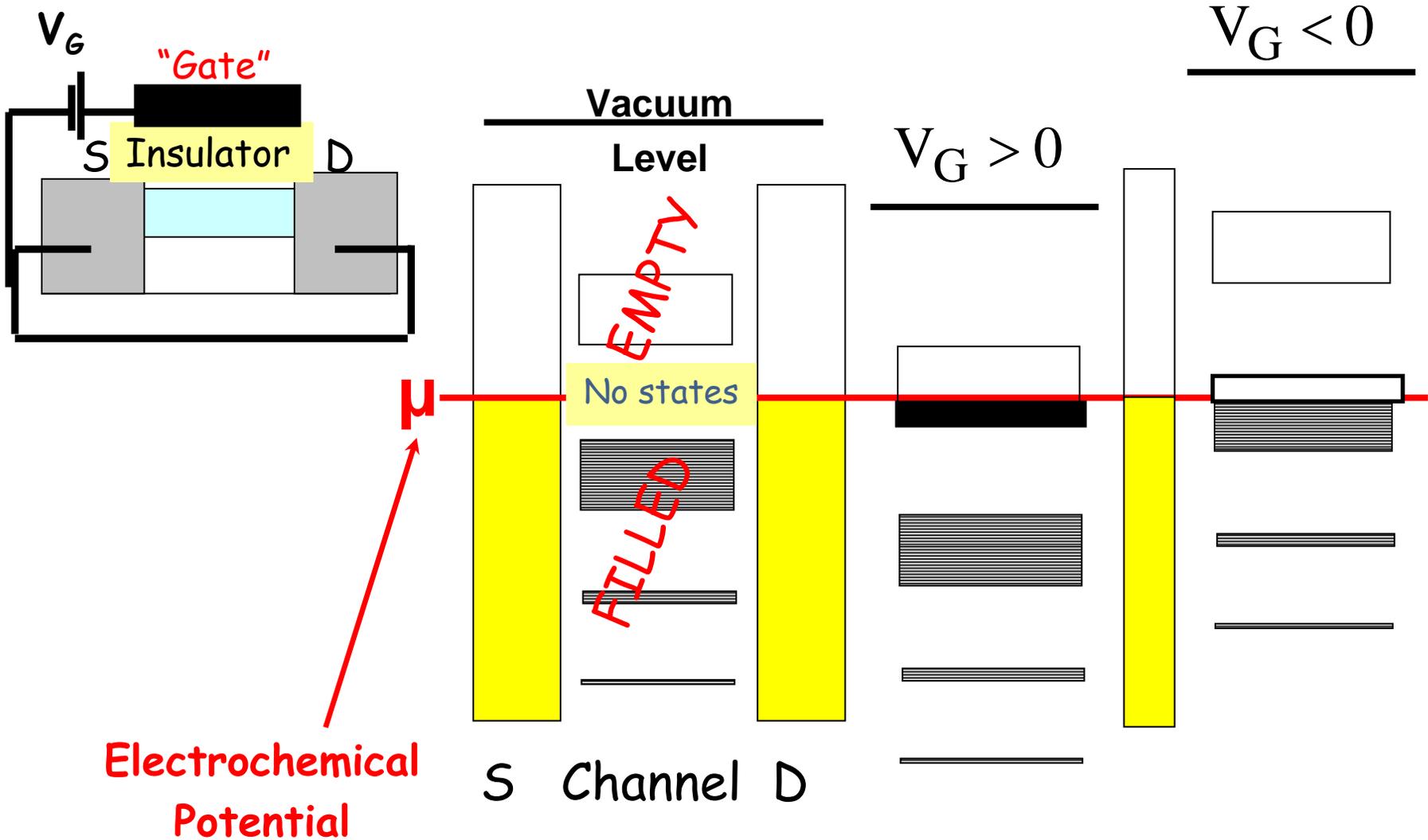
$$\frac{\gamma}{\hbar} \sim \frac{v}{L} \rightarrow D\gamma \sim A$$

$$G = \underbrace{(q^2 / h)}_{1/25.8 \text{ K}\Omega} \pi D \gamma$$

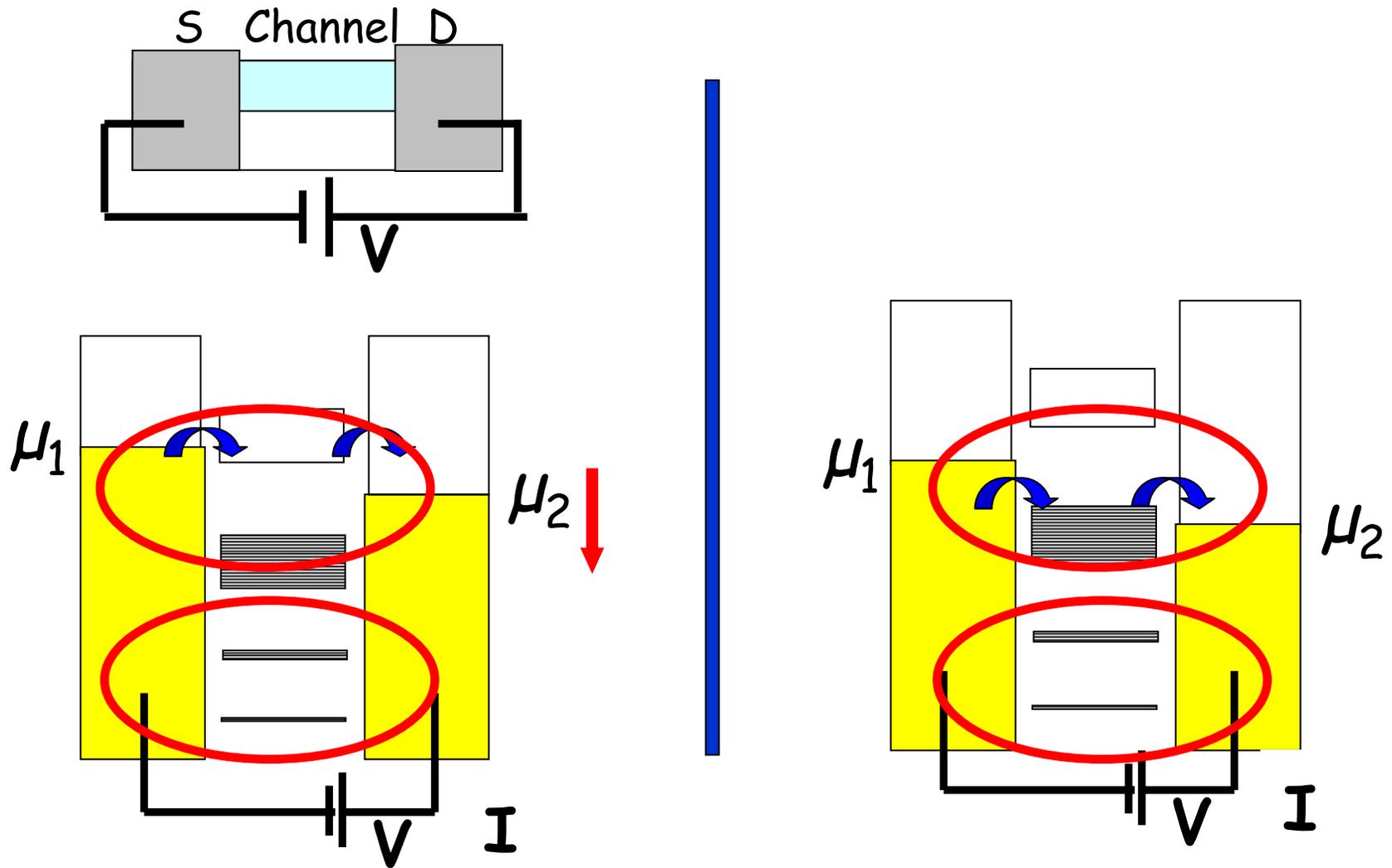
$$R = V/I, G = I/V$$

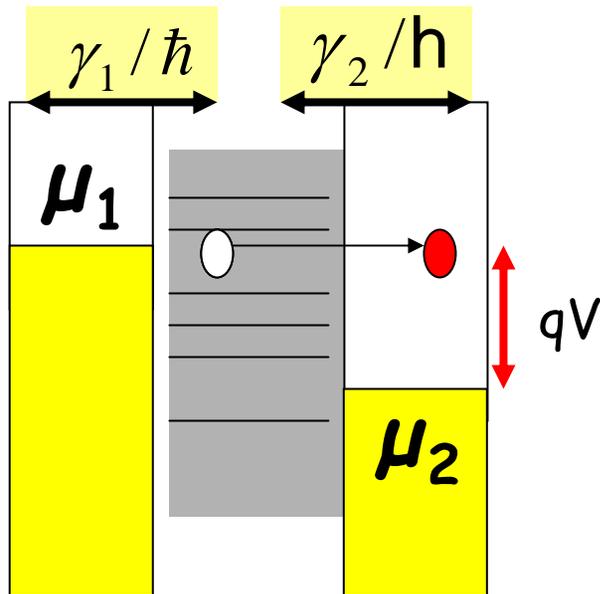


Equilibrium Energy Level Diagram



What makes electrons flow?





γ/\hbar : *Escape Rate*
per second

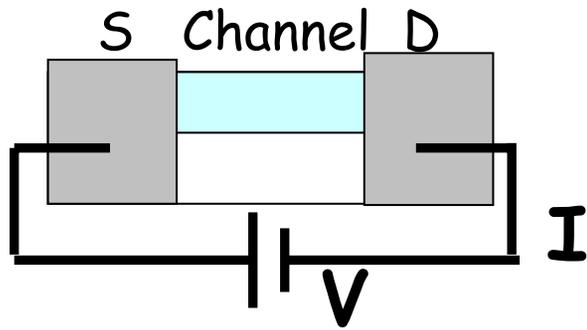
γ has dimensions of energy

$$\gamma = 1 \text{ meV}$$

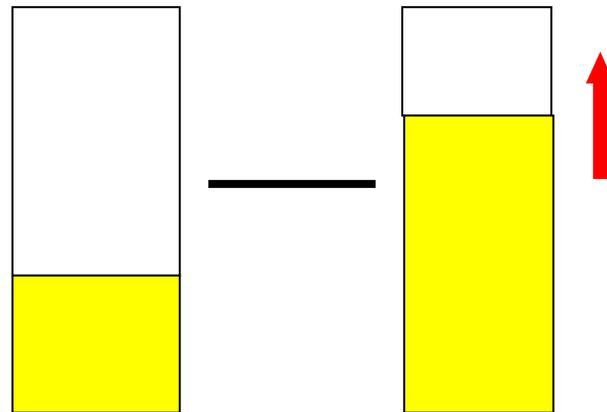
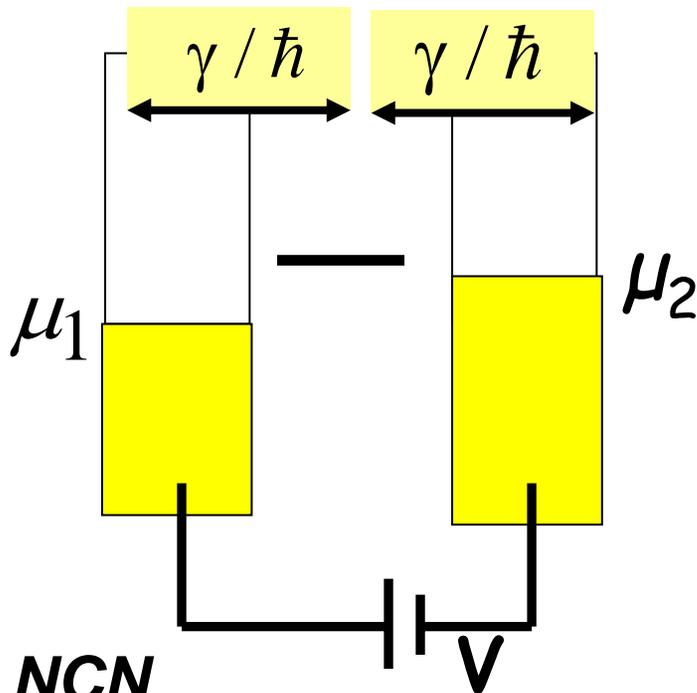
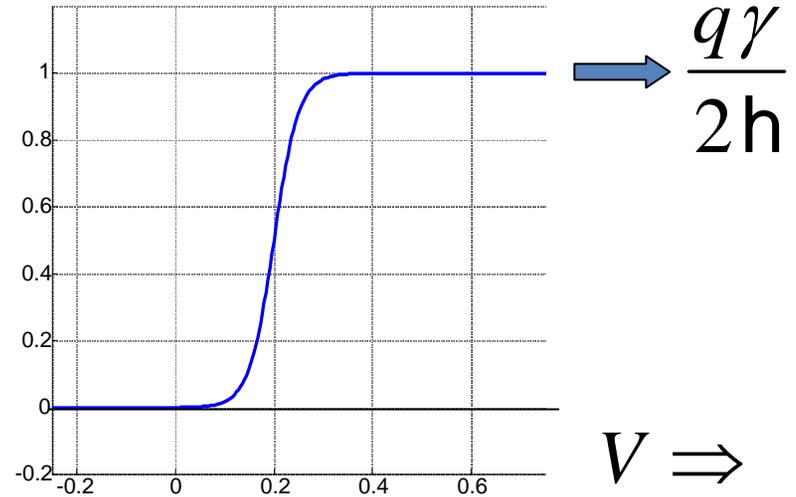
$$\gamma/\hbar = \frac{1.6e-22 \text{ J}}{1.06e-34 \text{ J-sec}}$$

$$\sim 10^{12} / \text{sec} = \frac{1}{1 \text{ ps}}$$

Current through ONE level

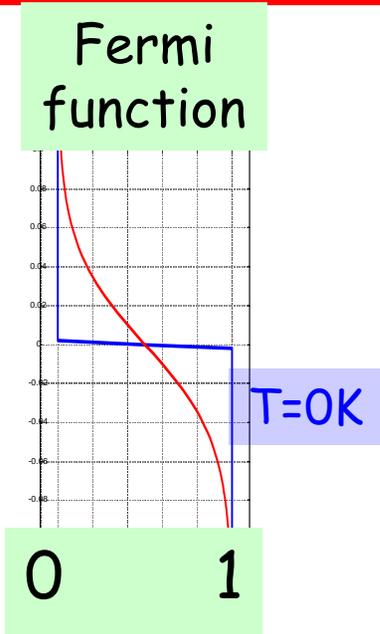
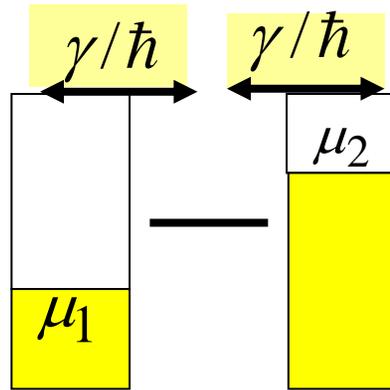


Normalized Current

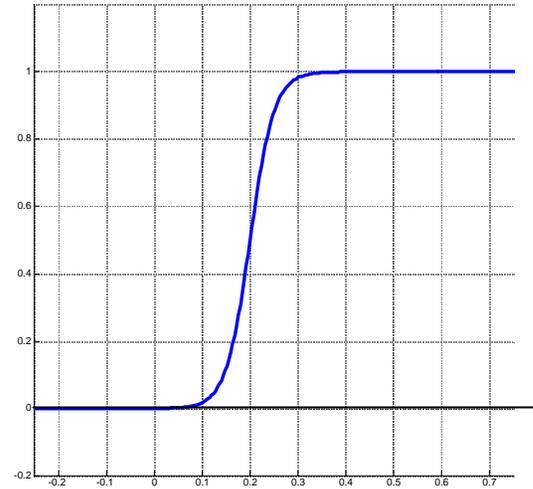


NCN

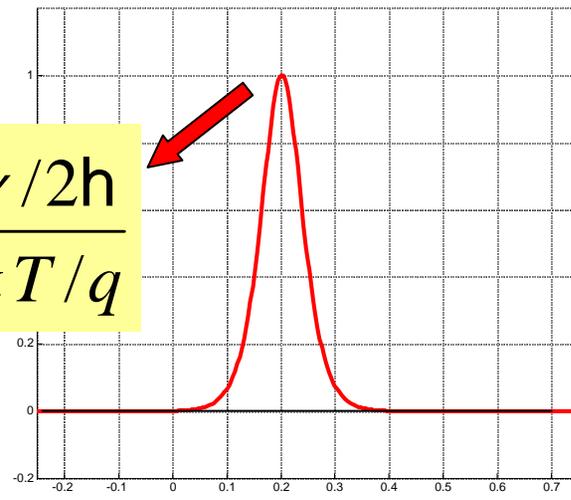
** Maximum Conductance ?



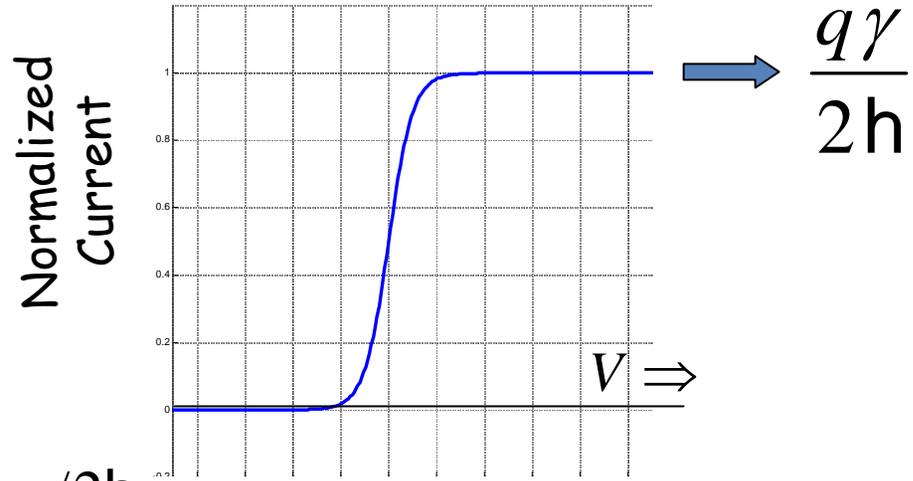
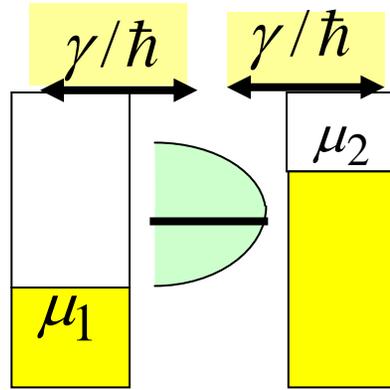
Normalized Current



$$\frac{dI}{dV} \sim \frac{q\gamma/2h}{4kT/q}$$



Conductance quantum

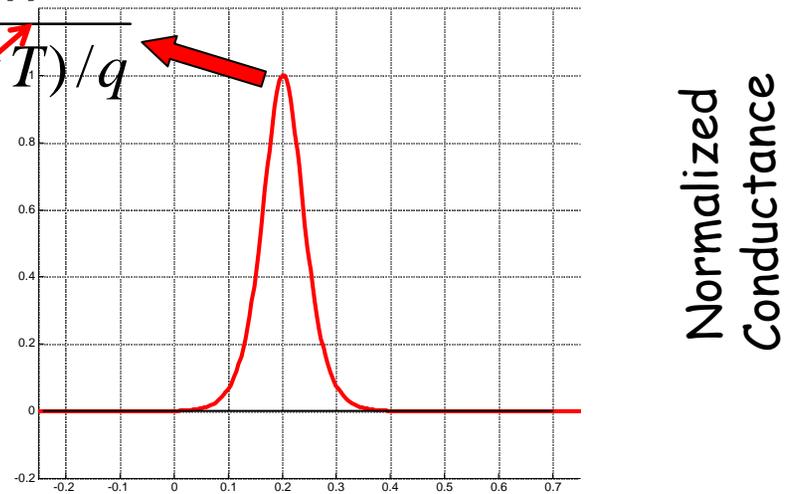


$$\frac{dI}{dV} \sim \frac{q\gamma/2h}{(2\gamma + 4kT)/q}$$

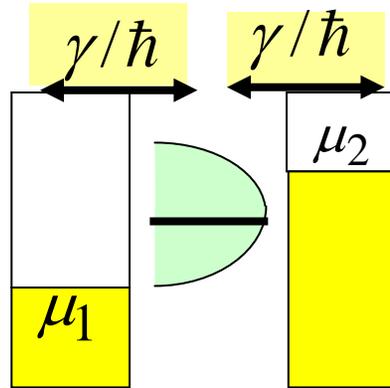
$$\sim q^2/4h \quad \text{if} \quad \gamma \gg kT$$

Conductance quantum

$$\sim q^2/2\pi h \sim 1/25.8 \text{ K}\Omega$$



Conductance quantum: experiment



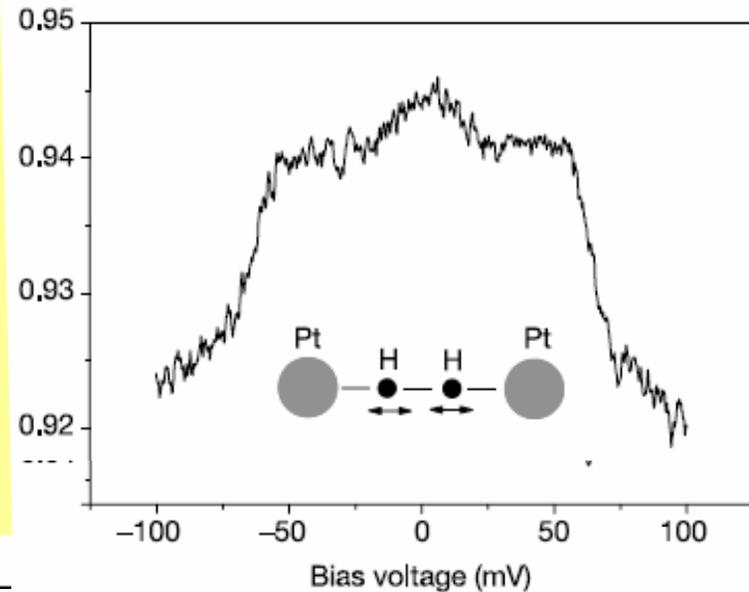
$$\frac{dI}{dV} \leq \underbrace{2}_{spin} \frac{q^2}{h}$$

Measurement of the conductance of a hydrogen molecule

R. H. M. Smit^{*}, Y. Noat^{*†}, C. Untiedt^{*}, N. D. Lang[‡], M. C. van Hemert[§] & J. M. van Ruitenbeek^{*}

^{*} Kamerlingh Onnes Laboratorium, Universiteit Leiden, PO Box 9504,

Differential conductance (Normalized)



CONTAINER.

NATURE | VOL 419 | 31 OCTOBER 2002 | www.nature.com

NCN

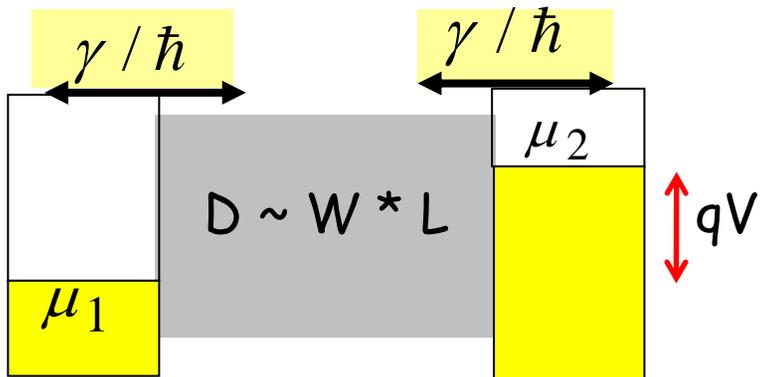
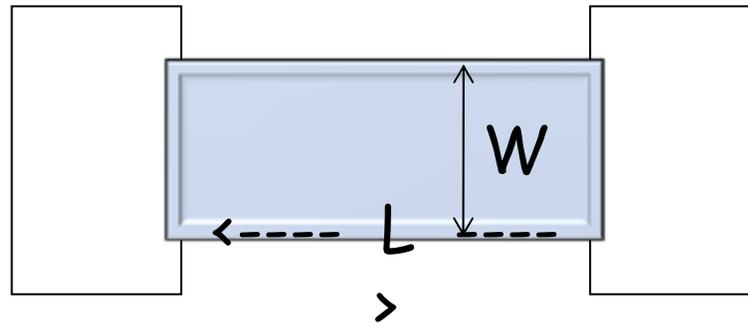
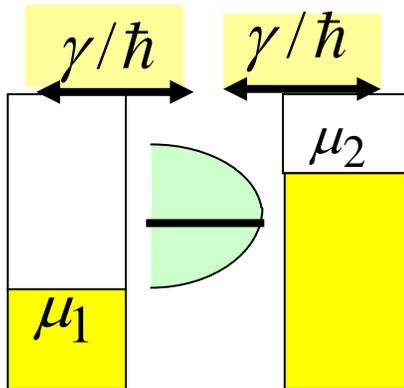
<http://www.nanohub.org/courses/cqt>

Supriyo Datta

PURDUE
UNIVERSITY

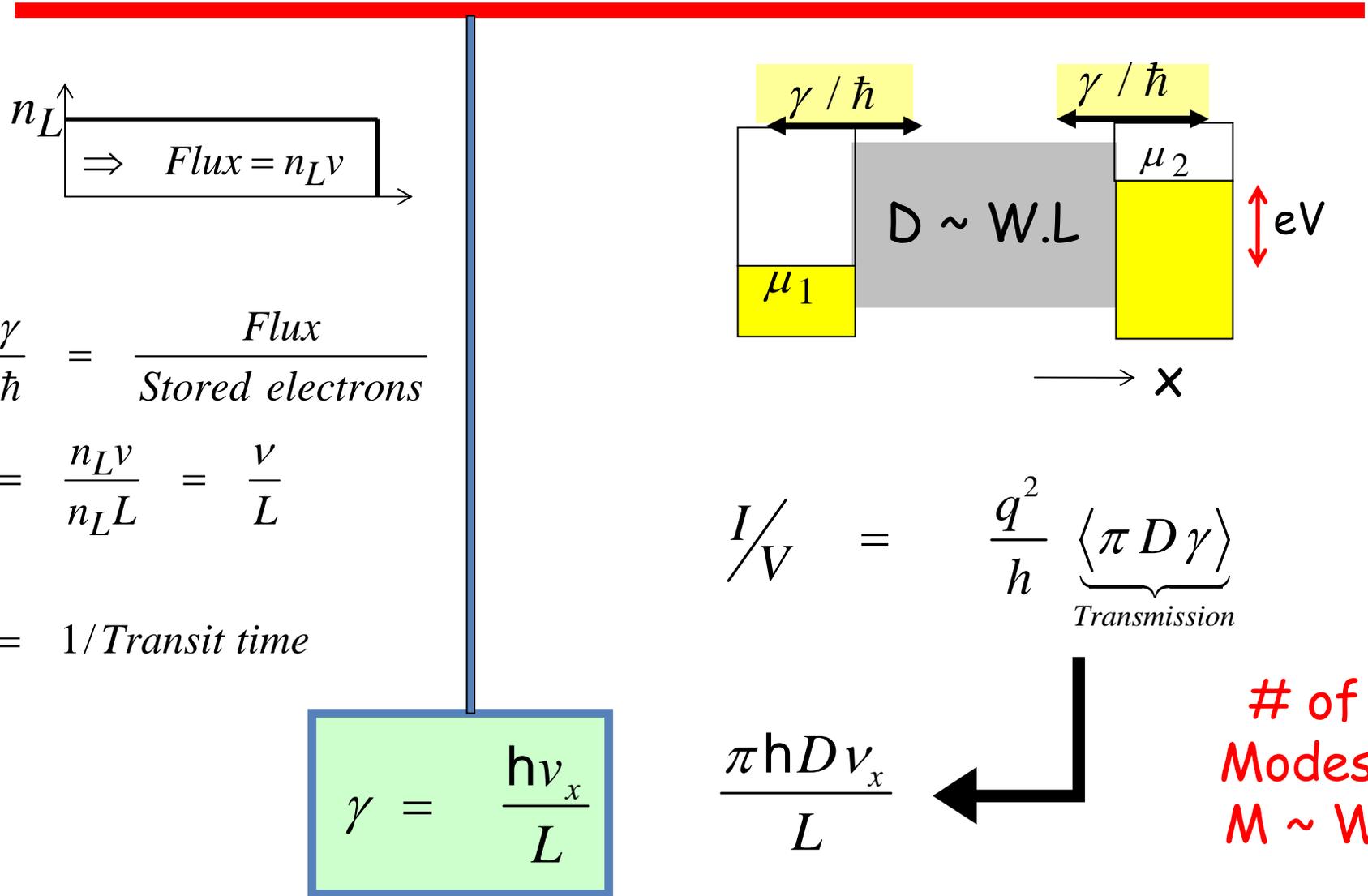
** Large conductors

One level

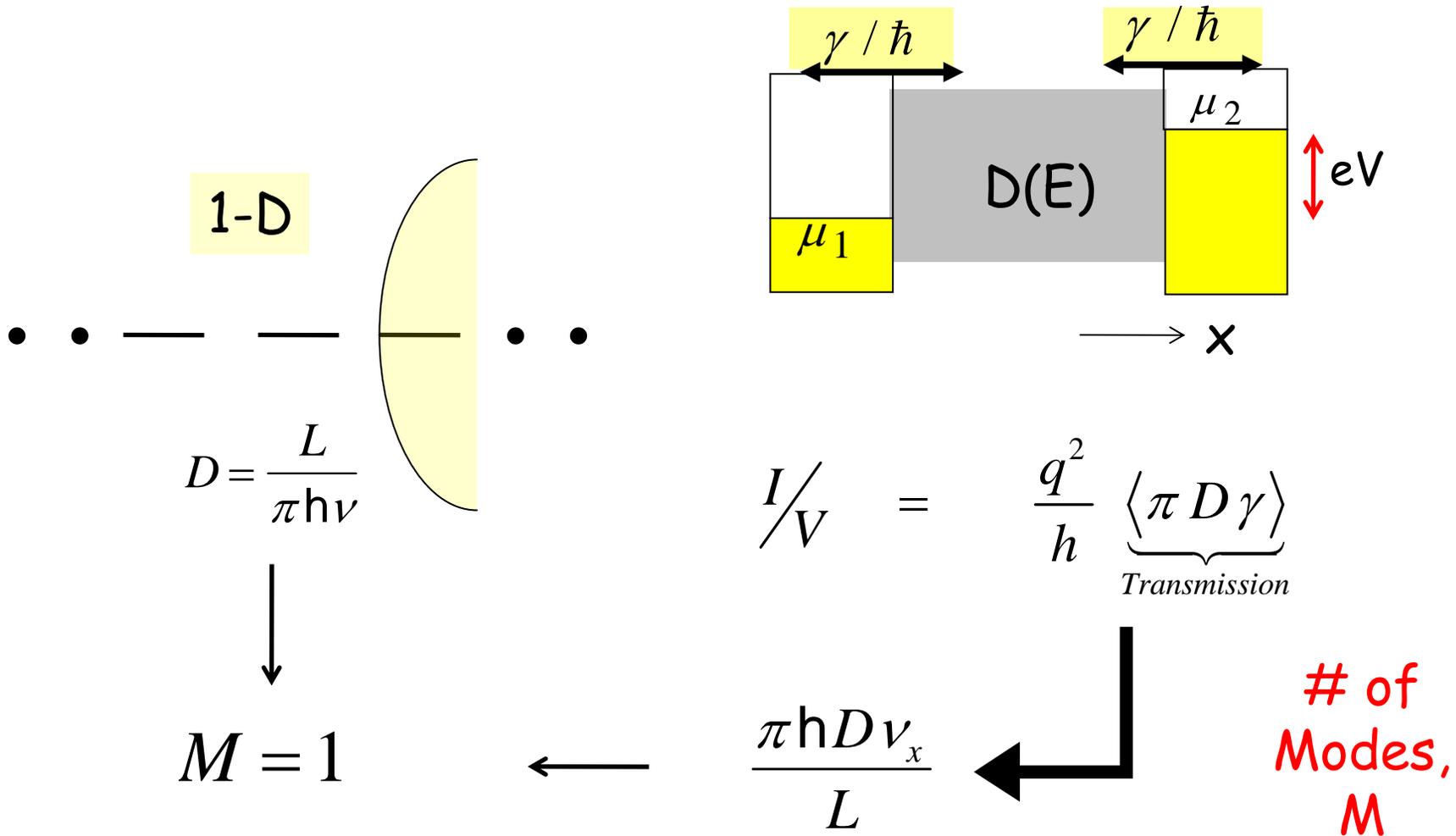


$$I \sim \underbrace{\frac{q\gamma}{2\hbar}}_{\text{Current per state}} \underbrace{D qV}_{\text{Number of states}}$$

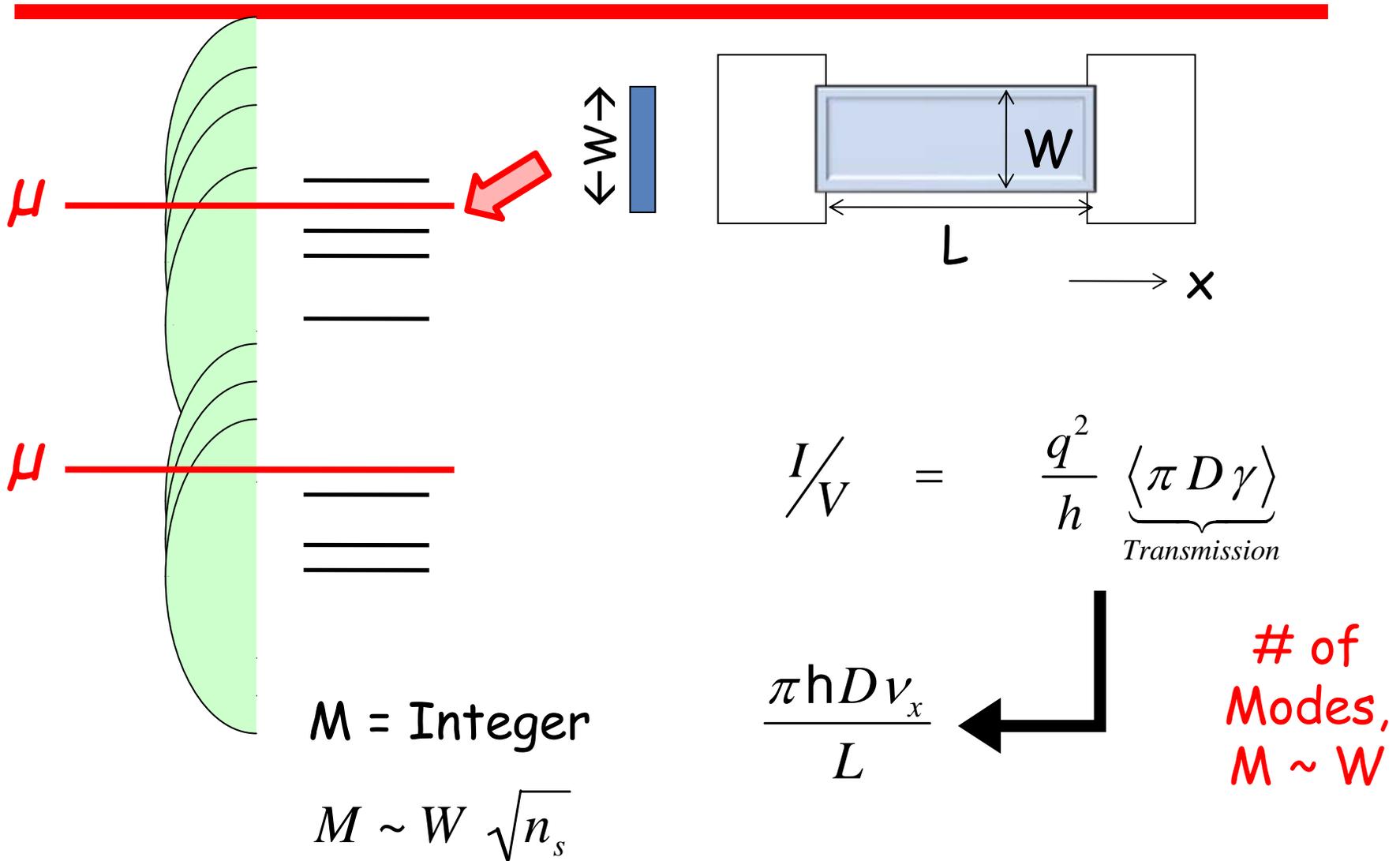
$$\frac{I}{V} = \frac{q^2}{h} \underbrace{\langle \pi D \gamma \rangle}_{\text{Transmission}}$$



Number of modes in a 1D channel



Number of modes in a 2-D channel



Quantum Point Contacts: Experiment

VOLUME 60, NUMBER 9

PHYSICAL REVIEW LETTERS

29 FEBRUARY 1988

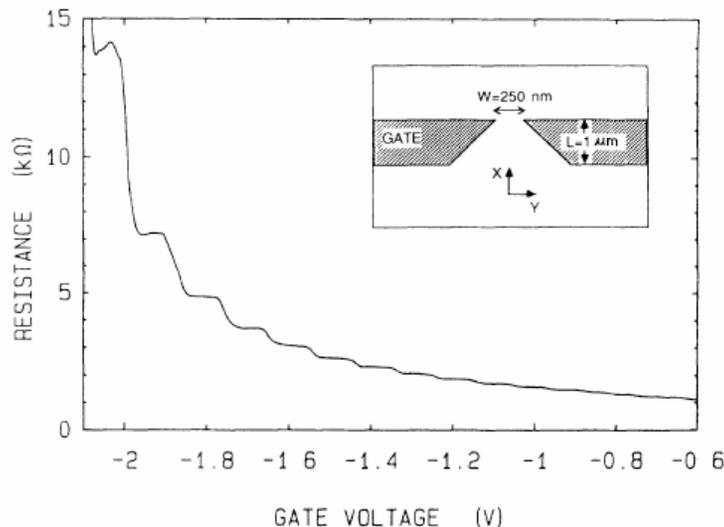


FIG. 1. Point-contact resistance as a function of gate voltage at 0.6 K. Inset: Point-contact layout.

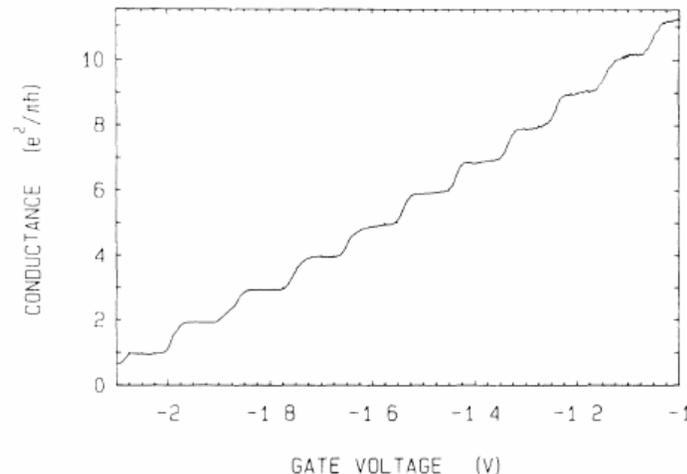
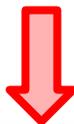


FIG. 2. Point-contact conductance as a function of gate voltage, obtained from the data of Fig. 1 after subtraction of the lead resistance. The conductance shows plateaus at multiples of $e^2/\pi h$.

Also,

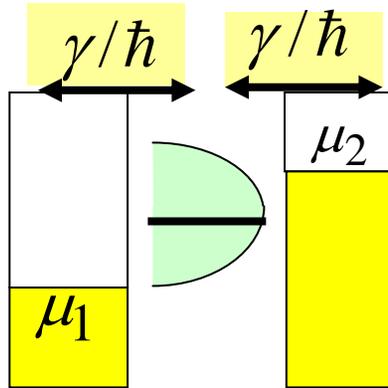


J. Phys. C: Solid State Phys. **21** (1988) L209–L214. Printed in the UK

LETTER TO THE EDITOR

$$G \sim \underbrace{2}_{\text{for spin}} \underbrace{\left(\frac{q^2}{h} \right)}_{1/25.8 \text{ K}\Omega} M$$

Conductance quantum: experiment



$$\frac{dI}{dV} \leq 2 \frac{q^2}{h}$$

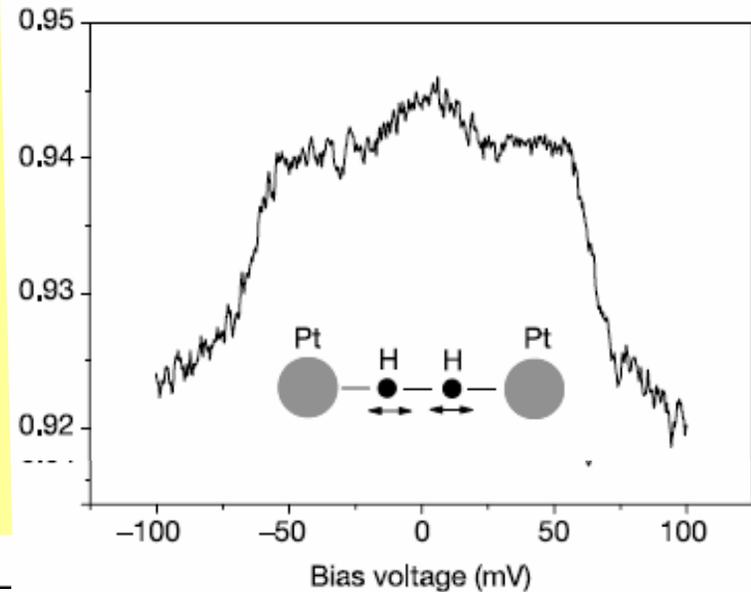


Measurement of the conductance of a hydrogen molecule

R. H. M. Smit^{*}, Y. Noat^{*†}, C. Untiedt^{*}, N. D. Lang[‡], M. C. van Hemert[§] & J. M. van Ruitenbeek^{*}

^{*} Kamerlingh Onnes Laboratorium, Universiteit Leiden, PO Box 9504,

Differential conductance (Normalized)



CONTAINS

NATURE | VOL 419 | 31 OCTOBER 2002 | www.nature.com

NCN



<http://www.nanohub.org/courses/cqt>

Supriyo Datta

PURDUE
UNIVERSITY

Quantum Point Contacts: Experiment

VOLUME 60, NUMBER 9

PHYSICAL REVIEW LETTERS

29 FEBRUARY 1988

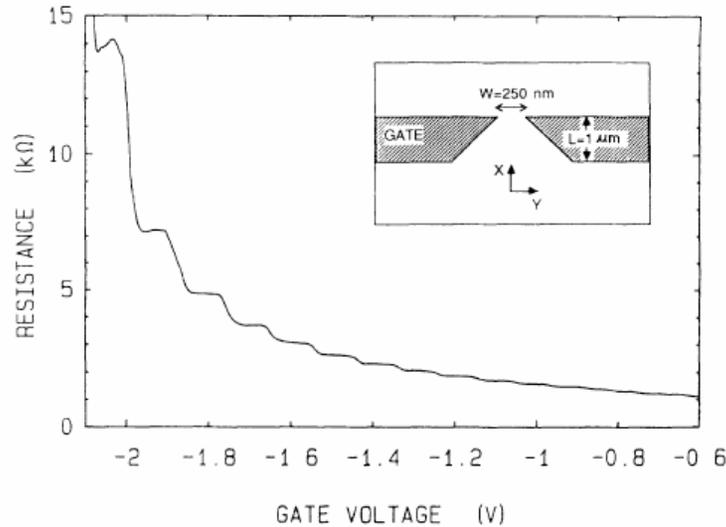


FIG. 1. Point-contact resistance as a function of gate voltage at 0.6 K. Inset: Point-contact layout.

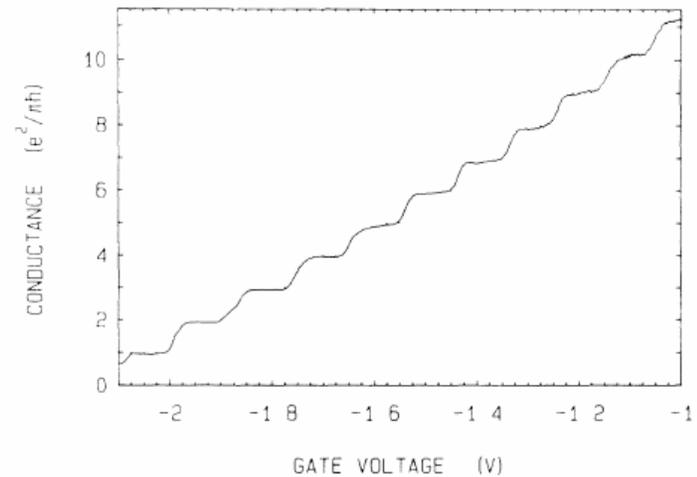


FIG. 2. Point-contact conductance as a function of gate voltage, obtained from the data of Fig. 1 after subtraction of the lead resistance. The conductance shows plateaus at multiples of $e^2/\pi h$.

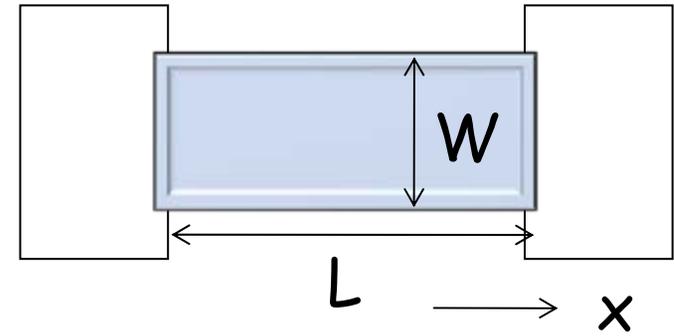
$$G = \underbrace{2}_{\text{for spin}} \underbrace{\left(\frac{q^2}{h} \right)}_{1/25.8 \text{ K}\Omega} M$$

$$M \sim W \sqrt{n_s}$$

Ballistic 2D channel

$$W = 0.1 \text{ } \mu\text{m}$$

$$n_s = 4e + 12 / \text{cm}^2$$



$$M \sim W \sqrt{n_s}$$

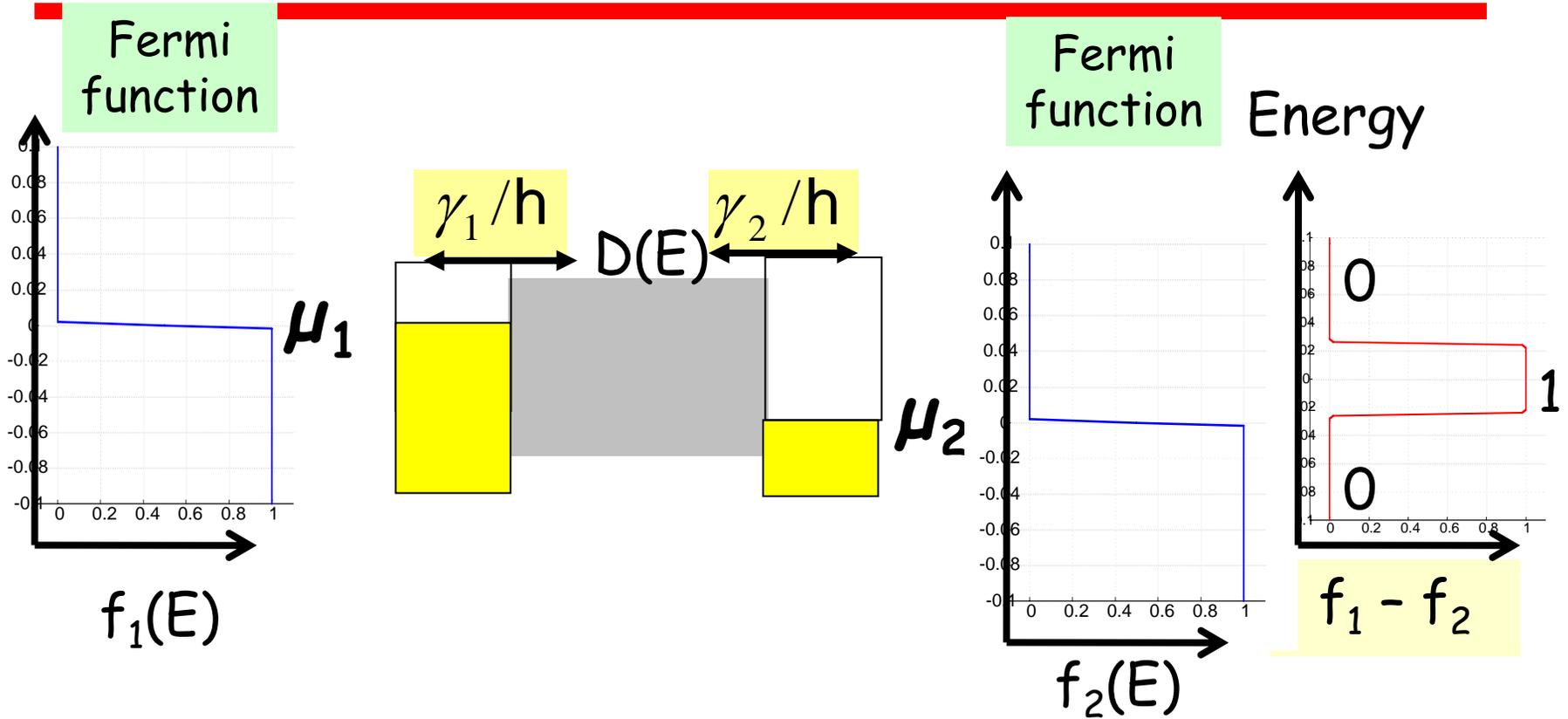
$$\sim 0.1 \text{ } \mu\text{m} \times 2e + 6 / \text{cm}$$

$$= 20$$

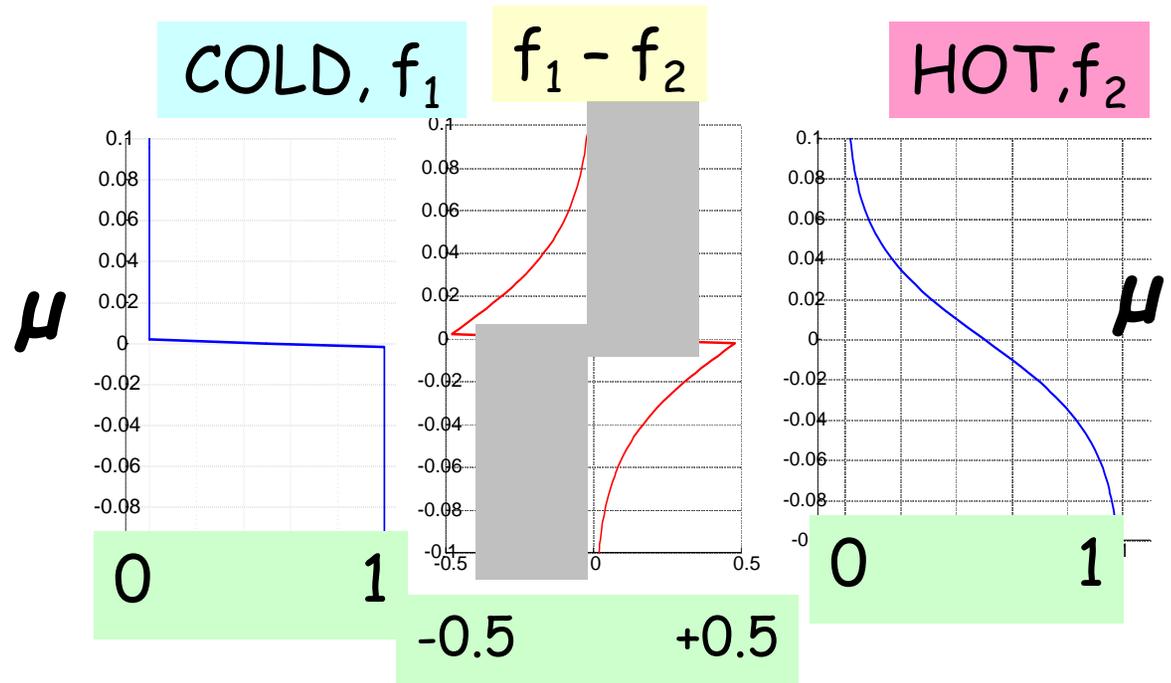
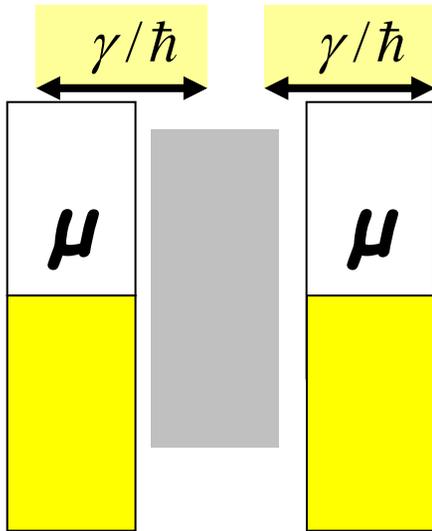
$$G = \underbrace{2}_{\text{for spin}} \underbrace{\left(\frac{q^2}{h} \right)}_{1/25.8 \text{ K}\Omega} M$$
$$= 2 * \frac{1}{25.8 \text{ K}\Omega} * 20$$

$$\sim \frac{1}{600 \text{ } \Omega}$$

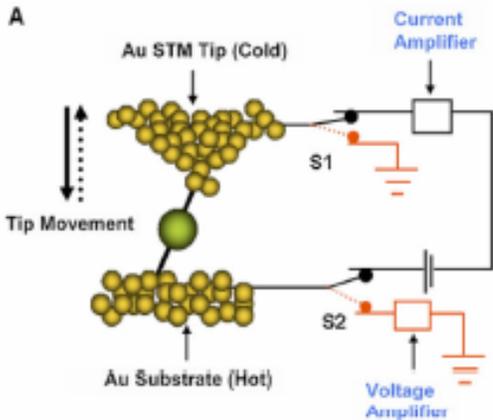
** Driving term: $f_1 - f_2$



TEMPERATURE driven current



Molecular "Seebeck Effect"



Thermoelectricity in Molecular Junctions

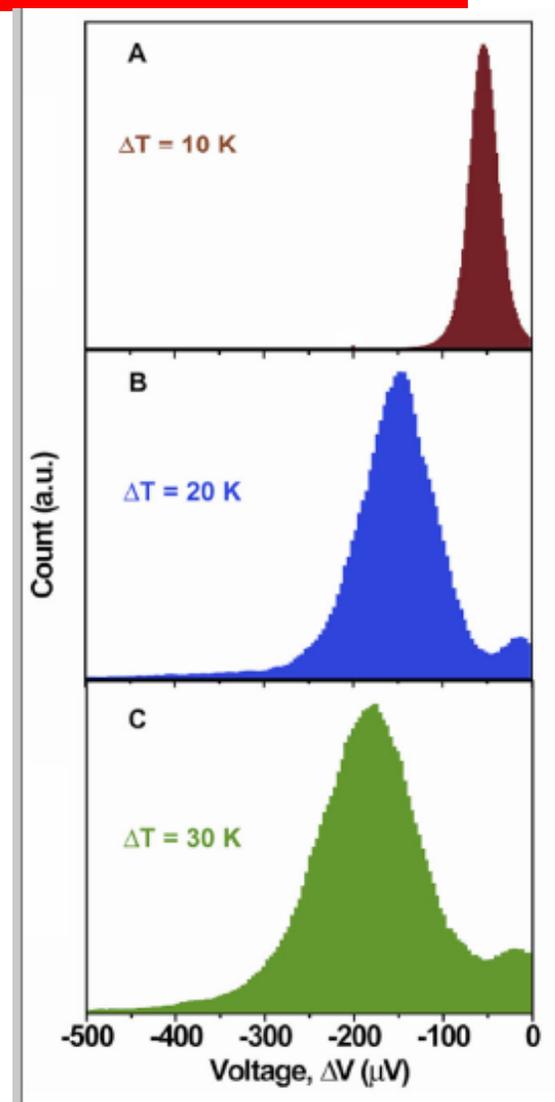
Pramod Reddy,^{1*} Sung-Yeon Jang,^{2,3*†} Rachel A. Segalman,^{1,2,3‡} Arun Majumdar^{1,3,4‡}

By trapping molecules between two gold electrodes with a temperature difference across them, the junction Seebeck coefficients of 1,4-benzenedithiol (BDT), 4,4'-dibenzenedithiol, and 4,4'-tribenzenedithiol in contact with gold were measured at room temperature to be $+8.7 \pm 2.1$

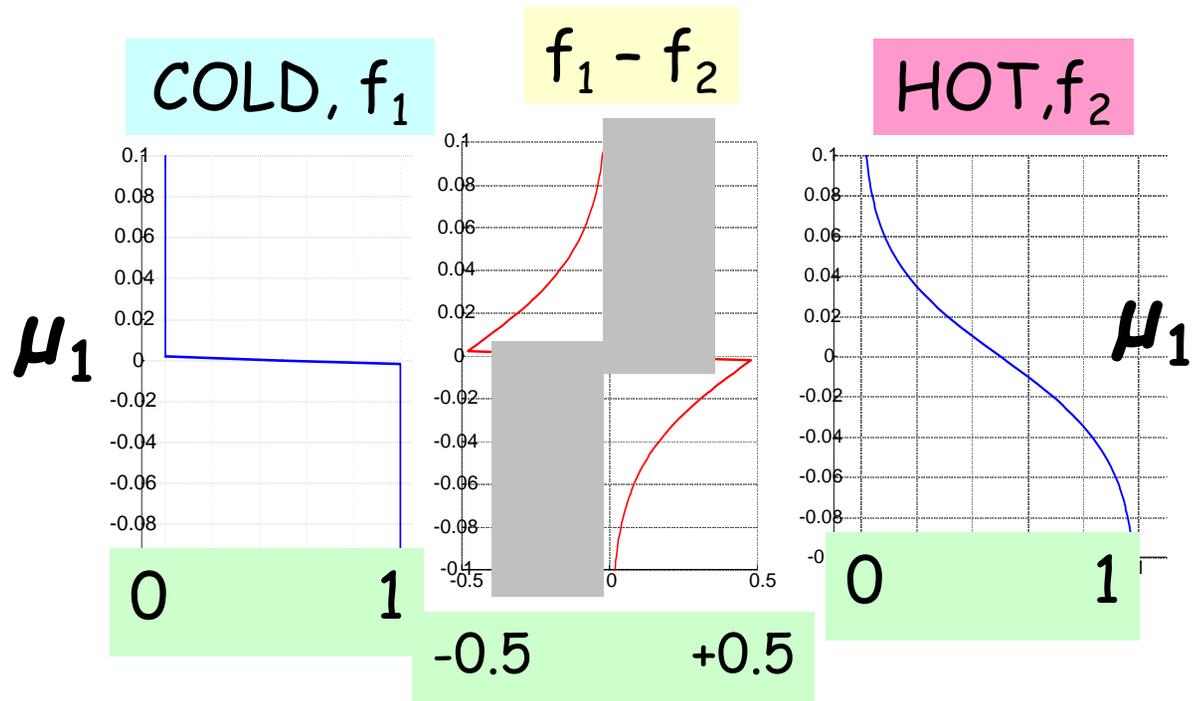
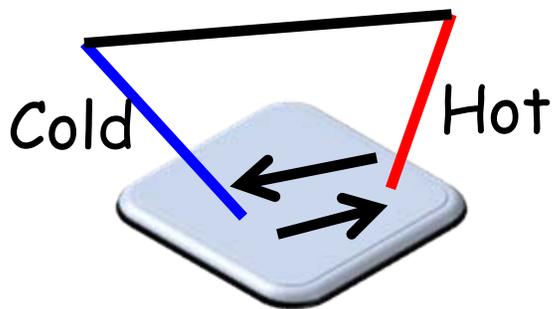
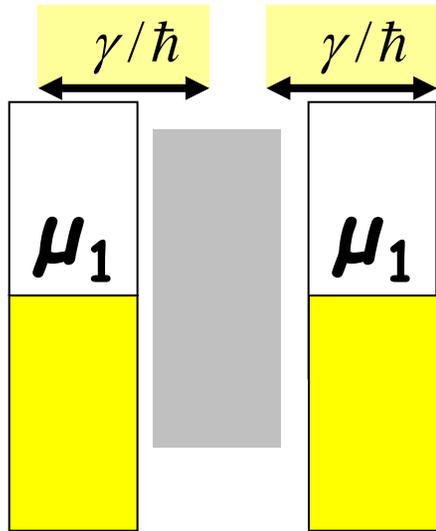
Experiment: Reddy, et al., *Science*, 315, 16 March, 2007.

Theory: Paulsson and Datta, *Phys.Rev.B* 67, 241403 (2003).

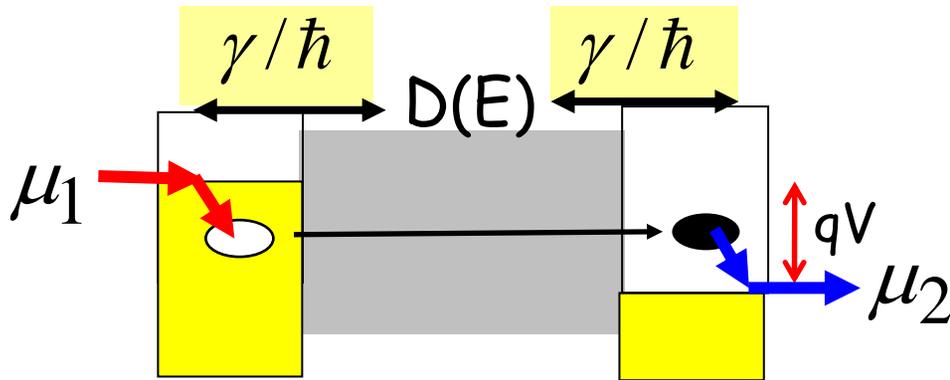
$\pm 3.2 \mu\text{V/K}$, respectively (where the positive sign indicates a p-type junction). The positive sign indicates a p-type junction, whereas the Au Fermi level is 1.2 eV above the highest occupied molecular orbital. Thermoelectricity in molecular junctions provides new questions about their electronic structure and energy conversion.



Why electrons flow from cold to hot .. sometimes



Where is the heat (I^2R) ?

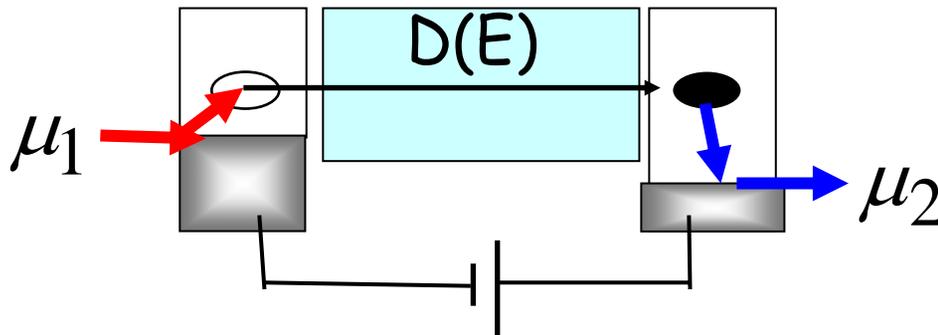


$$\frac{V}{I} = \frac{25.8 \text{ K}\Omega}{2} \frac{1}{M}$$

$$P = VI$$

$$= qV * \frac{N}{t}$$

Thermoelectric cooler



Seebeck & Peltier effects:
Kelvin relation