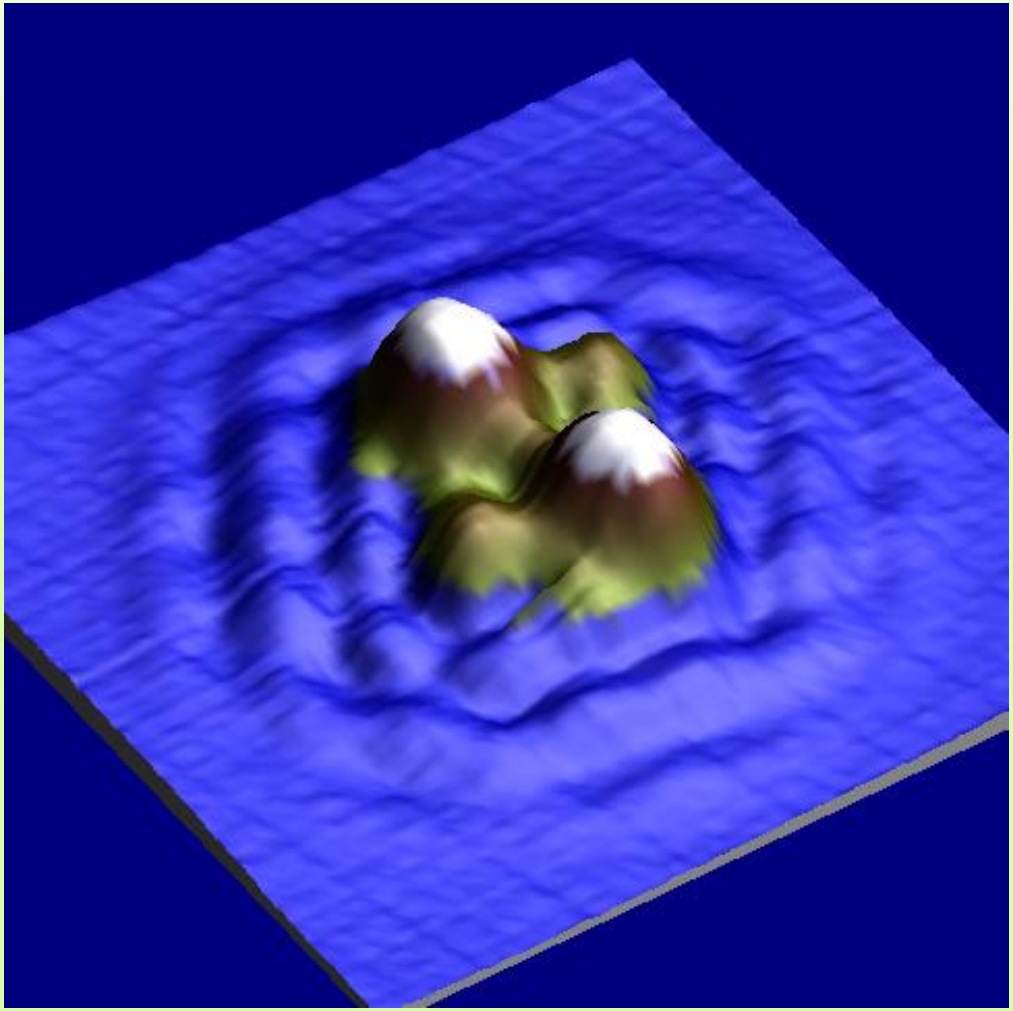
Scanning tunnelling microscopy:

Using a quantum effect to investigate quantum effects

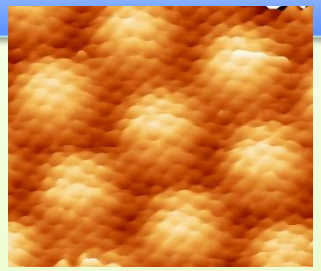
Karina Morgenstern

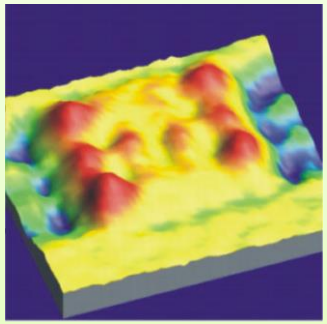
Physical Chemistry I, Ruhr-Universität Bochum, Germany



Inelastic Friedel-Like Surface Oscillations
Nano Lett. 11, 2720 (2011)

Outline



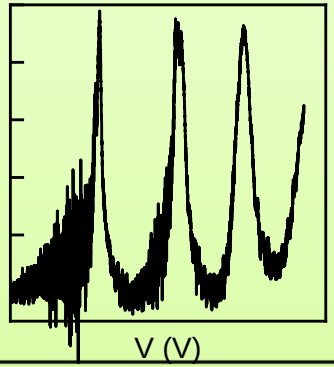


1) STM, STS, IETS, and manipulation

   An extended introduction

2) Quantum effects on surface imaged by STM

   Electron in a box I

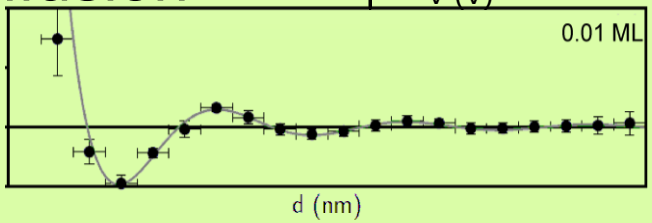


3) Quantum effects on surfaces measured by STS

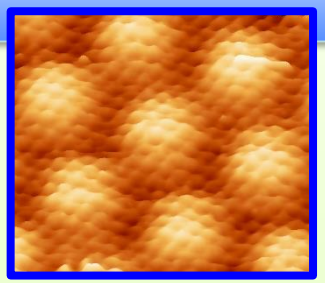
   Electron in a box II

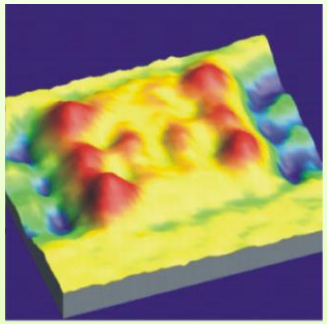
4) Electron interference effects surface diffusion

   Influence of Friedel oscillations on diffusivity



Outline



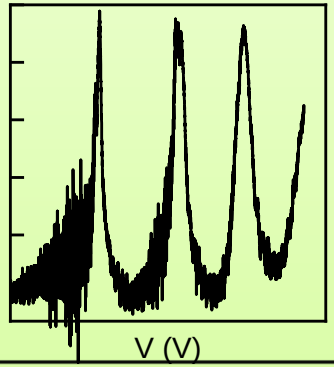


1) STM, STS, IETS, and manipulation

   An extended introduction

2) Quantum effects on surface imaged by STM

   Electron in a box I

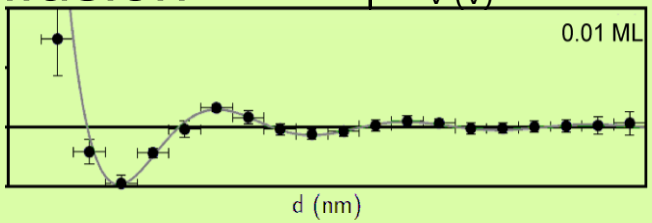


3) Quantum effects on surfaces measured by STS

   Electron in a box II

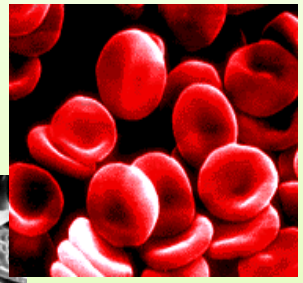
4) Electron interference effects surface diffusion

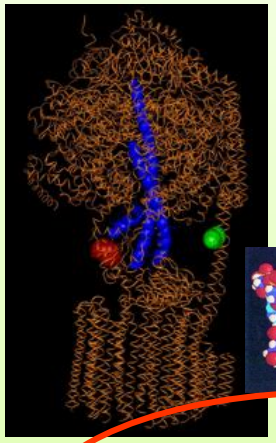
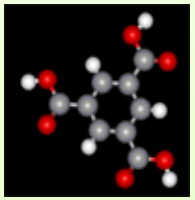
   Influence of Friedel oscillations on diffusivity



Methods for imaging the nanoworld




Cu(111)

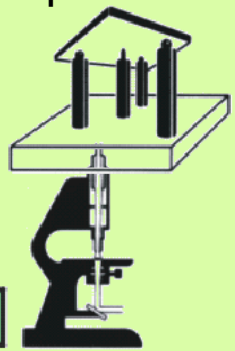
0.1 nm

100 nm 10 nm 1 nm

nano world

1 cm 1 mm 100 µm 10 µm 1 µm

human eye

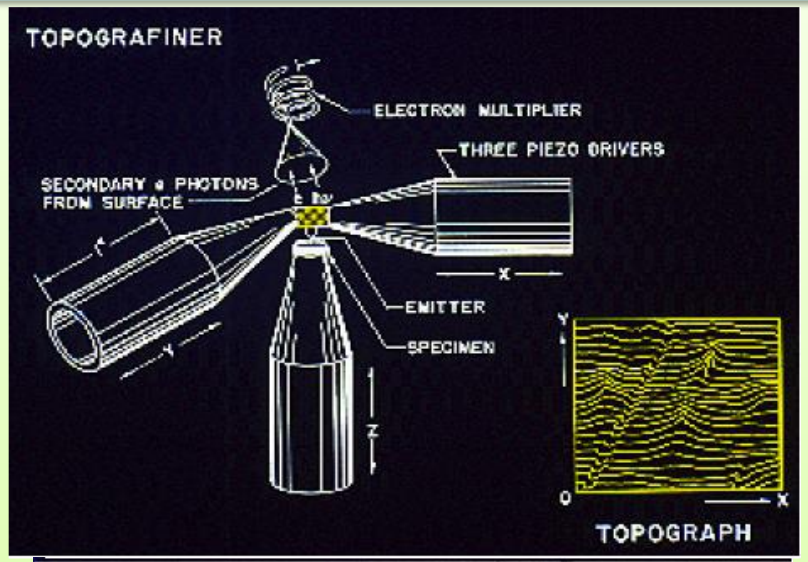


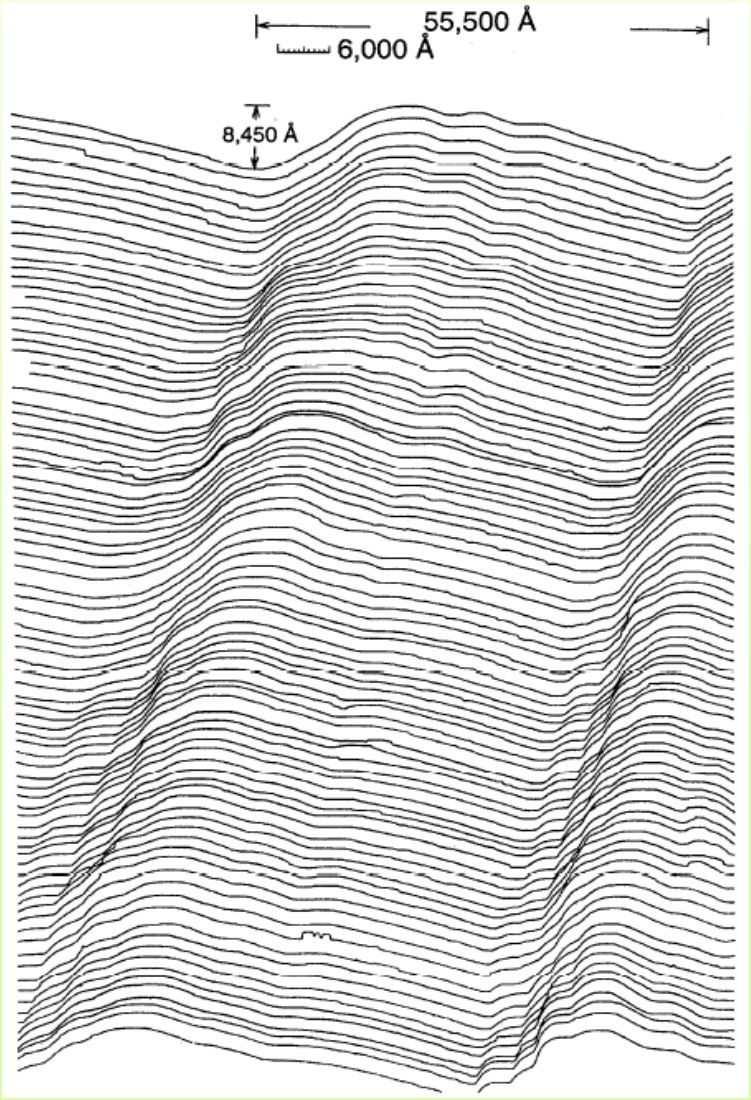
light microscope

scanning tunneling microscope

nano = dwarf

Topographiner



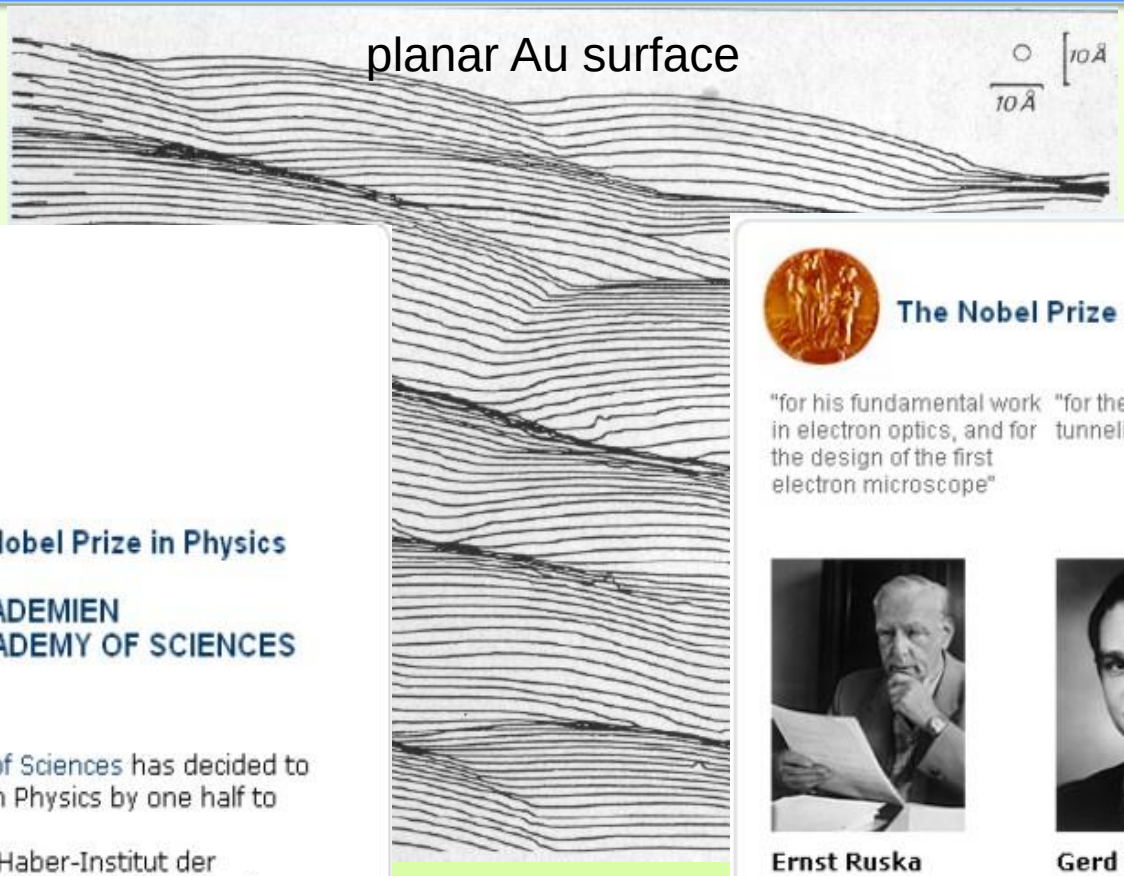


grating

tip-sample distance: 20 nm

R. Young, J. Ward, F. Scire, Rev. Sci. Instrum. 43, 999 (1972)

Scanning tunnelling microscopy



1981

Press Release: The 1986 Nobel Prize in Physics

KUNGL. VETENSKAPSAKADEMIEN
THE ROYAL SWEDISH ACADEMY OF SCIENCES

15 October 1986

The Royal Swedish Academy of Sciences has decided to award the 1986 Nobel Prize in Physics by one half to

Professor. **Ernst Ruska**, Fritz-Haber-Institut der Max-Planck-Gesellschaft, Berlin, Federal Republic of Germany, **for his fundamental work in electron optics, and for the design of the first electron microscope**

and the other half, jointly to

Dr **Gerd Binnig** and Dr **Heinrich Rohrer**, IBM Research Laboratory, Zurich, Switzerland, **for their design of the scanning tunnelling microscope**.

The Nobel Prize in Physics 1986

"for his fundamental work in electron optics, and for the design of the first electron microscope"

"for their design of the scanning tunneling microscope"

Ernst Ruska

Federal Republic of Germany

Fritz-Haber-Institut der Max-Planck-Gesellschaft

Berlin, Germany

1906 - 1988

Gerd Binnig

Federal Republic of Germany

IBM Zurich Research Laboratory Rüschlikon, Switzerland

1947 -

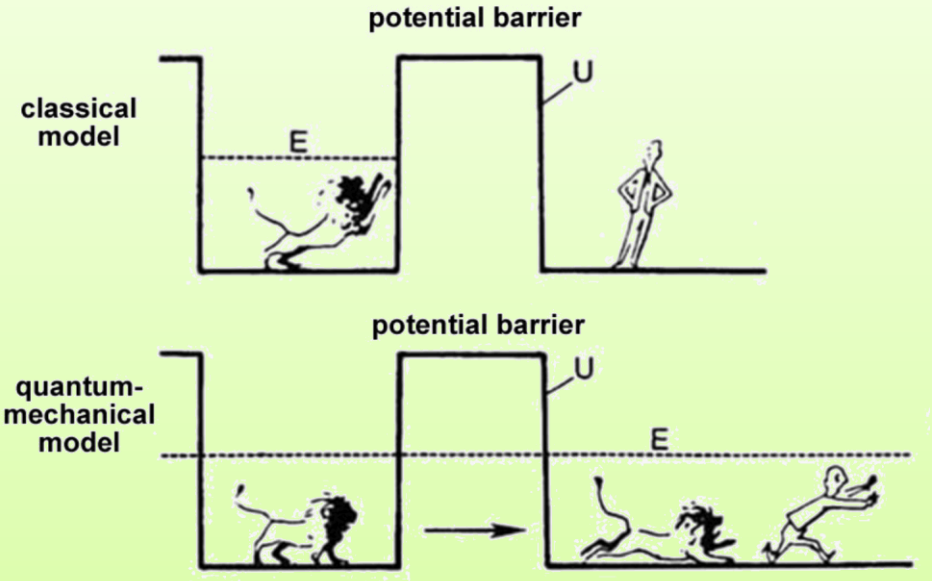
Heinrich Rohrer

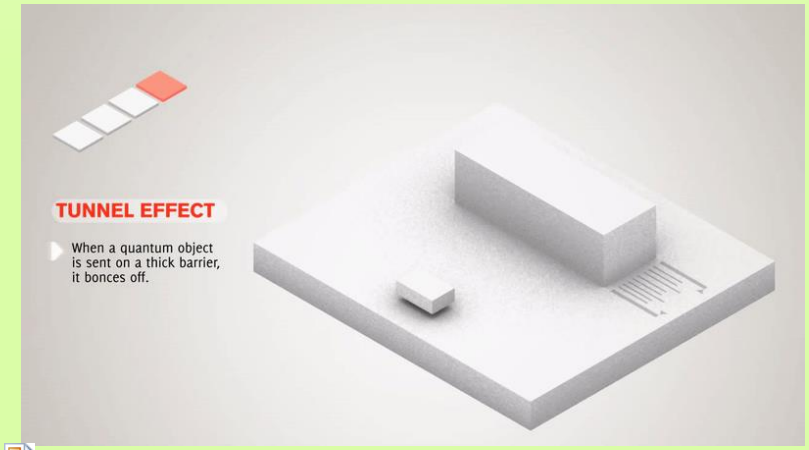
Switzerland

IBM Zurich Research Laboratory Rüschlikon, Switzerland

1933 -

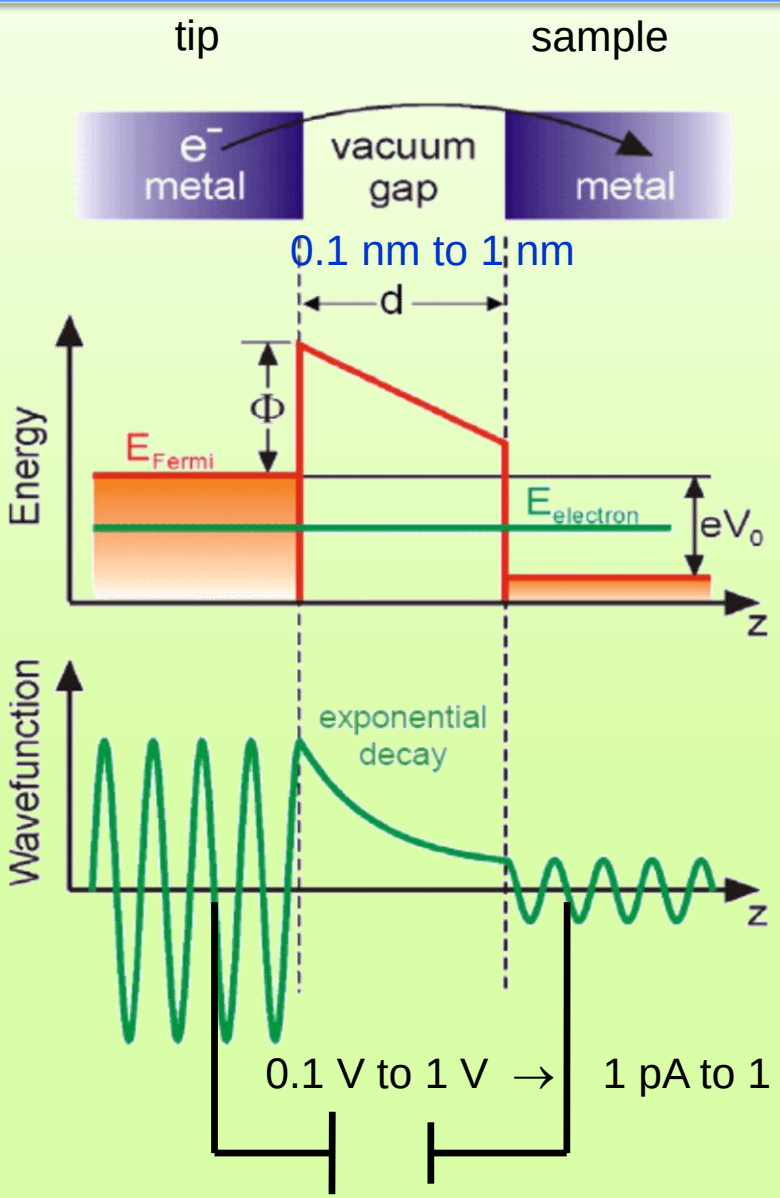
Scanning **tunneling** microscopy





https://toutestquantique.fr/en/tunnel-effect/

Scanning **tunneling** microscopy



E_F: Fermi level

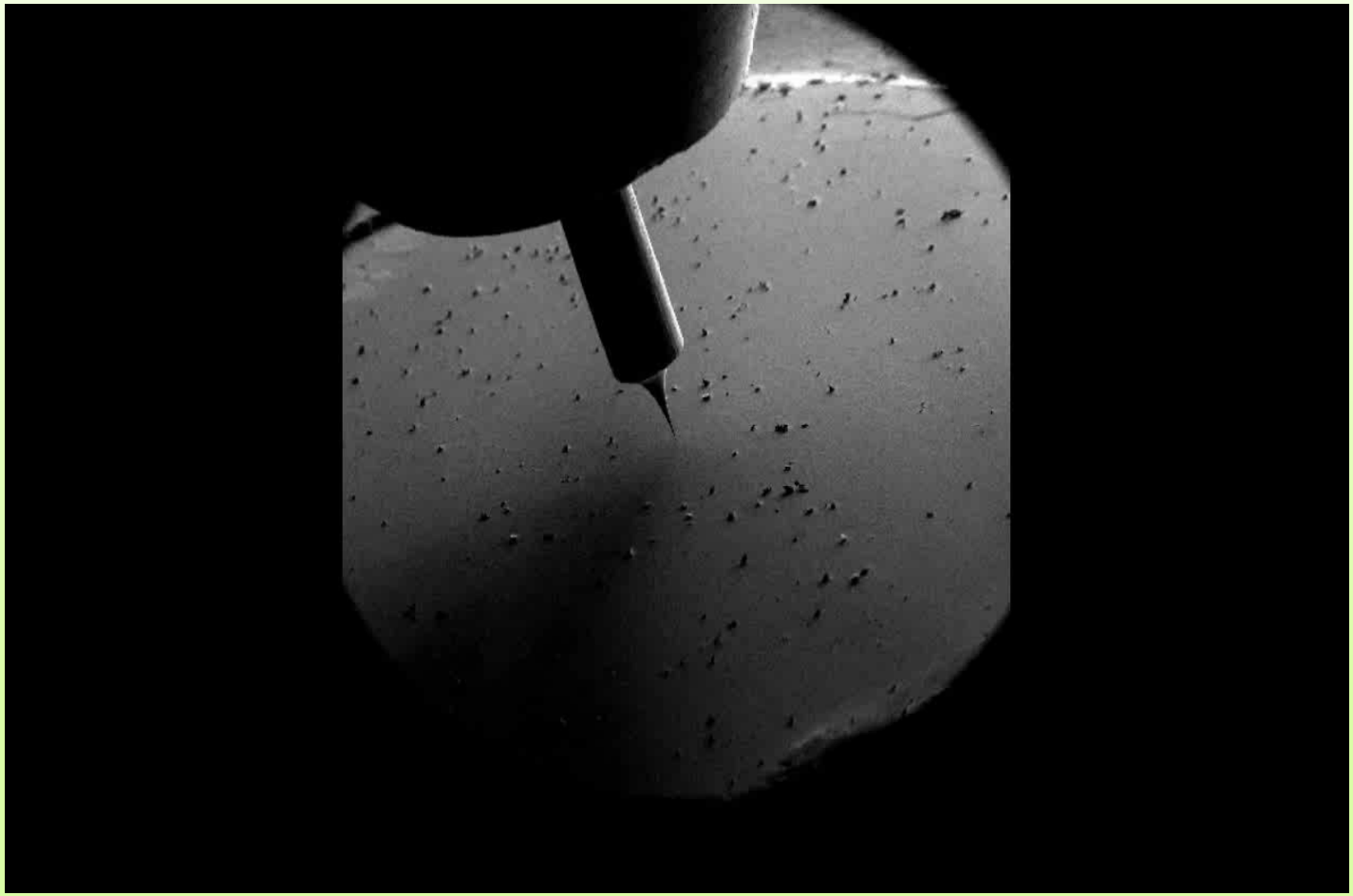
eV_0: potential difference

ϕ: work function

$$I_{tunnel} \propto V_{bias} e^{-2kd}$$

$\Psi(x)$: electron wave function

Scanning tunneling microscopy

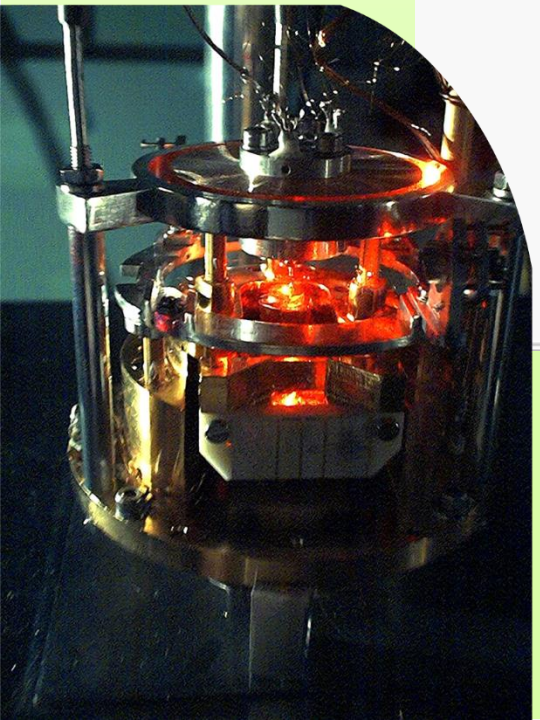


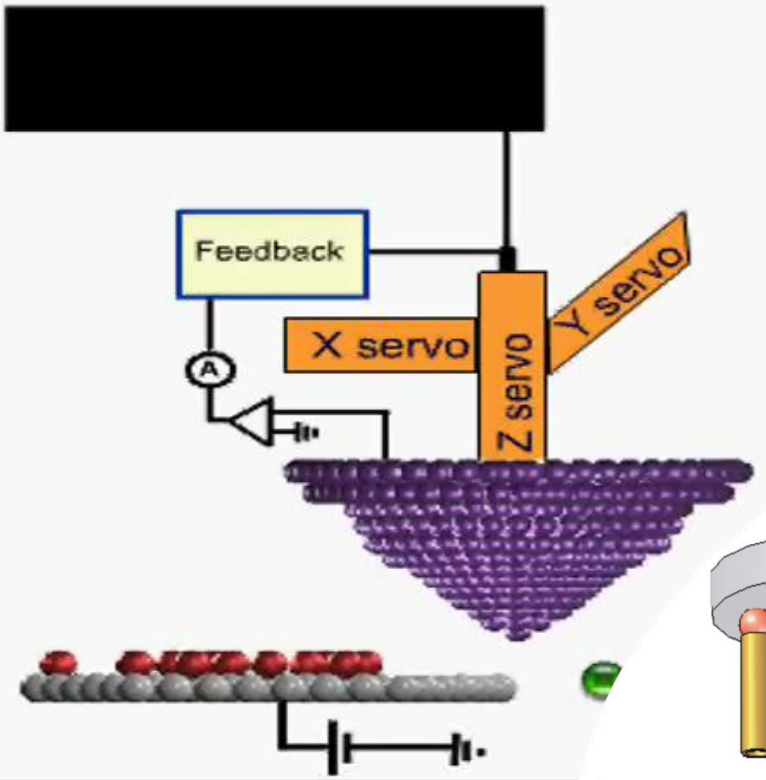
constant current mode

Pentacene/Au/Mica

Lars Ruppel, PCI, R.U.B.

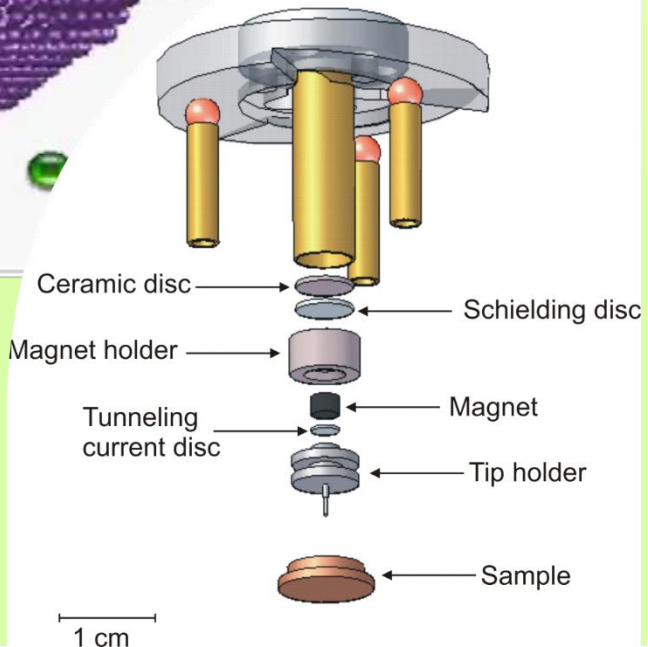
Scanning tunneling microscopy



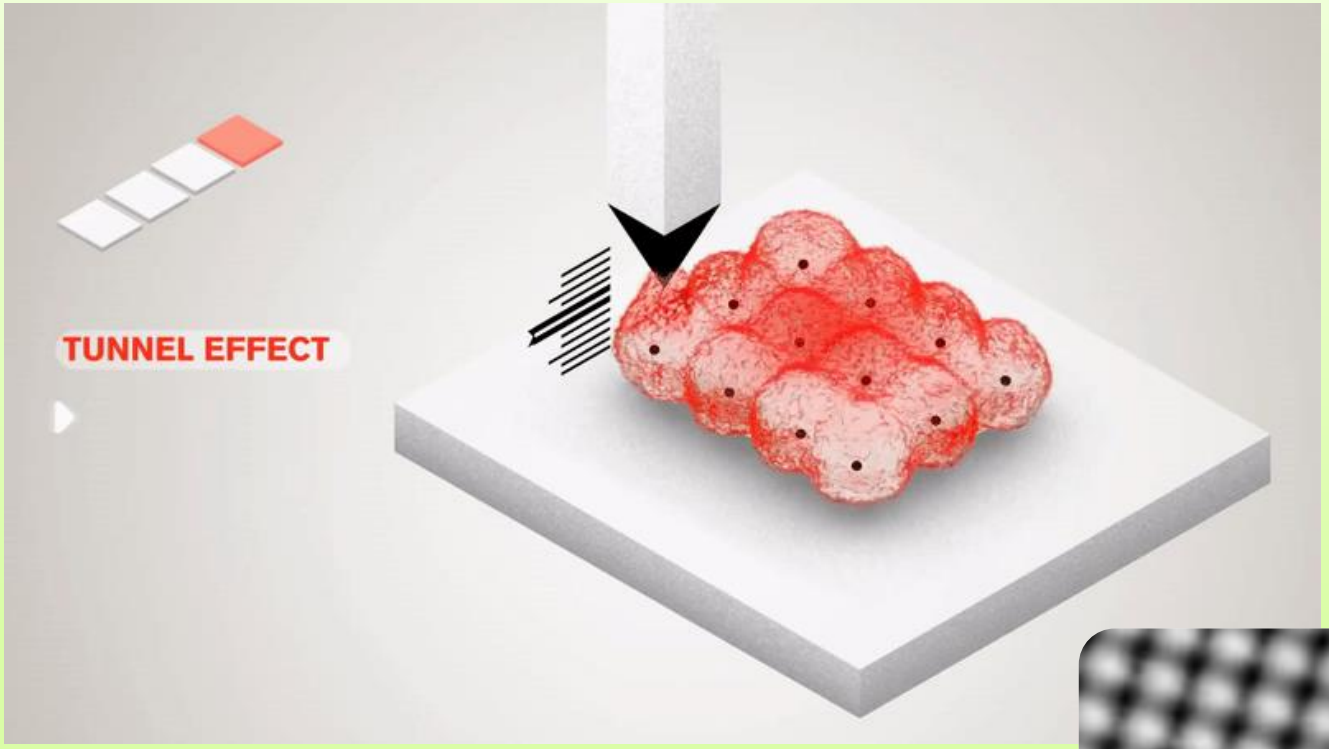


constant
current
mode

imaging at ~ 5 K
in ultra-high vacuum

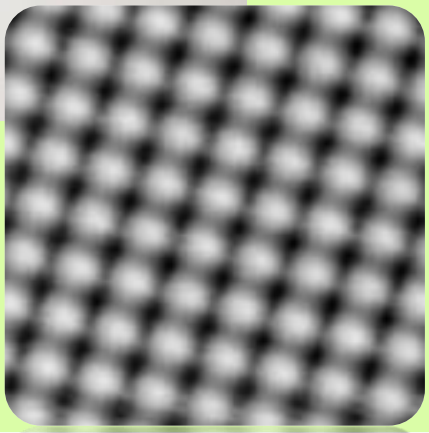


Tunneling effect in STM



constant
height mode

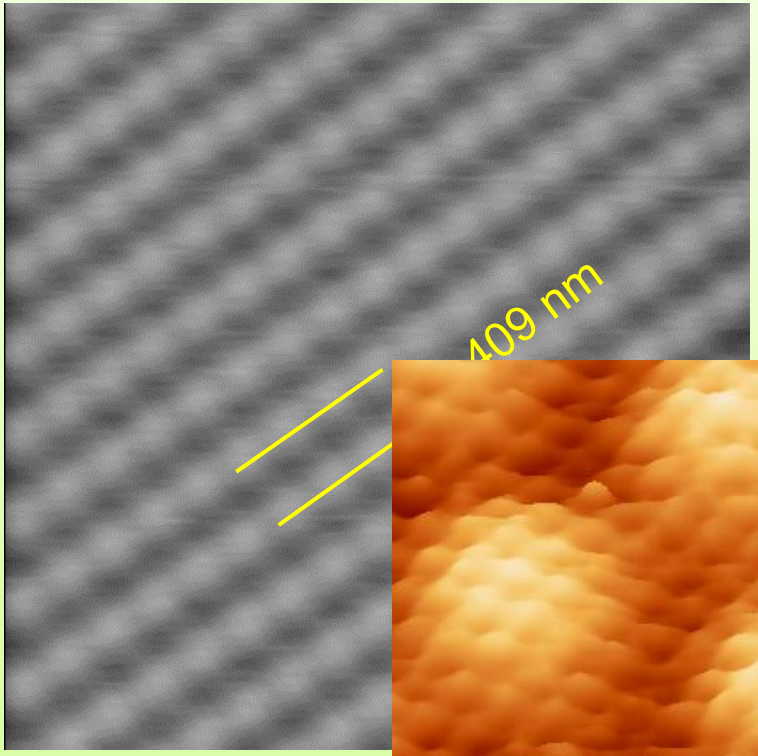
Ag(100)



https://toutestquantique.fr/en/tunnel-effect/

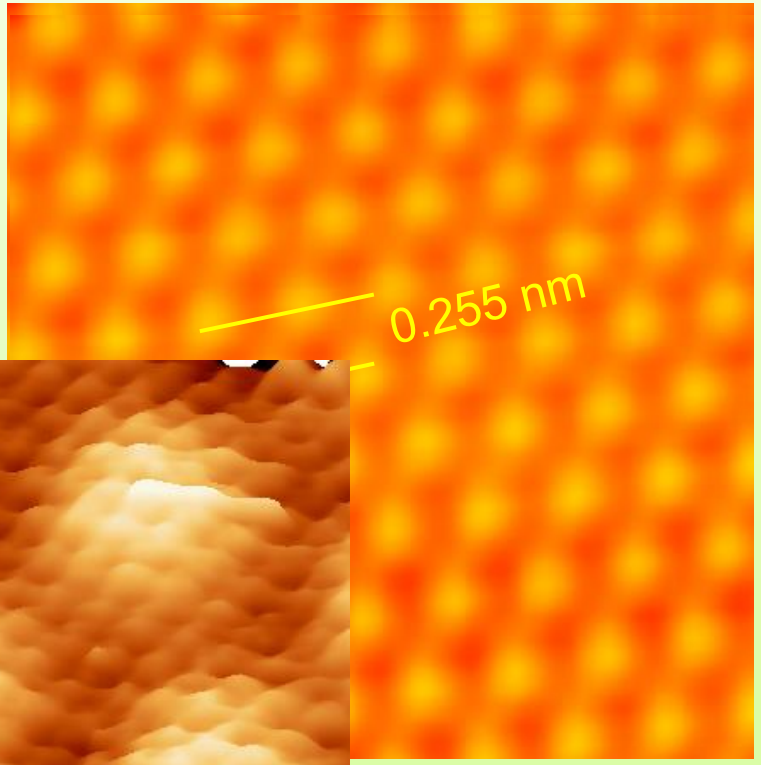
STM: Atomic resolution

Ag(110)

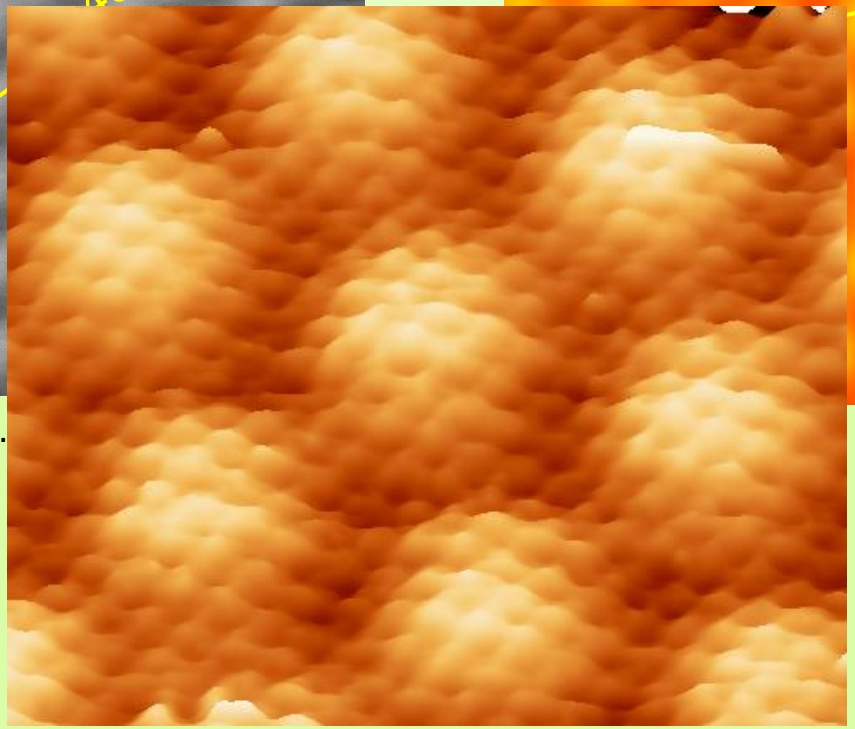


0.

Cu(111)



25 mV, 30 pA, 5 K

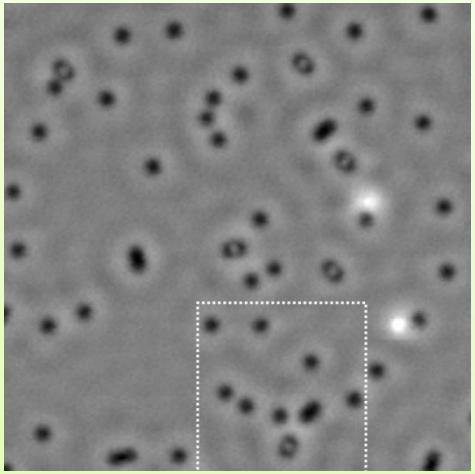


moiré pattern of ZnO/Ag(111)

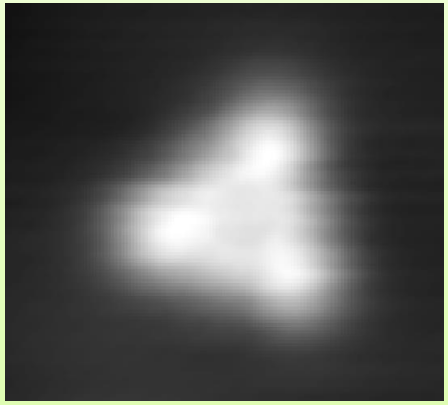
J. Phys. Chem. C 126, 12500 (2022)

STM: Images of molecules

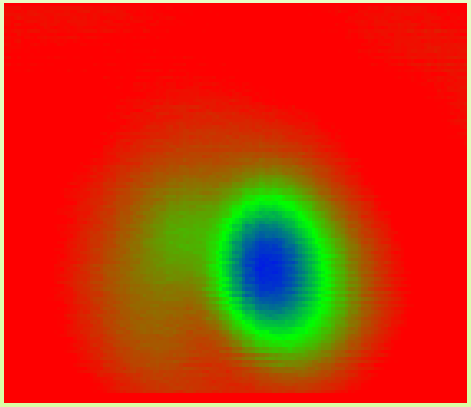
Where are the atoms,
what do we see?



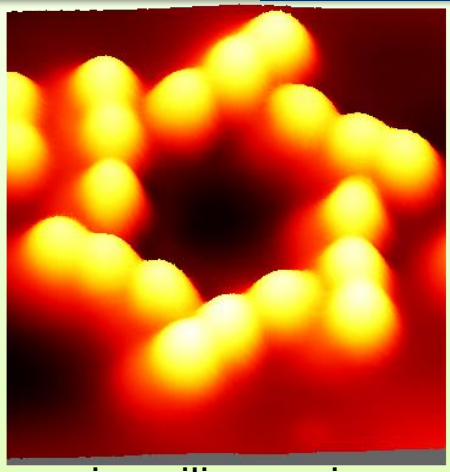
CO / Cu(111)



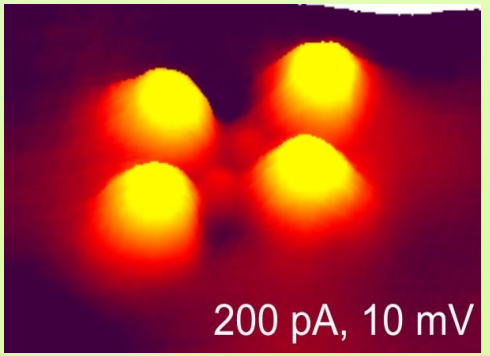
9 water molecules
/ Ag(111)



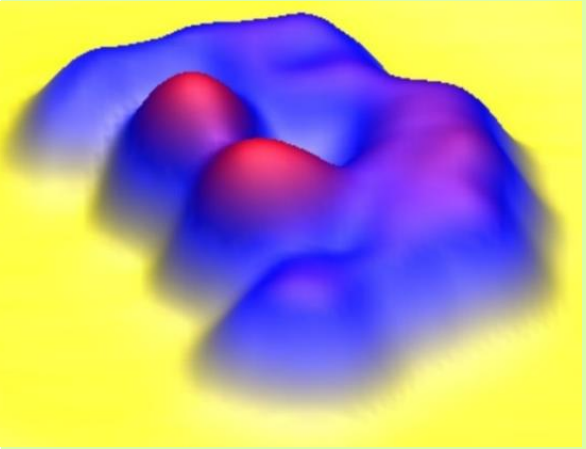
one chloronitro-
benzene / Au(111)



six anilino-amino-
azobenzene / Au(111)

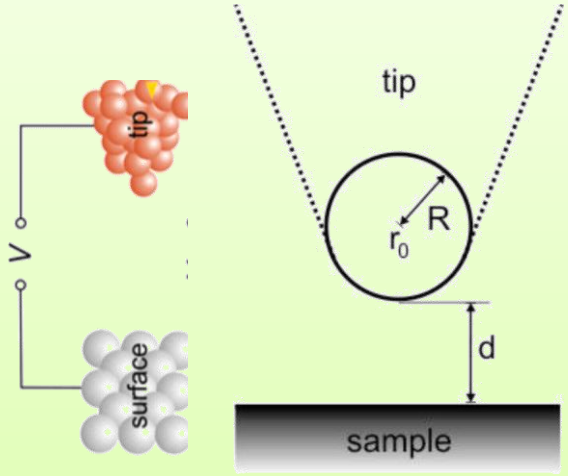


two amino-nitro-
azobenzene / Au(111)



one azobenzene derivative solvated by water / Ag(111)

Tersoff-Hamann theory



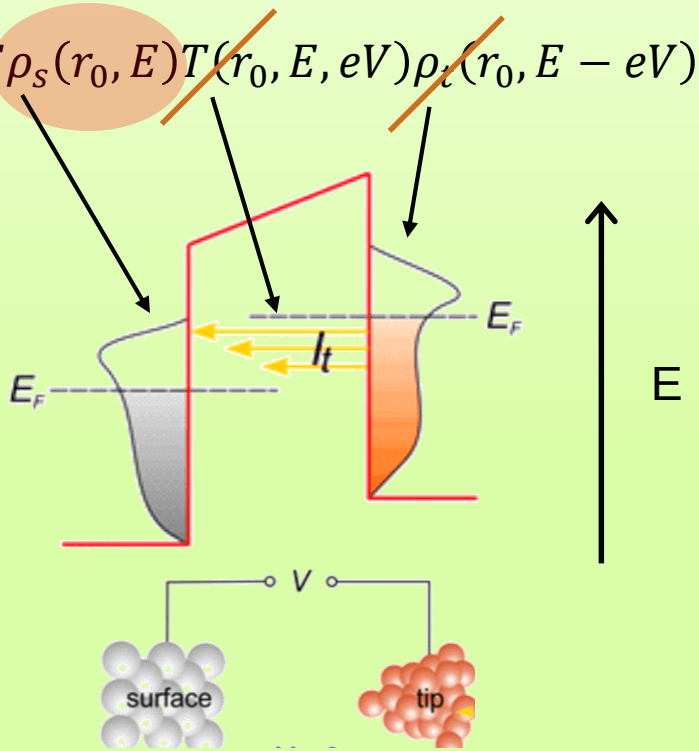
Where are the atoms, what do we see?

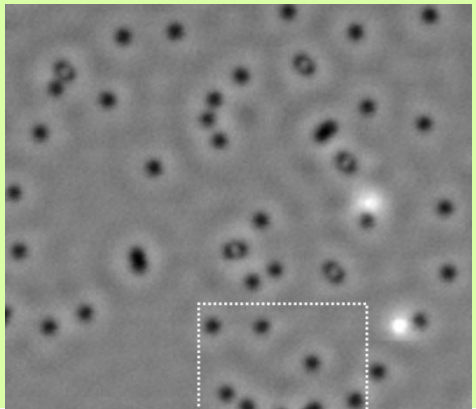
J. Tersoff, D.R. Hamann
Phys. Rev. Lett. 50,1998 (1983)
based on J. Bardeen
Phys. Rev. Lett. 6, 57 (1961)

ρ: density-of-states

$$I(r_0, V) = \frac{2\pi}{\hbar} \int_{E_F}^{E_F+eV} dE \rho_s(r_0, E) T(r_0, E, eV) \rho_t(r_0, E - eV)$$

⇨ STM measures the local density of states of the sample from the Fermi level up to the bias voltage energy at the tip position





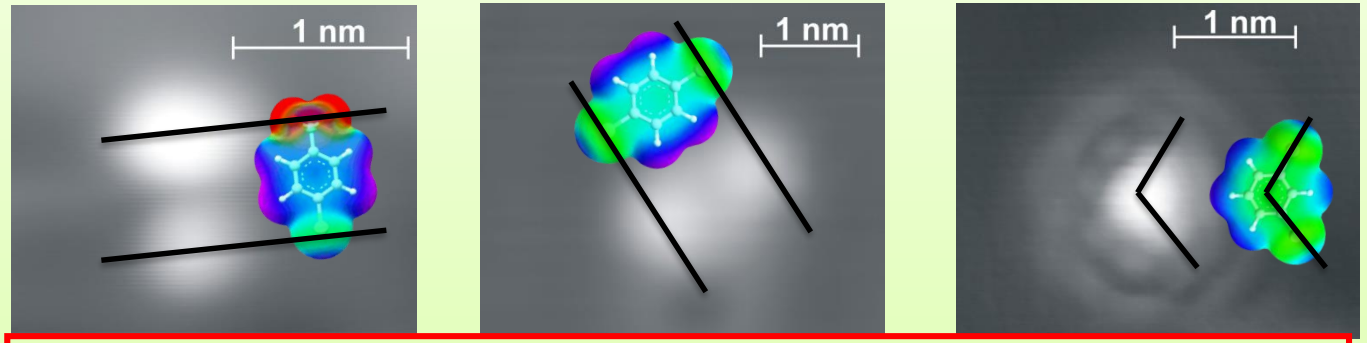
CO / Cu(111)

STM: Images of molecules

chloronitrobenzene
para

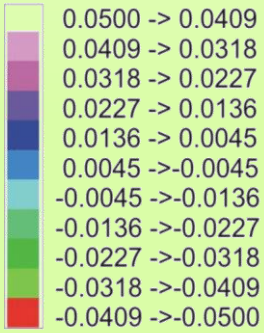
dichlorobenzene
para

dichlorobenzene
meta

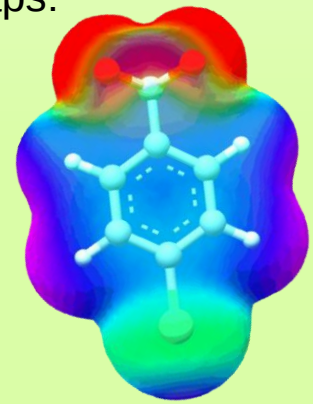


⇨ STM images: Convolution of LDOS with topography

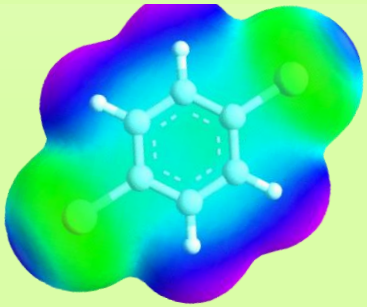
electrostatic potential maps:

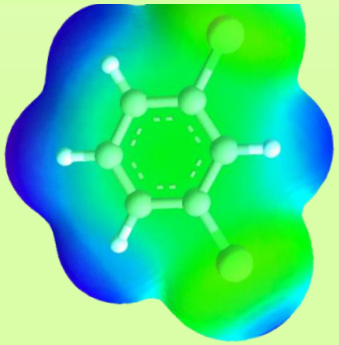


Hartree



⊗ Pauli repulsion (for molecular tips)

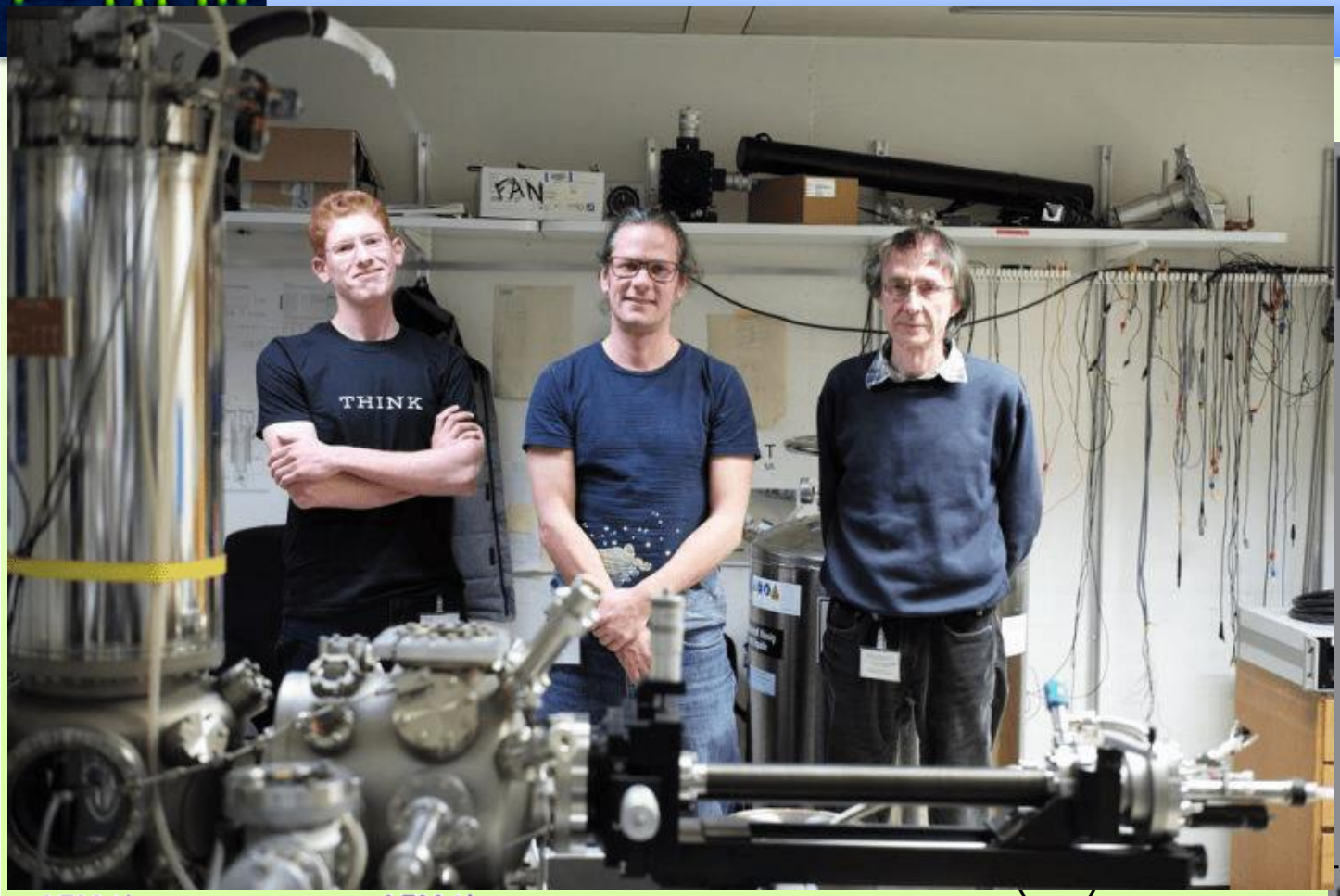




evaporation @ 17 K
measurement @ 5 K

Appl. Surf. Sci. 253, 9047 (2007)

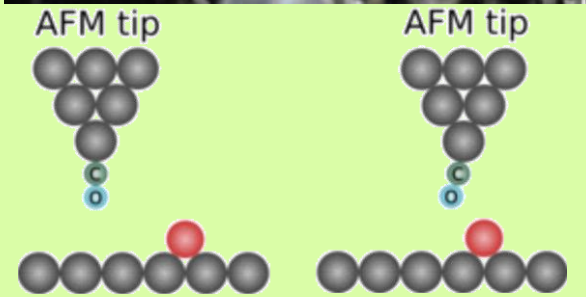
Bond pictures



AFM - CO tip

CH: 170mV, 110 pA

Pentacene
Gross et al.
Science 325, 5944 (2009)



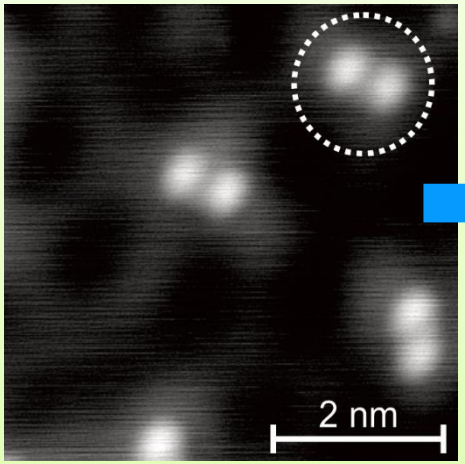
Jelínek
J. Phys.: Condens. Matter
29, 343002 (2017)

Temirov et al.
New J. Phys. 10, 053012 (2008)

STM: Bond pictures

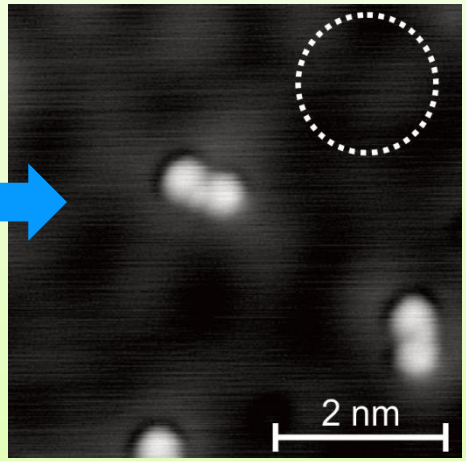
unpublished

metallic tip

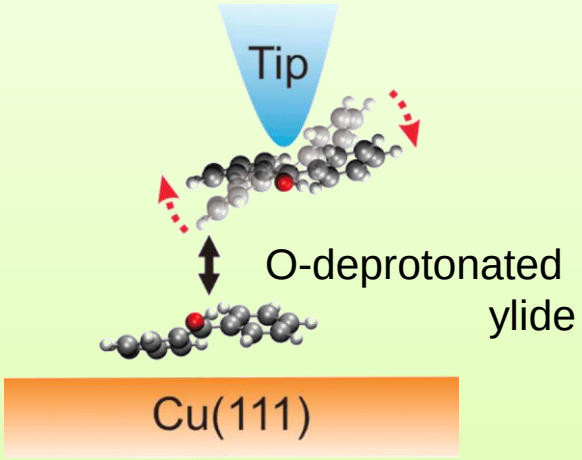


−10 mV, 10 pA

molecular tip



−100 mV, 10 pA

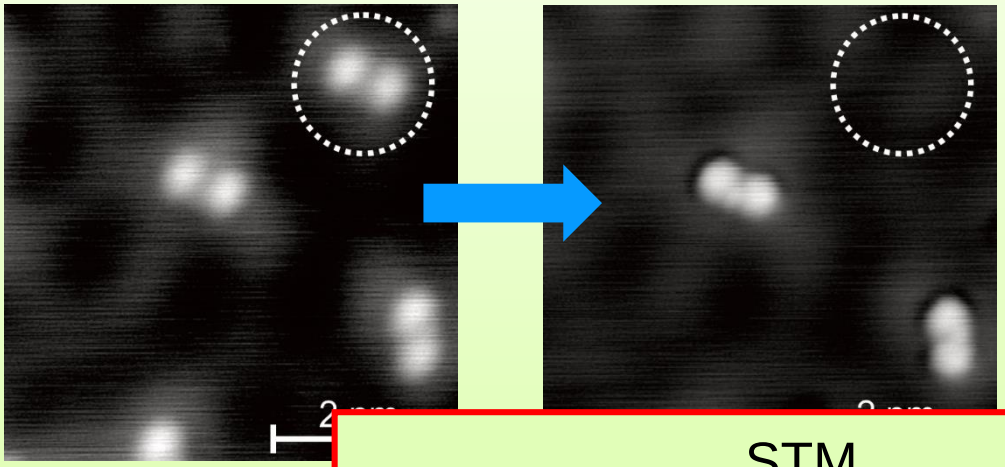


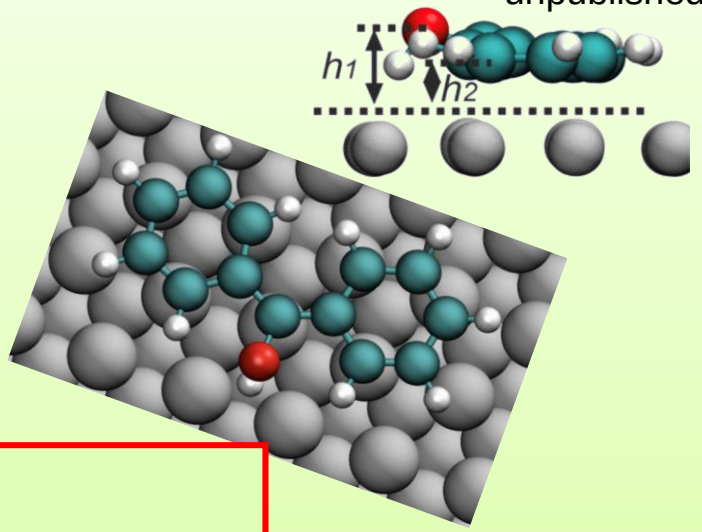
STM: Bond pictures

metallic tip

molecular tip

unpublished





−10 mV, 10 pA

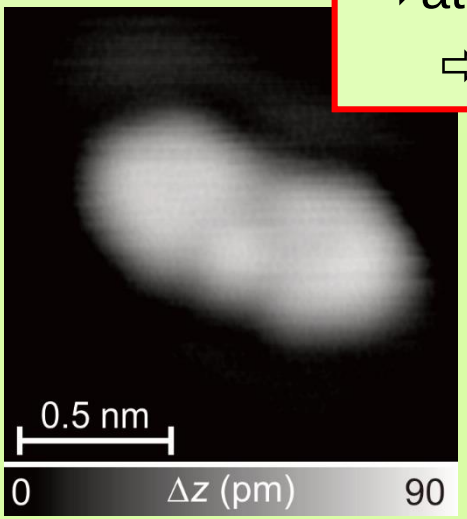
constant curre

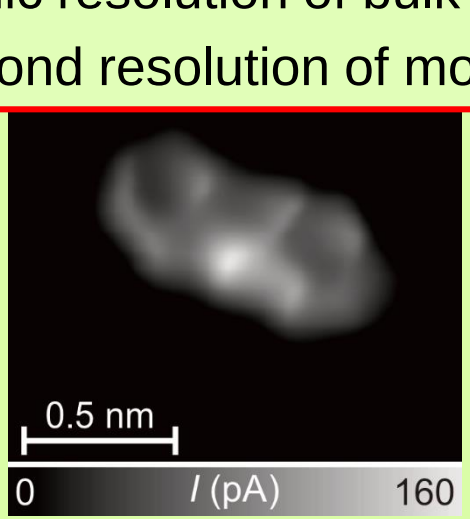
ce filtered

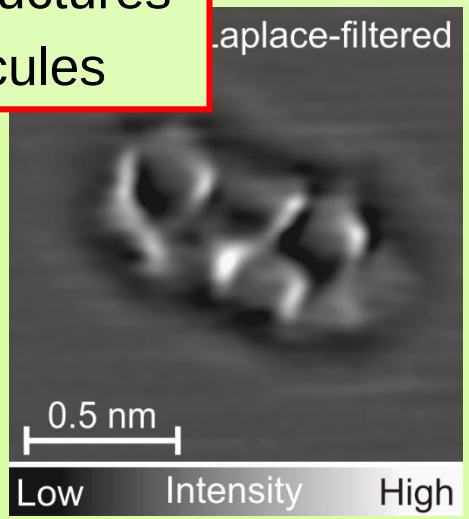
STM

⇨atomic resolution of bulk structures

⇨ bond resolution of molecules



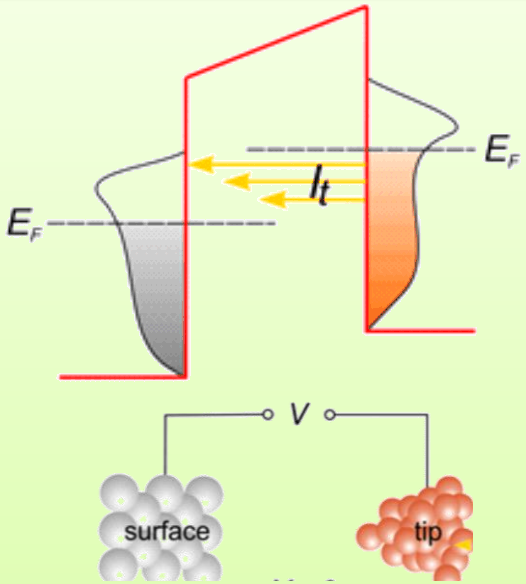




5 mV, 10 pA

5 mV, 10 pA, Δz = −50 pm

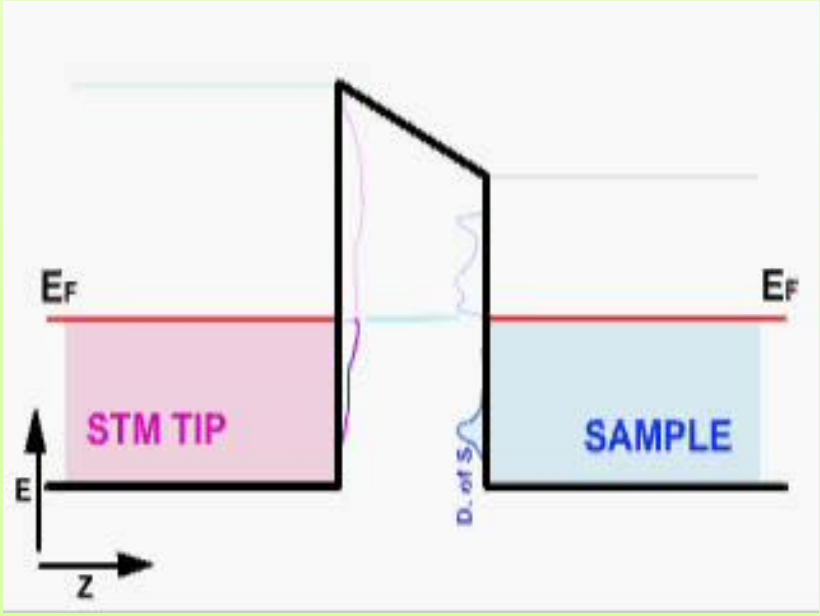
STS: Scanning Tunneling Spectroscopy



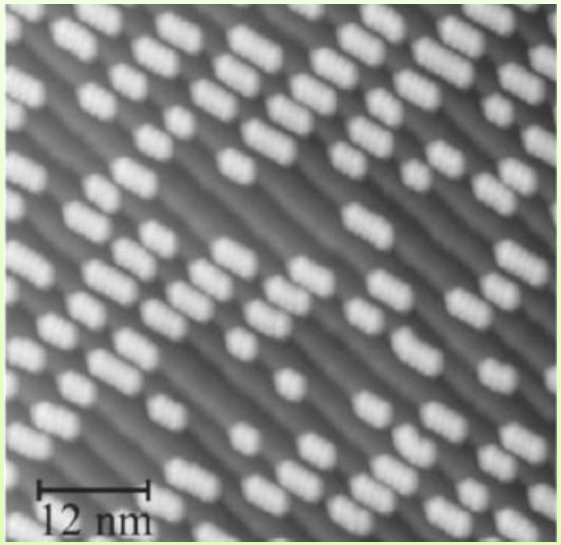
$$I(r_0, V) = \frac{2\pi}{\hbar} \int_{E_F}^{E_F+eV} dE \rho_s(r_0, E) T(r_0, E, eV) \rho_t(r_0, E$$

$$\rightarrow \frac{dI}{dV} \propto \rho_s(r_0, E)$$

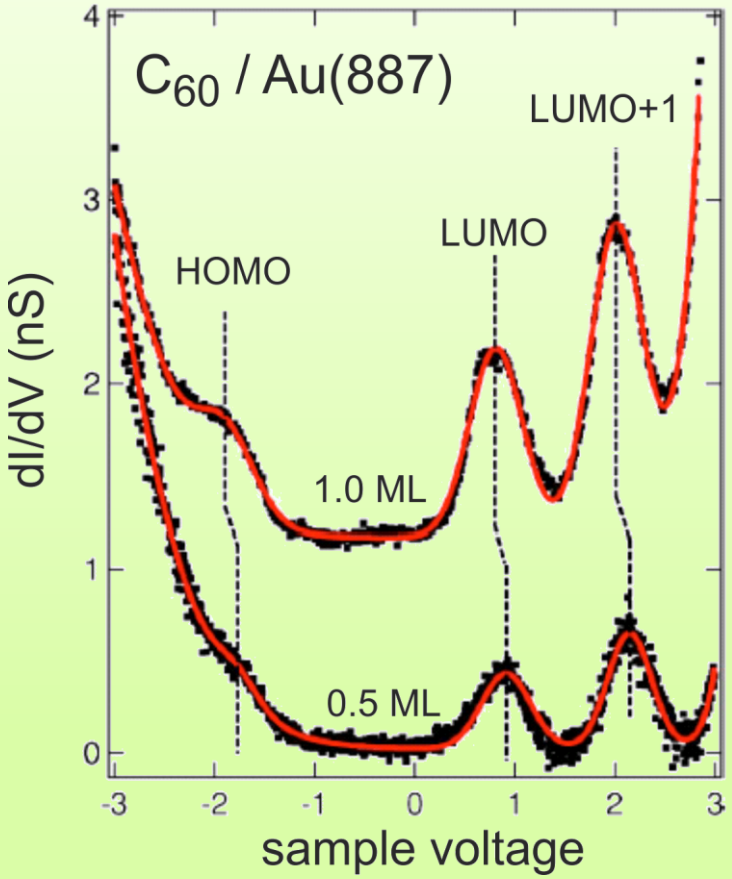
local density of states
of the sample
at the position of the tip

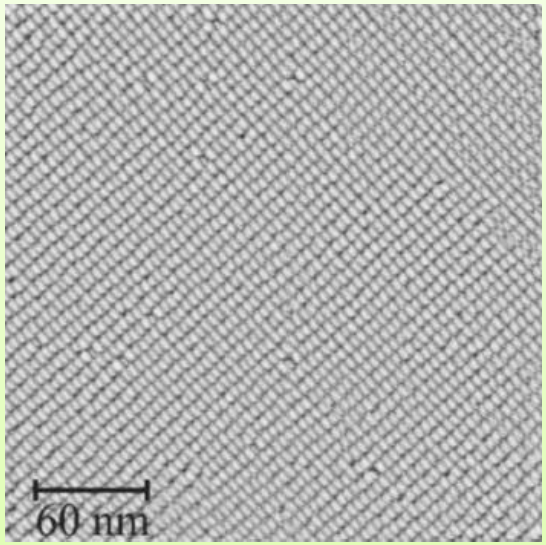


HOMO-LUMO gap



0.5 ML





1 ML

F. Schiller et al., J. Chem. Phys. 125, 144719 (2006)

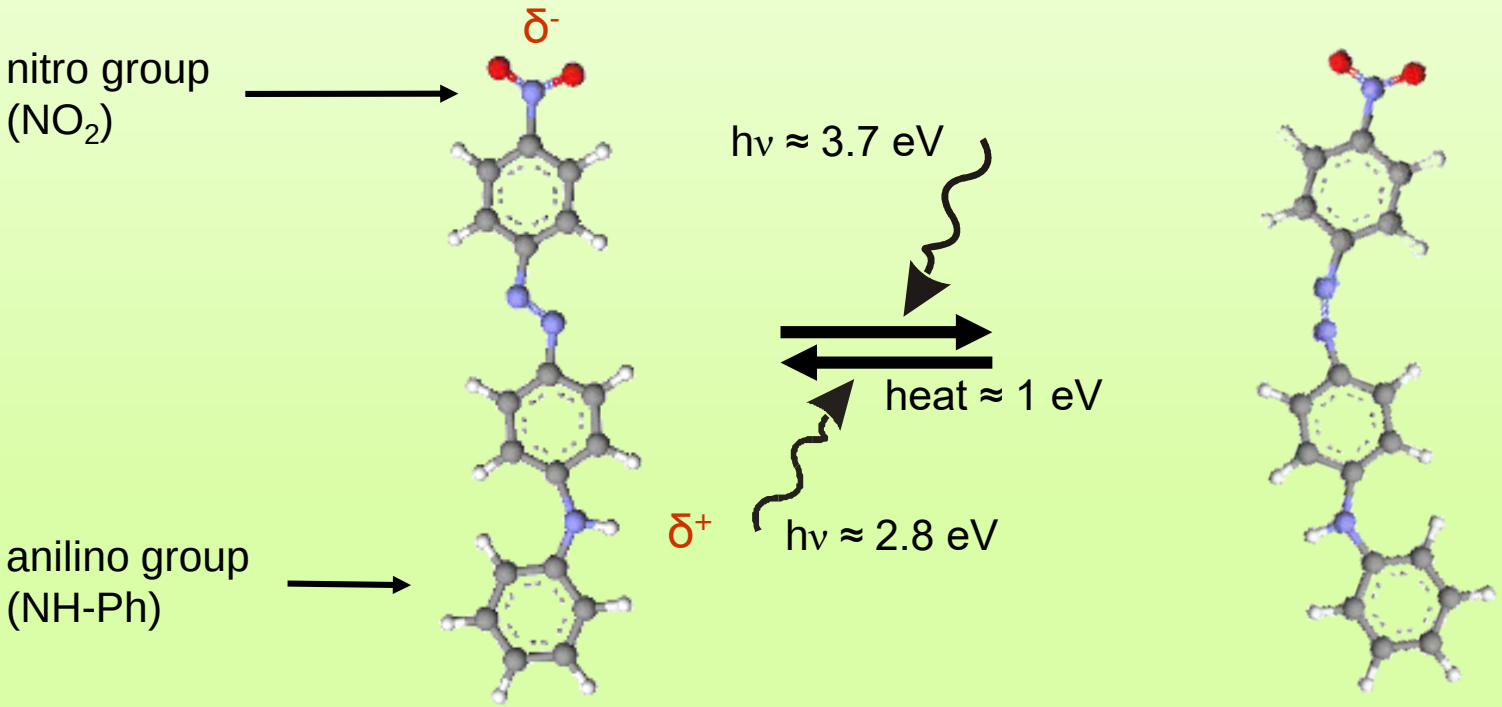
Identification of molecular orientation

PCCP 12, 6035 (2010)

4-anilino-4'-nitro azobenzene

trans-configuration

cis-configuration

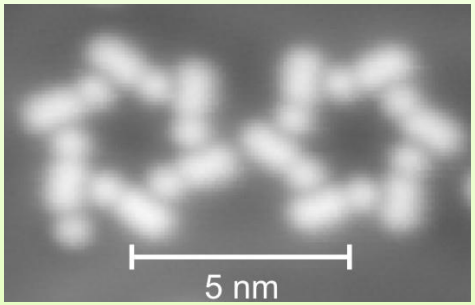


Identification of molecular orientation

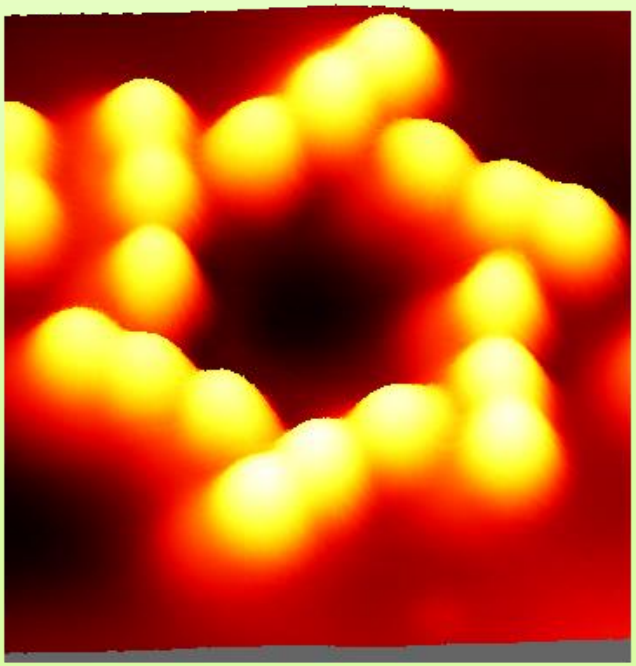
PCCP 12, 6035 (2010)

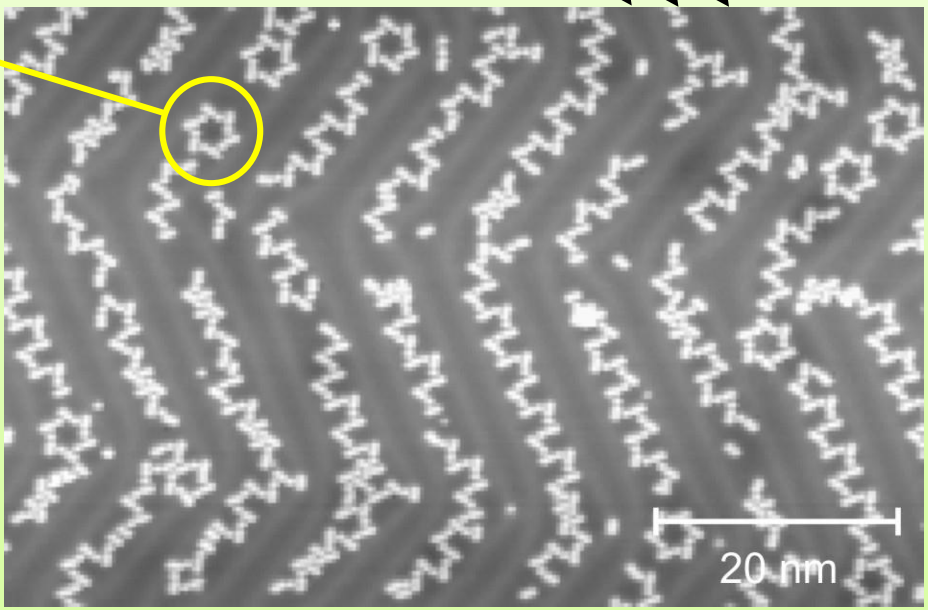
star structures

4-anilino-4'-nitro azobenzene / Au(111)



310 pA, 125 mV



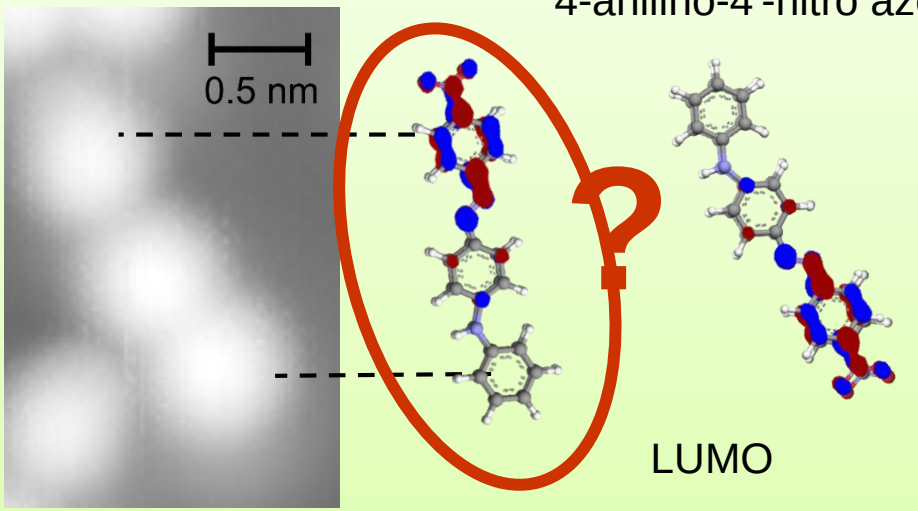


27 pA, 96 mV

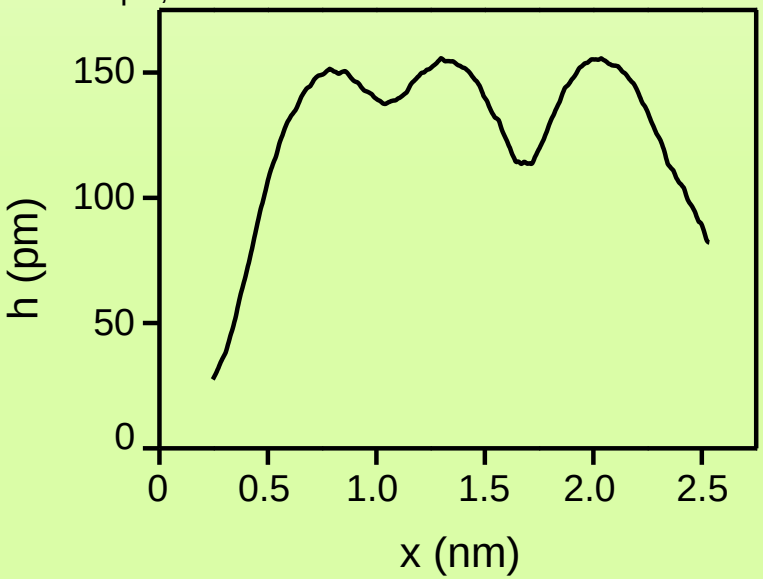
Identification of molecular orientation

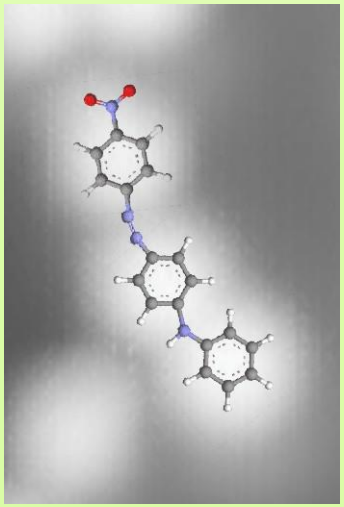
PCCP 12, 6035 (2010)

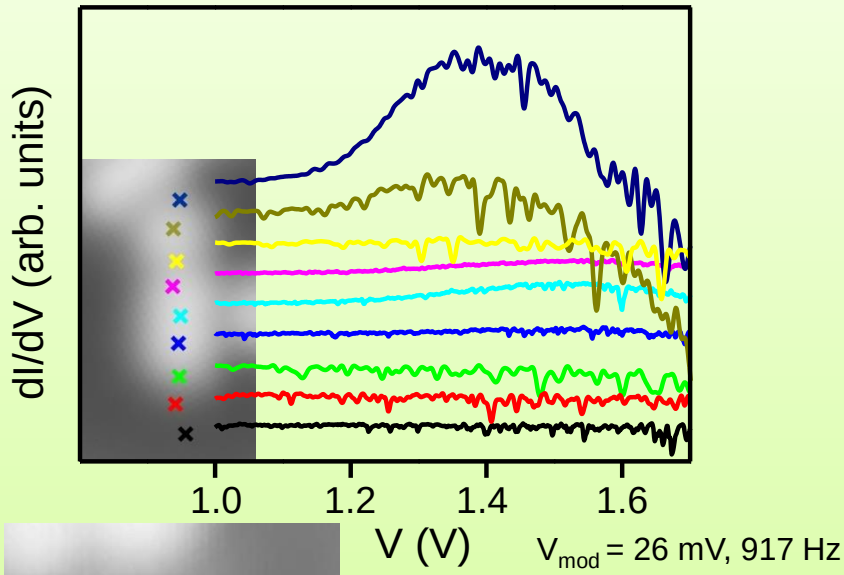
4-anilino-4'-nitro azobenzene / Au(111)



310 pA, 125 mV



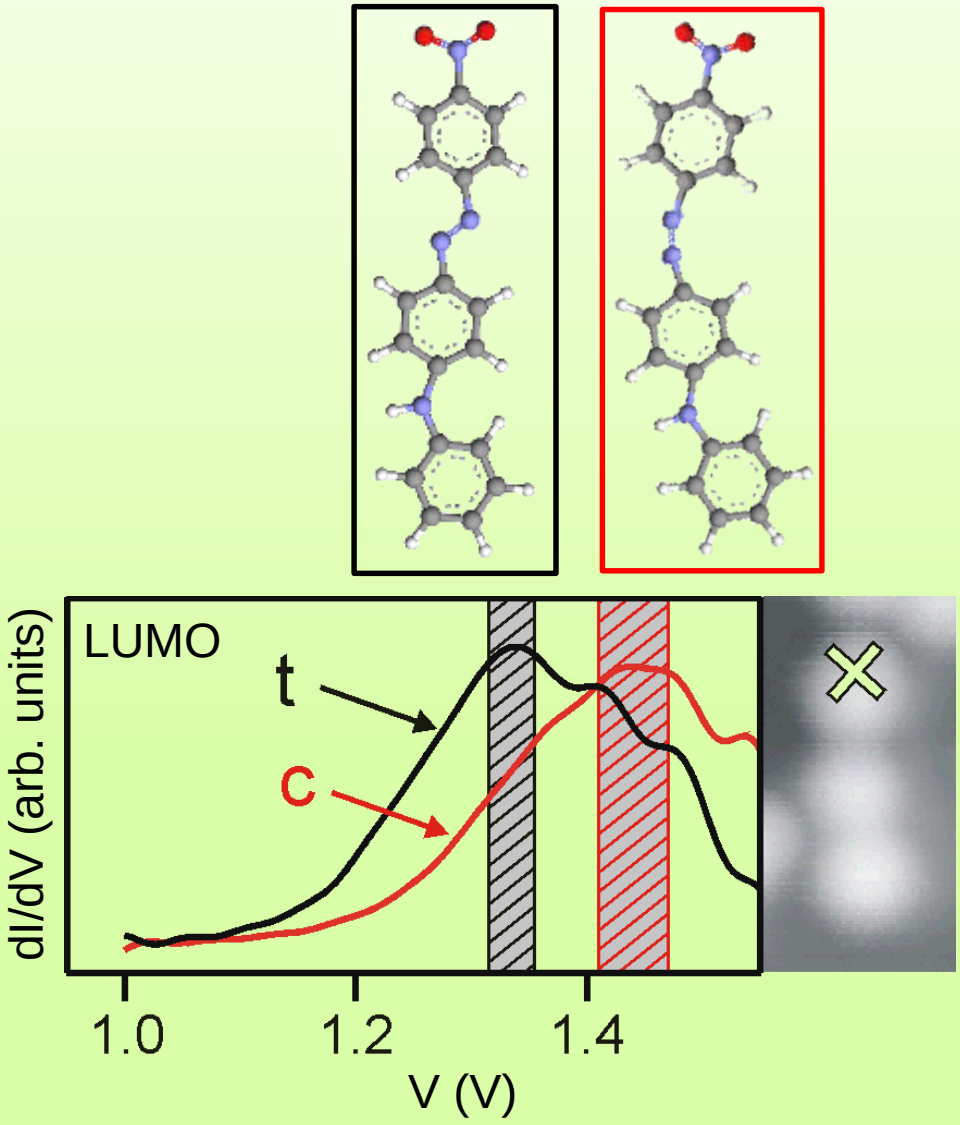




V_{mod} = 26 mV, 917 Hz

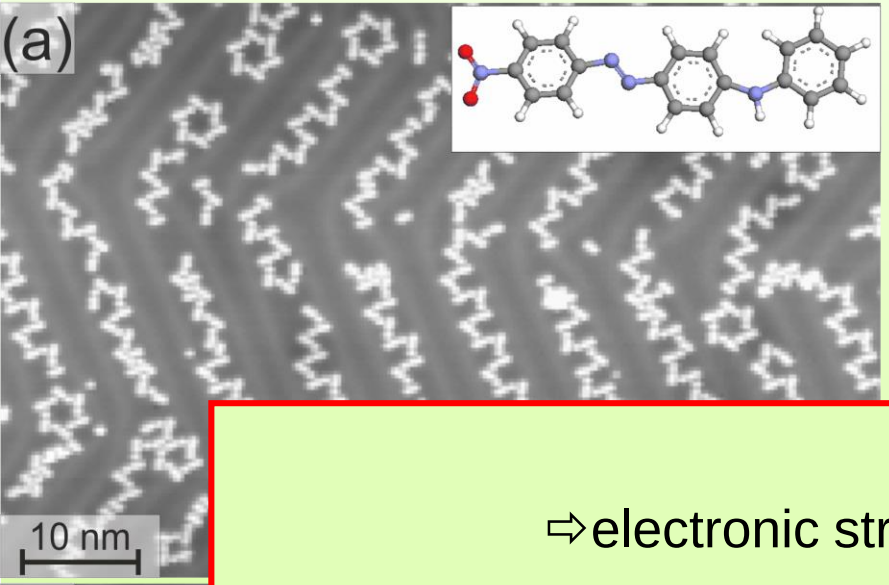
Electronic structure of conformers

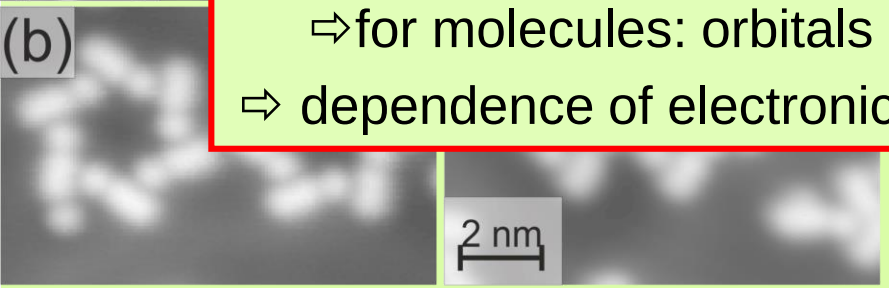
PCCP 12, 6035 (2010)

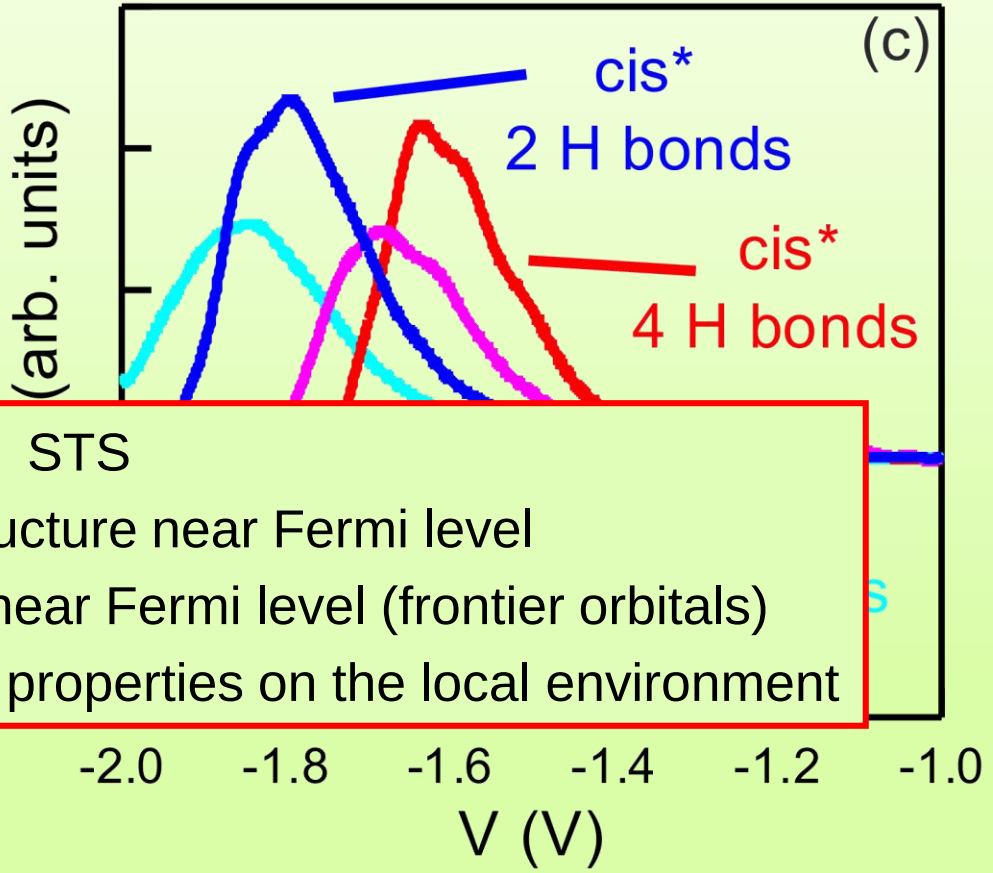


Influence of bonding on HOMO

PCCP 12, 6035 (2010)







STS

⇨electronic structure near Fermi level

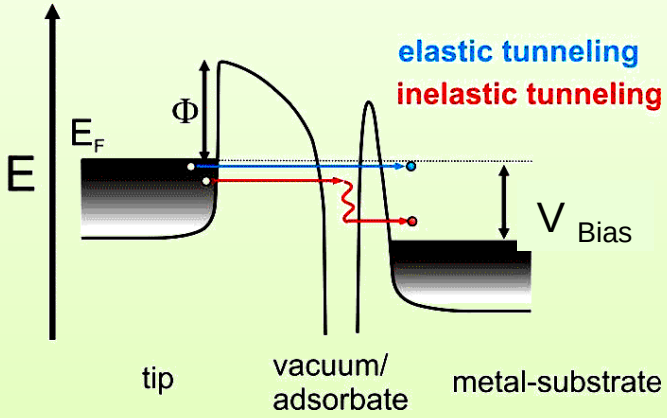
⇨for molecules: orbitals near Fermi level (frontier orbitals)

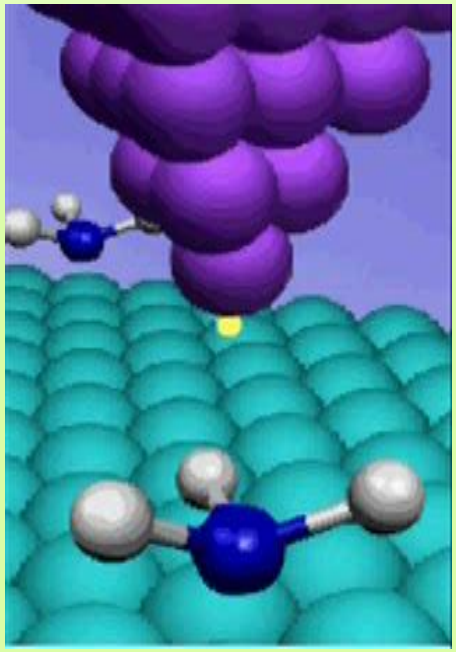
⇨ dependence of electronic properties on the local environment

Inelastic electron tunneling spectroscopy (IETS)

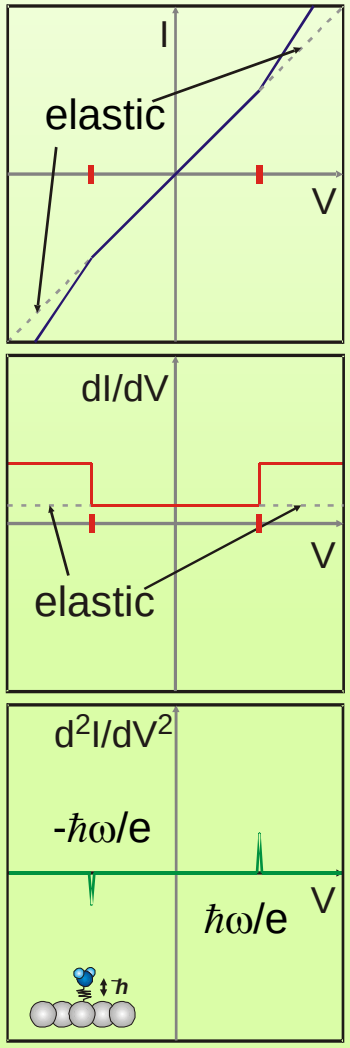
Wilson Ho

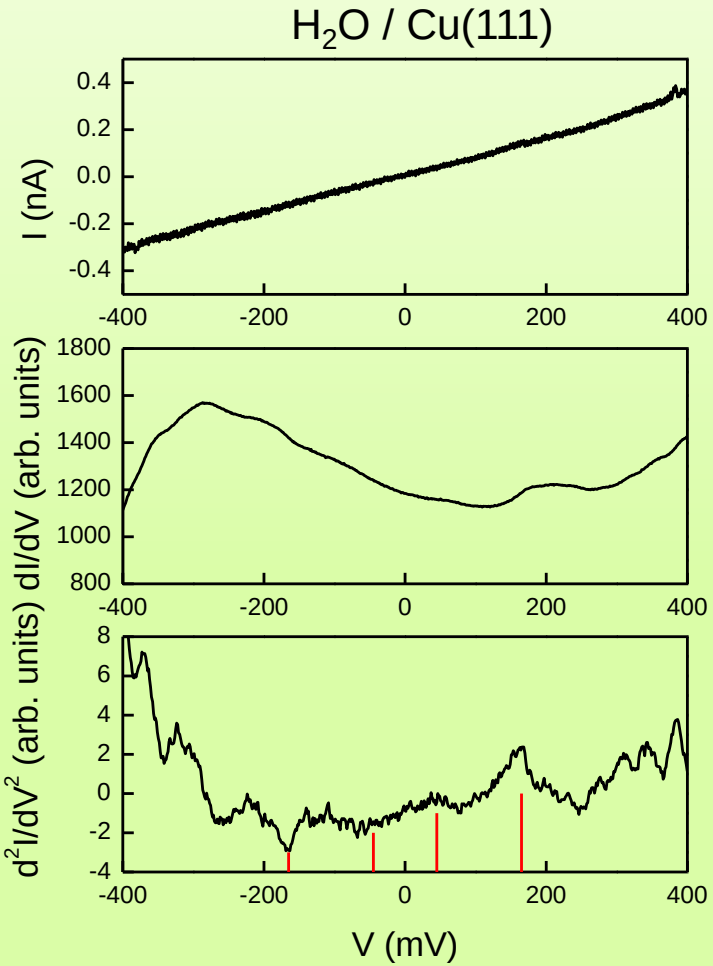
J. Chem. Phys. 117, 11033 (2002)





with courtesy of I. J. Pascual



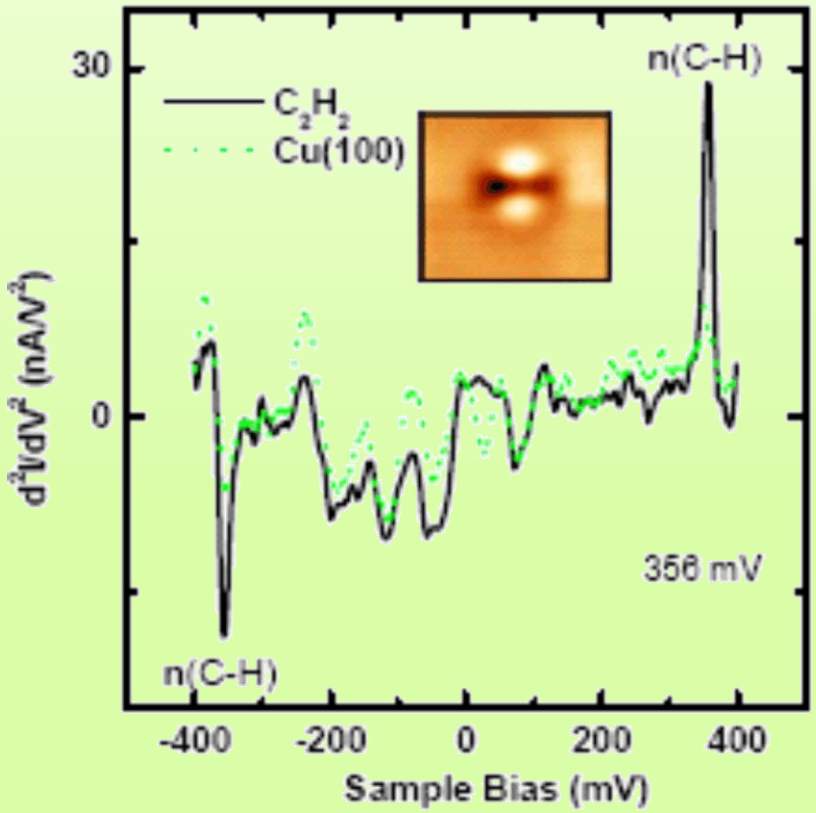


J. Chem. Phys. 116, 5746 (2002)

IETS: Internal and external molecular modes

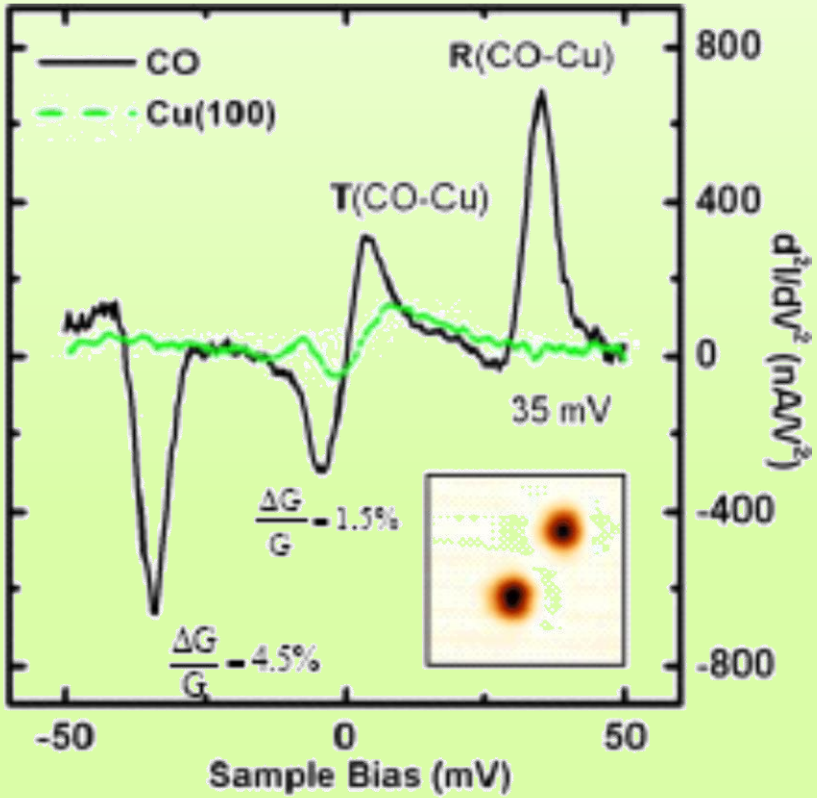
Intramolecular vibrational modes

C_2H_2 / Cu(100)



Adsorbate-surface vibrational modes

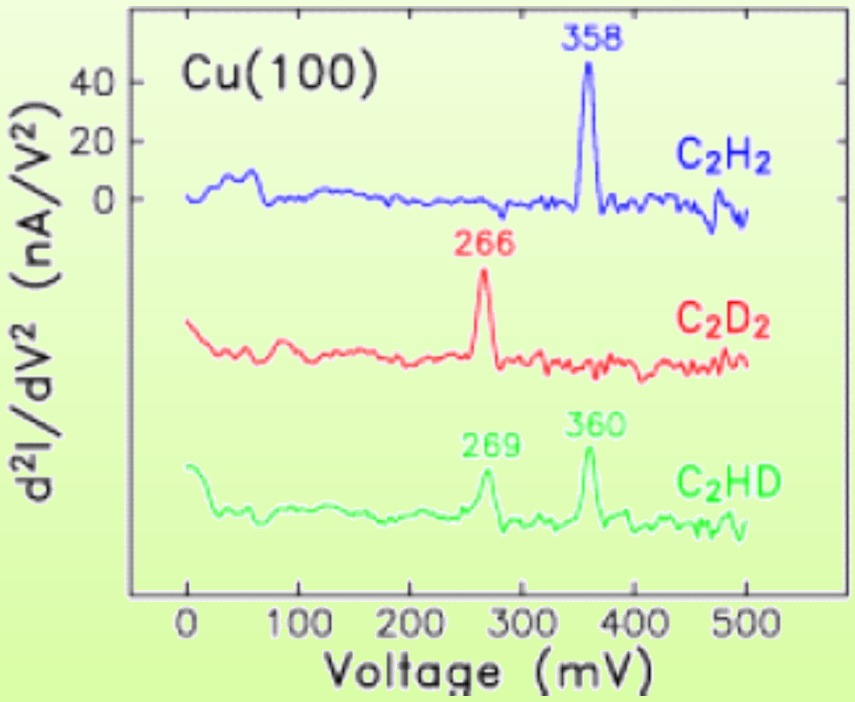
CO / Cu(100)

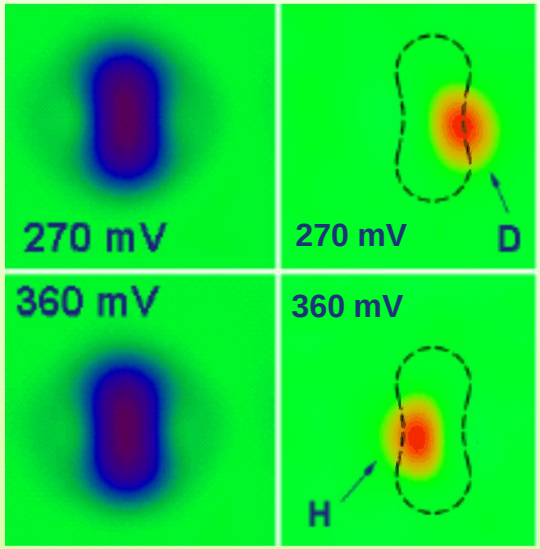


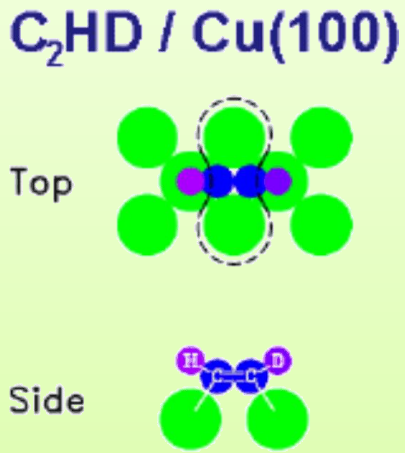
W. Ho, J. Chem. Phys. 117, 11033 (2002)

IETS: Isomer identification

Wilson Ho, UC Irvine







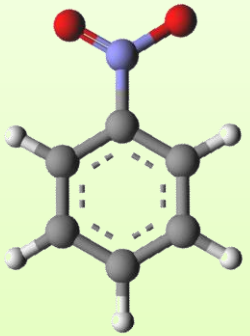
⇨submolecular vibrational contrast

IETS of organic molecules

nitrobenzene on Cu(111)

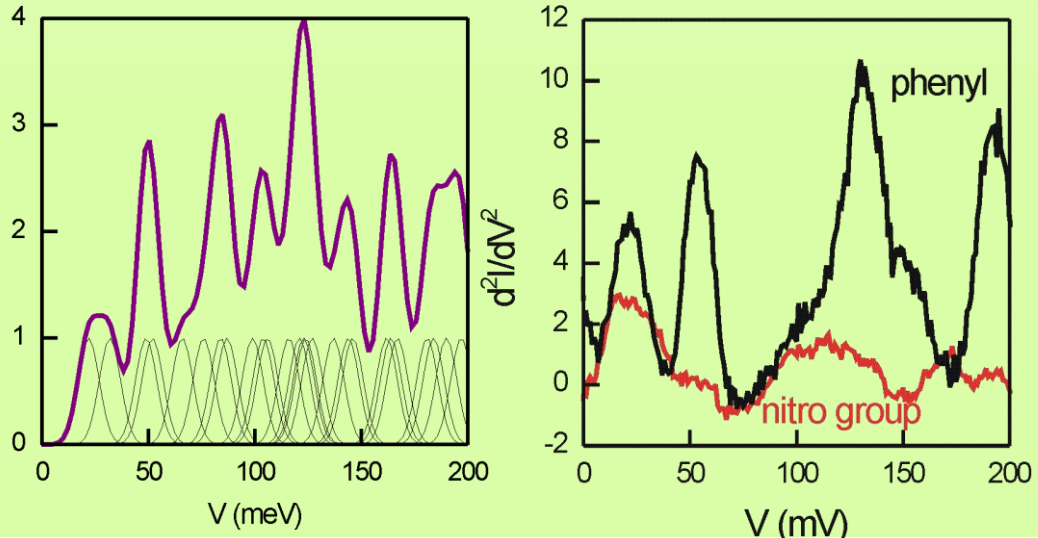
J. Phys.: Condens. Mat. 23, 484007 (2011)

Ring related	symmetry	Energy (meV)	Nitro group related	symmetry	Energy (meV)
C-H stretch	A1	386/382/378			
	B2	384/376			
C-C stretch	A1	197/184			
	B2	197/181/164			
C-H in-plane bent	A1	146/127	NO_2 stretch	A1	167
	B2	162/144/133		B2	190
breathing	A1	124	C-NO_2 stretch	A1	137
C-H out-of-plane bent	A2	121/104	NO_2 bent	A1	106
	B1	123/116/99	NO_2 Out-of-plane bent	B1	87
Out-of-plane deformation	A2	49	NO_2 in-plane bent	A2	66
	B1	84/52	C-NO_2 in-plane bent	B2	32
In-plane deformation	A1	84/49	C-NO_2 out-of-plane bent	B1	22
	B2	76			



35 modes

IRAS: D. Syomin et al. Surf. Sci. Lett. 495 (2001) L827

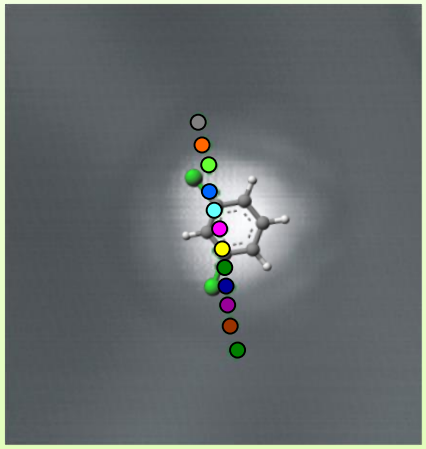


limited energy resolution due to thermal and modulation broadening

⇨vibrational bands

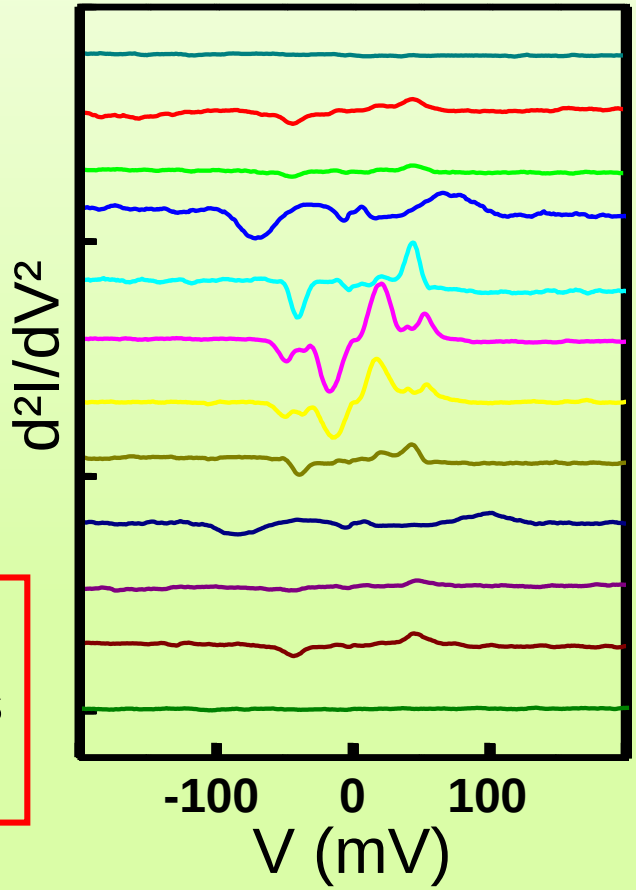
IETS: Spatial resolution

dichlorobenzene / Au(111)



210 pA, -246 mV

Phys. Rev. B 89, 125420 (2014)



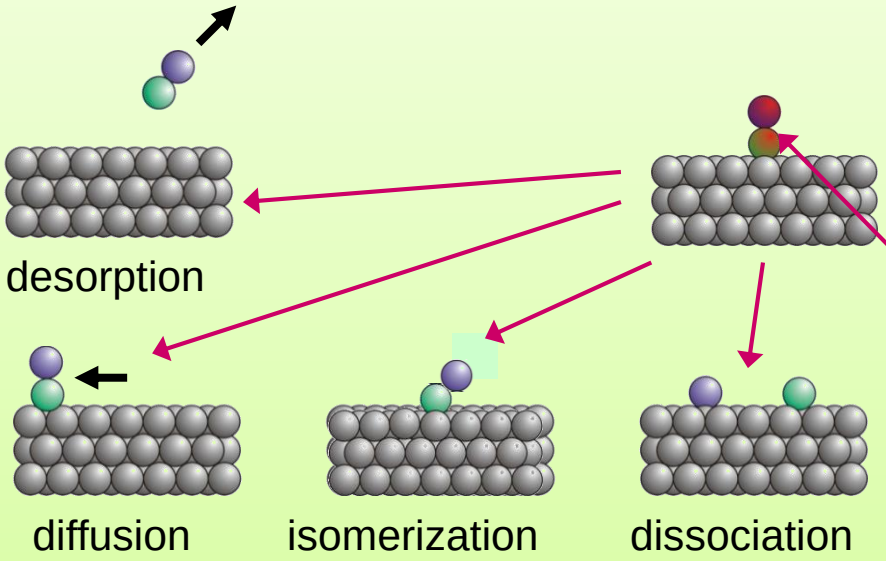
IETS

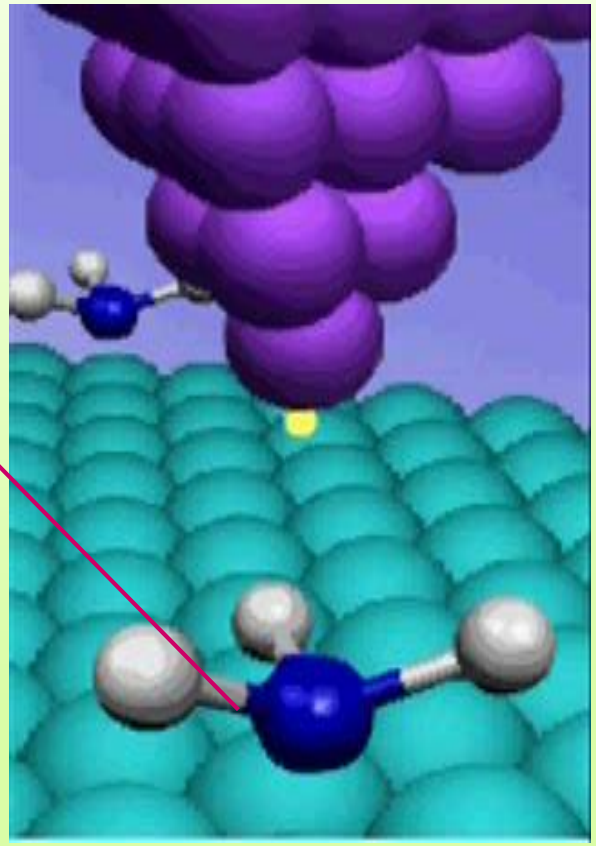
⇨local excitation of molecular vibrations

⇨chemical and isomeric identification

IET manipulation

Phys. Status Solidi B, 250, 1671 (2013)





O_2 dissociation on Pt(111)
B.C. Stipe et al.,
Phys. Rev. Lett. 78, 4410 (1997)

with courtesy of
I.J. Pascual

ISSN 0370-1972
Phys. Status Solidi B
250 · No. 9 September
1665–1948 (2013)

Progress in Surface Science 86 (2011) 115–161

Contents lists available at ScienceDirect

Progress in Surface Science

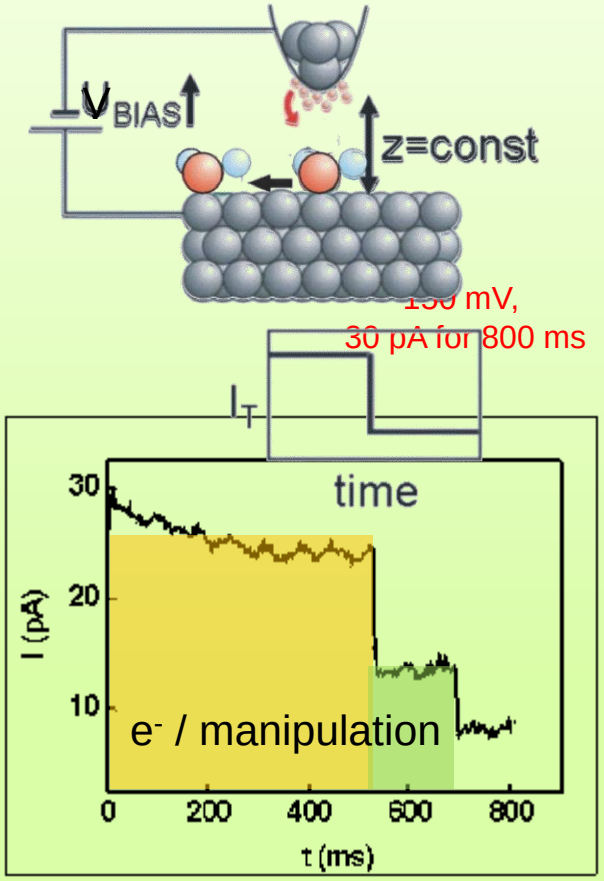
journal homepage: www.elsevier.com/locate/progsurf

Review

Switching individual molecules by light and electrons: From isomerisation to chirality flip

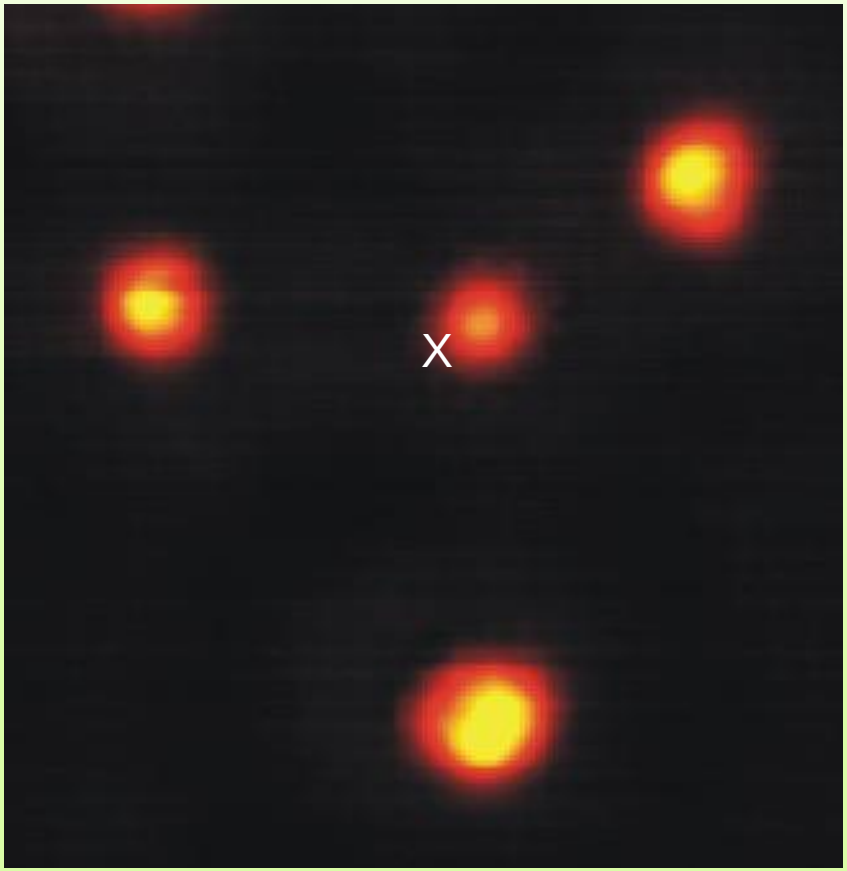
Karina Morgenstern *

IET manipulation



D_2O on Ag(111)

J. Chem. Phys. 116, 5746 (2002)



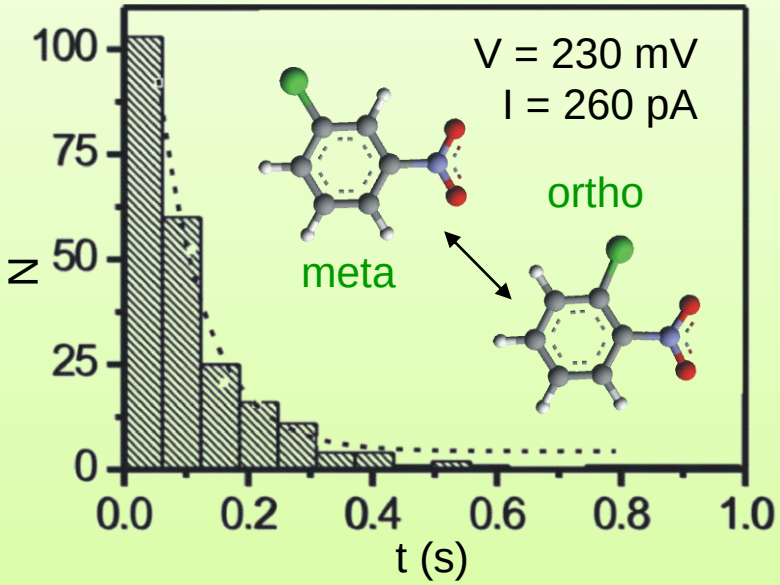
71 mV, 12 pA

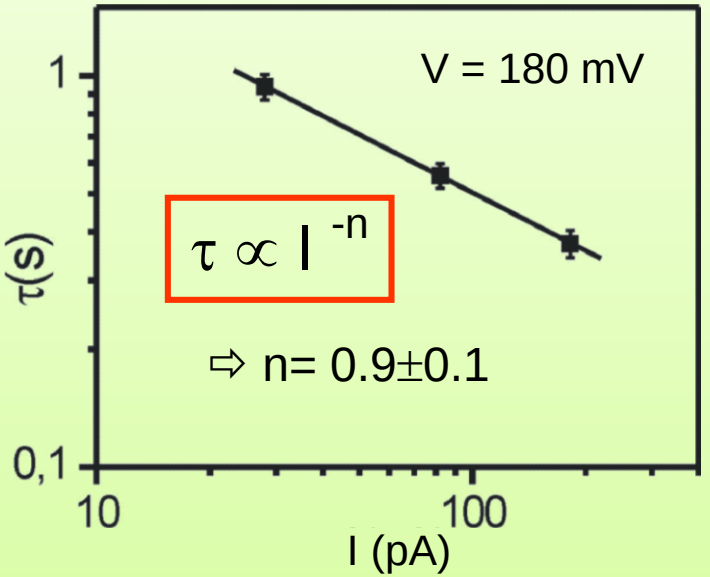
⇨induced diffusion

IET manipulation: Reaction order

chloronitrobenzene on Cu(111)

Phys. Rev. Lett. 98, 116102 (2007)
Angew. Chem. Int. Ed. 48, 6041 (2009)



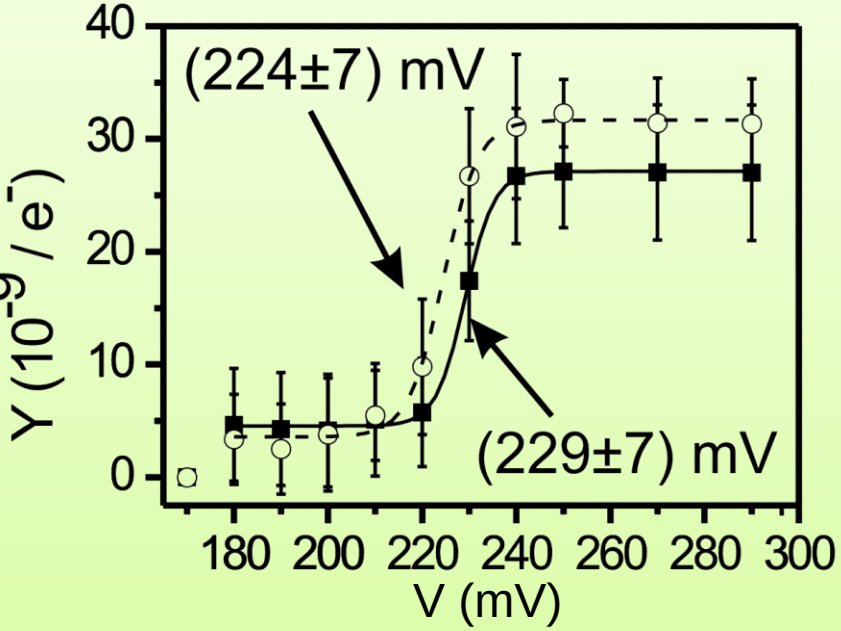


residence time
before isomerisation
⇨ decay constant τ

reaction order n
⇨ one electron process

Action spectroscpy

chloronitrobenzene on Cu(111)

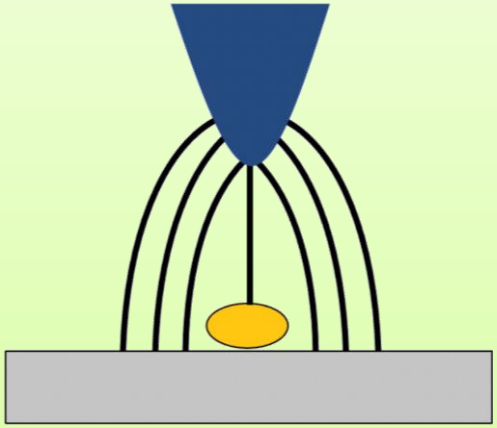


⇨energy of molecular vibrations

⇨ action spectroscopy

M. Kawai et al.
Phil. Trans. R. Soc. Lond. A 362, 1163 (2004)

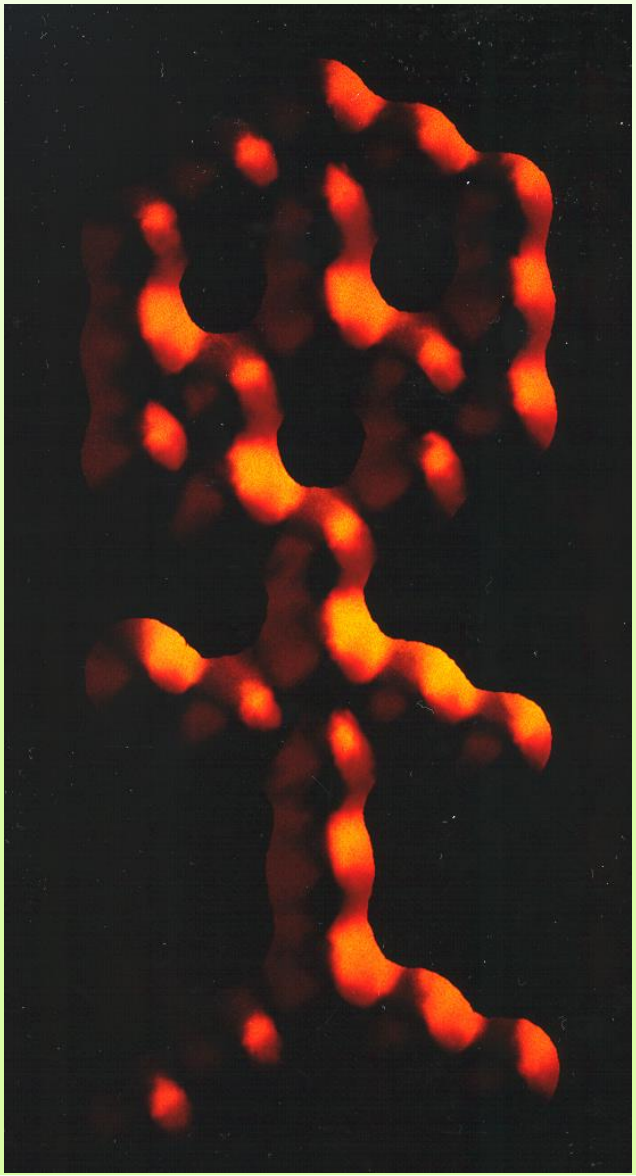
Phys. Rev. Lett. 98, 116102 (2007)
Phys. Rev. Lett. 101, 136102 (2008)
Angew. Chem. Int. Ed. 48, 6041 (2009)



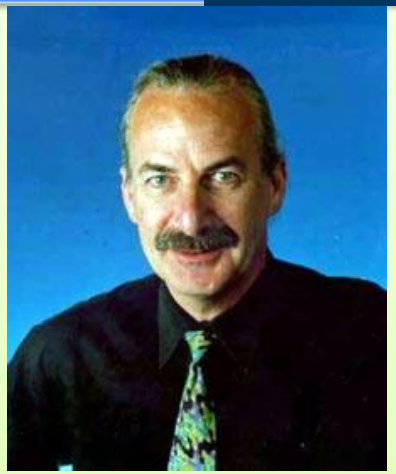
100 mV over 1 nm
⇒ E = 10^8 V/m

⇨ influence of the electric field on IET manipulation and spectrosopy

Manipulation by tip interaction

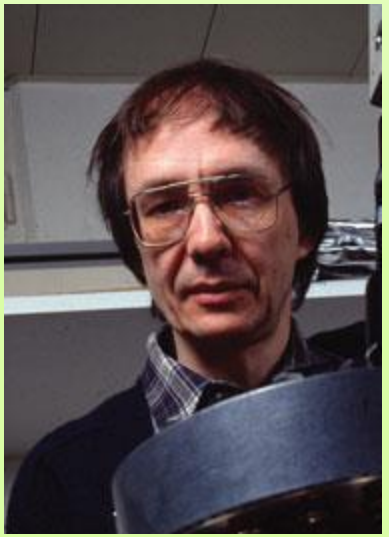


P. Zeppenfeld et al.
Ultramicroscopy 42-44, 128 (1992)



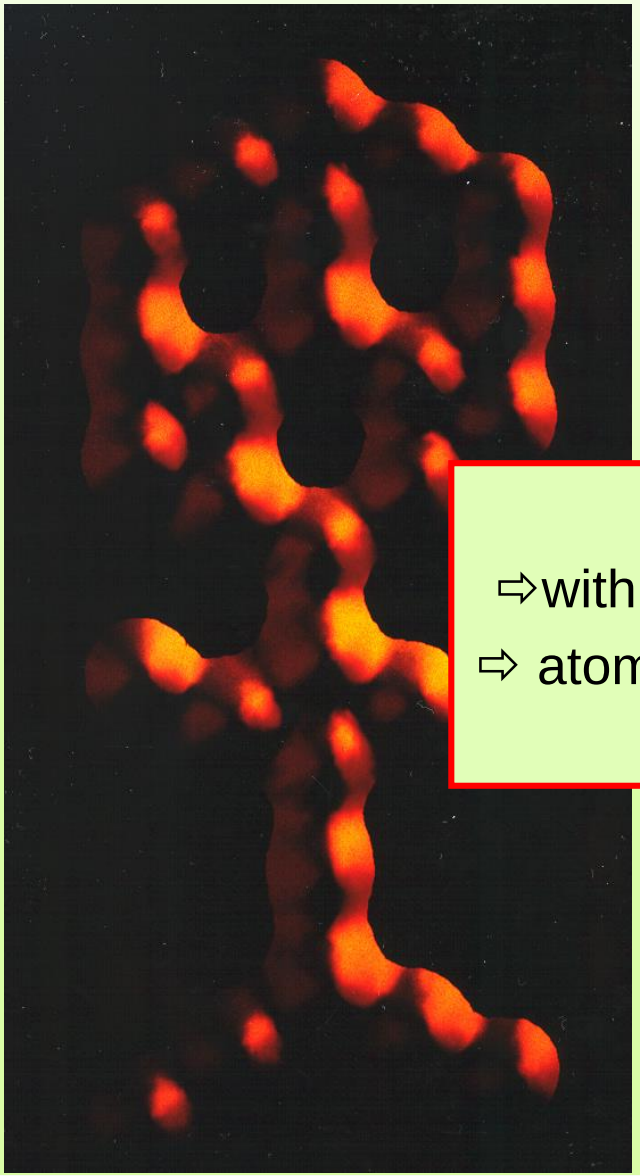
Don Eigler

Karl-Heinz Rieder

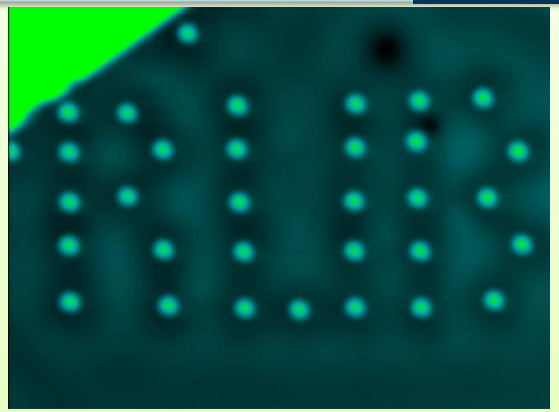


Gerhard Meyer

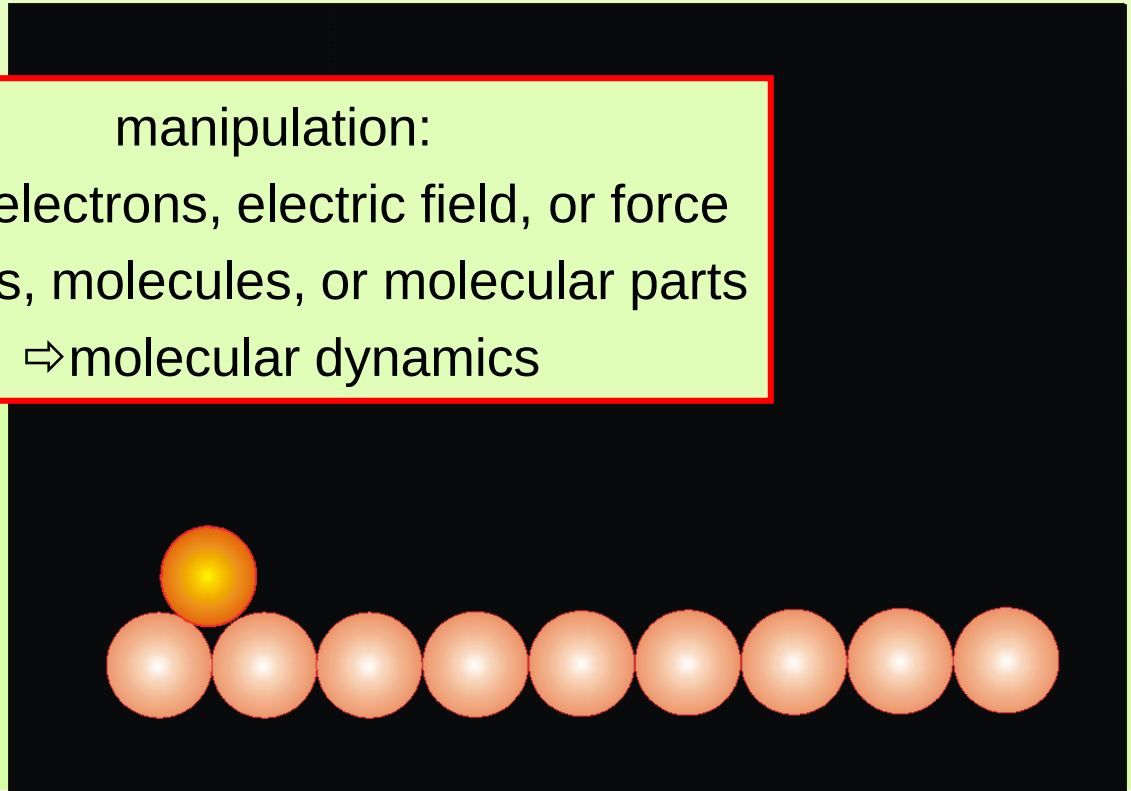
Manipulation by tip interaction



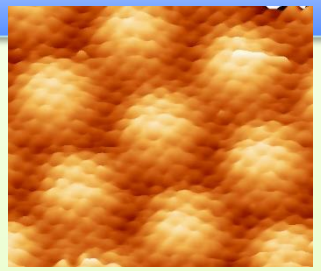
P. Zeppenfeld et al.
Ultramicroscopy 42-44, 128 (1992)

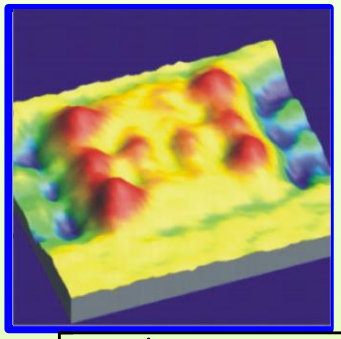


manipulation:
⇨with electrons, electric field, or force
⇨ atoms, molecules, or molecular parts
⇨molecular dynamics



Outline



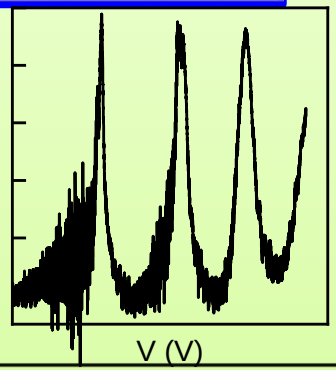


1) STM, STS, IETS, and manipulation

   An extended introduction

2) Quantum effects on surface imaged by STM

   Electron in a box I

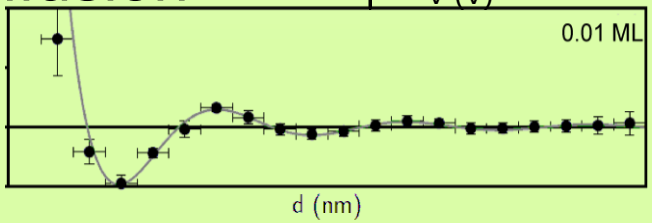


3) Quantum effects on surfaces measured by STS

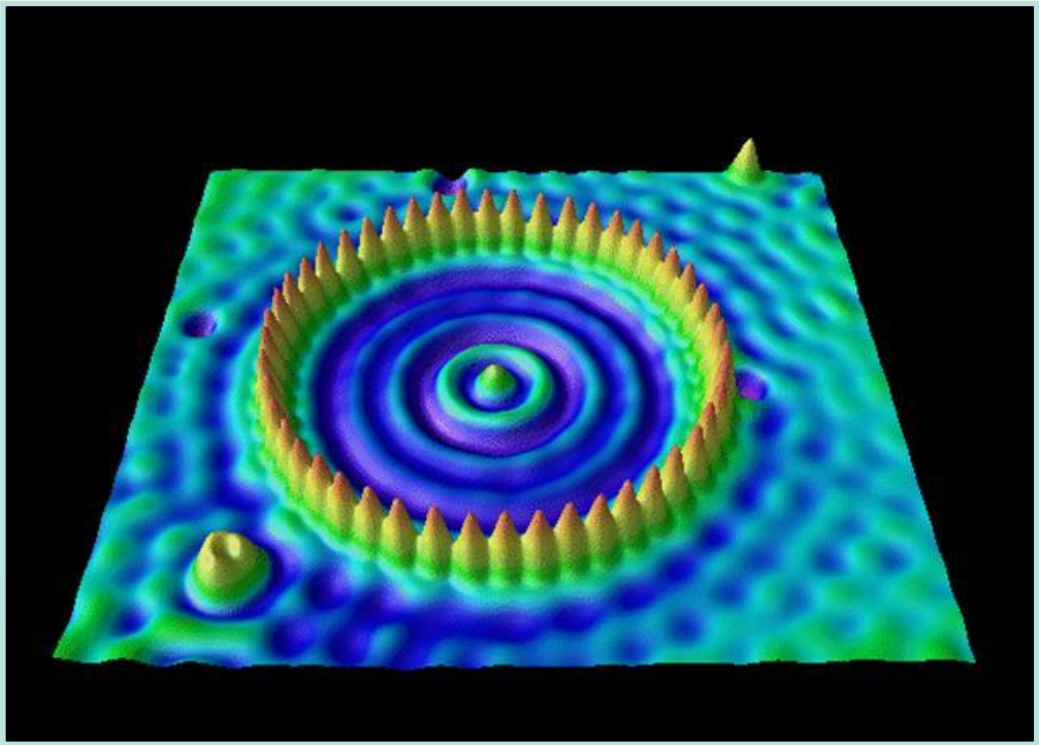
   Electron in a box II

4) Electron interference effects surface diffusion

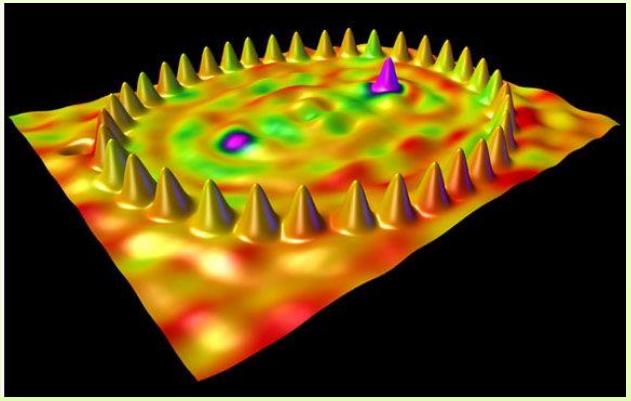
   Influence of Friedel oscillations on diffusivity



Quantum corral/quantum mirage

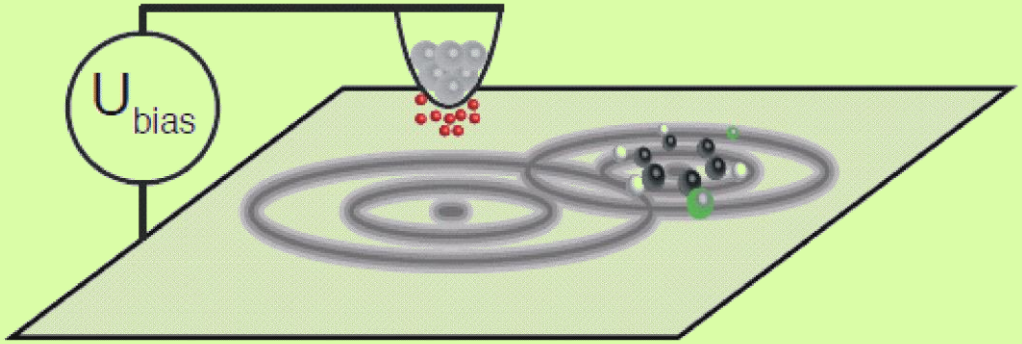


M. F. Crommie et al.,
Science 262, 218 (1993)

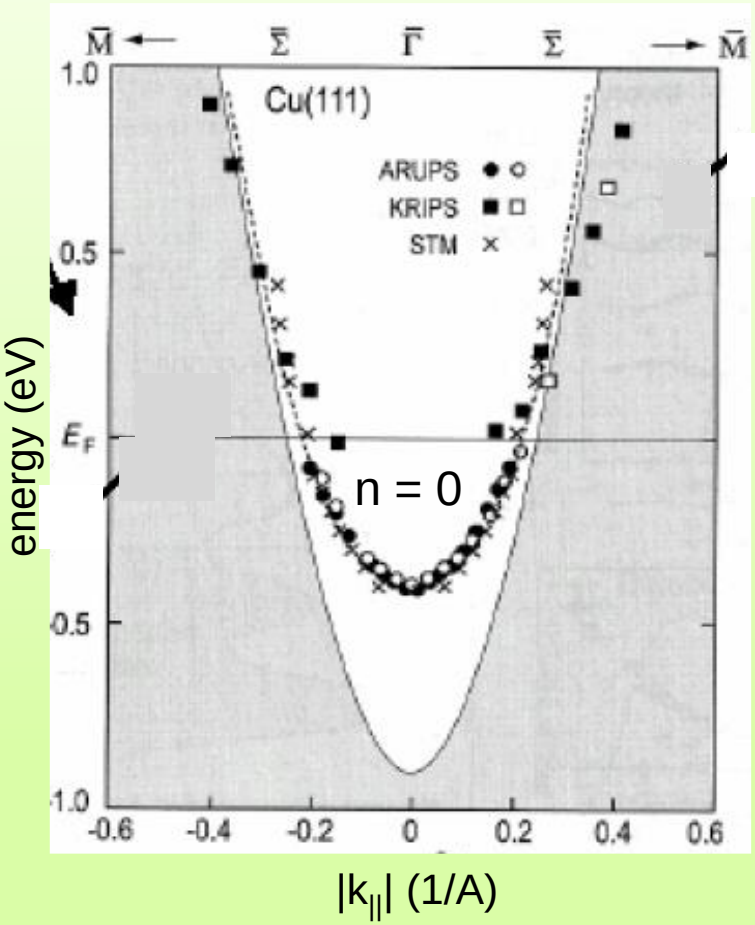


Friedel-like oscillations

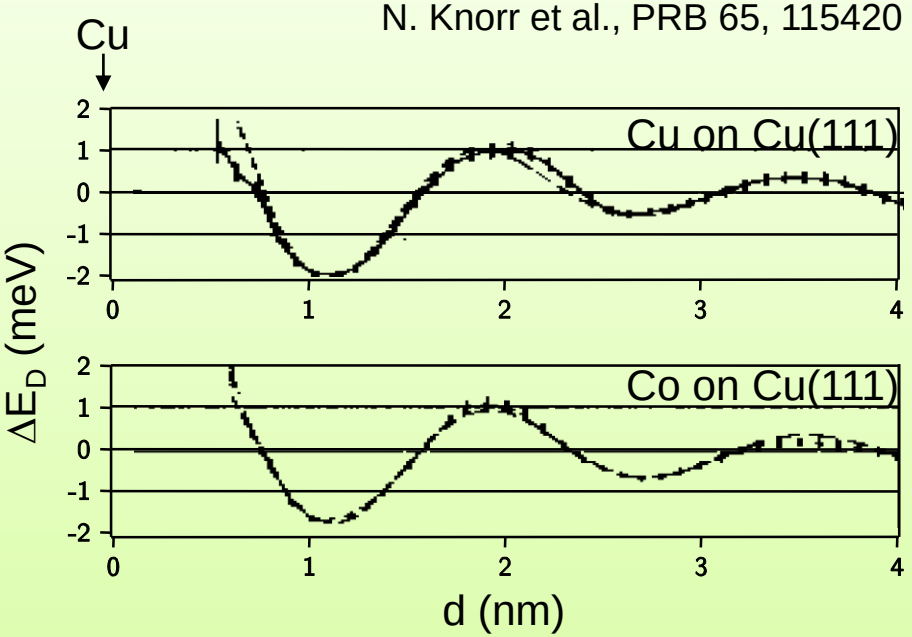
⇨ interference pattern of electrons



Surface state on fcc(111) surfaces



N. Knorr et al., PRB 65, 115420 (2002)



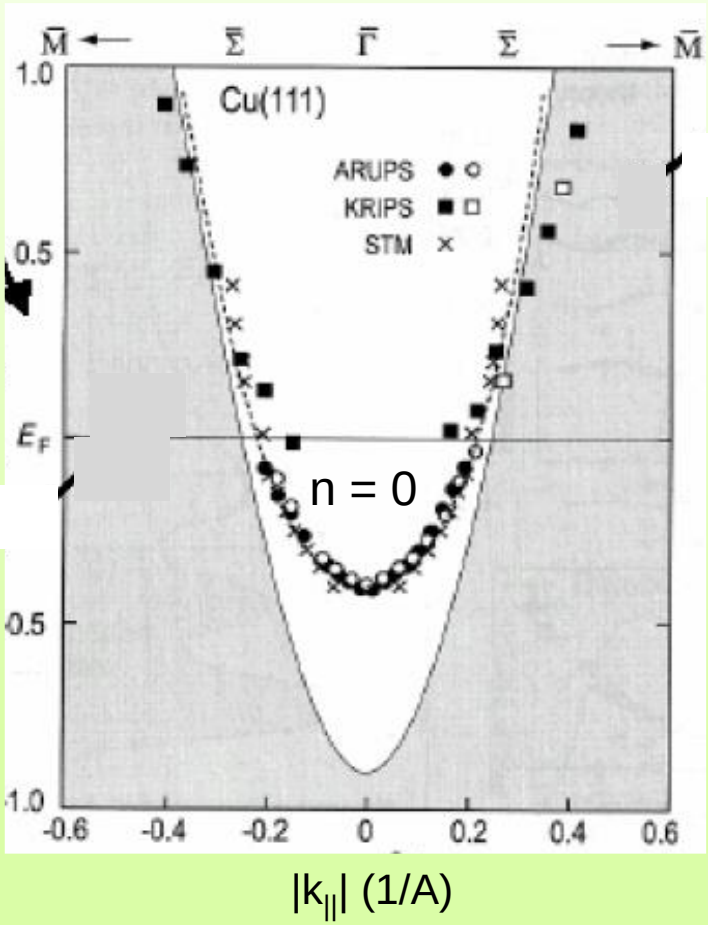
$k_F = \boxed{(2.0 \pm 0.1)}\ \mathrm{nm}^{-1}$ $\varphi_F = \boxed{(0.49 \pm 0.03)\,\pi}$

$$\Delta E(R) = -\alpha \cdot \frac{\sin(2k_F R + 2\varphi)}{(k_F R)^2}$$

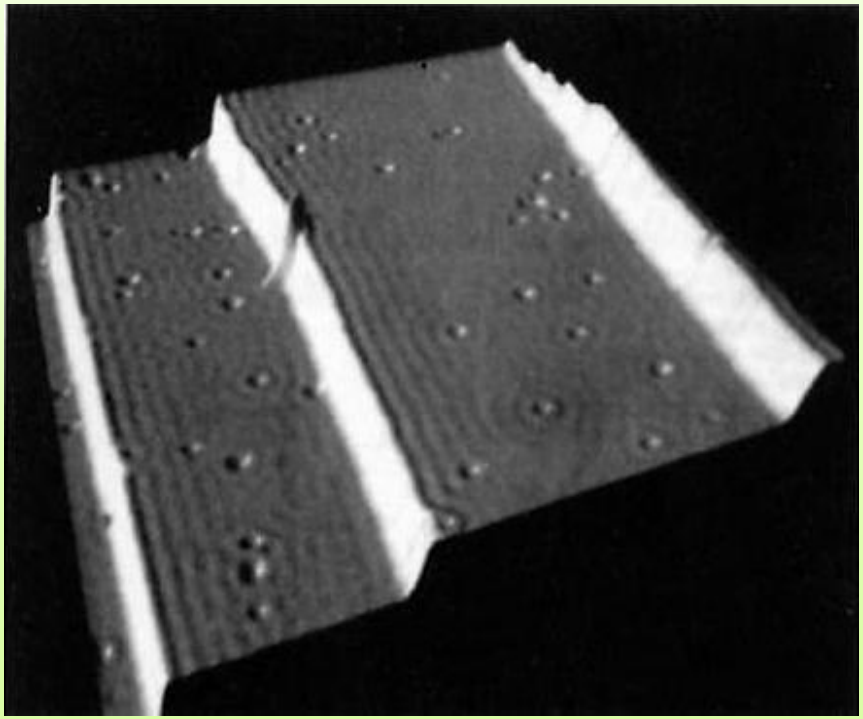
P. Hyldgaard, M. Persson,
J. Phys. Condens. Matter 12, L13 (2000)

N. V. Smith Rep. Prog. Phys. 51, 1227 (1988)

Surface state on fcc(111) surfaces



Crommie et al. Nature 363, 524 (1993)



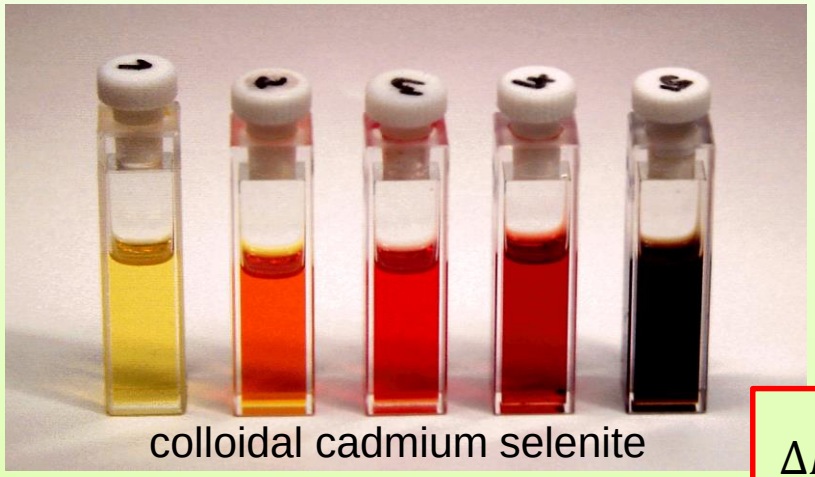
0.1 V; 50 x 50 nm^2

$$\Delta E(R) = -\alpha \cdot \frac{\sin(2k_F R + 2\varphi)}{(k_F R)^2}$$

P. Hyldgaard, M. Persson,
J. Phys. Condens. Matter 12, L13 (2000)

N.V. Smith Rep. Prog. Phys. 51, 1227 (1988)

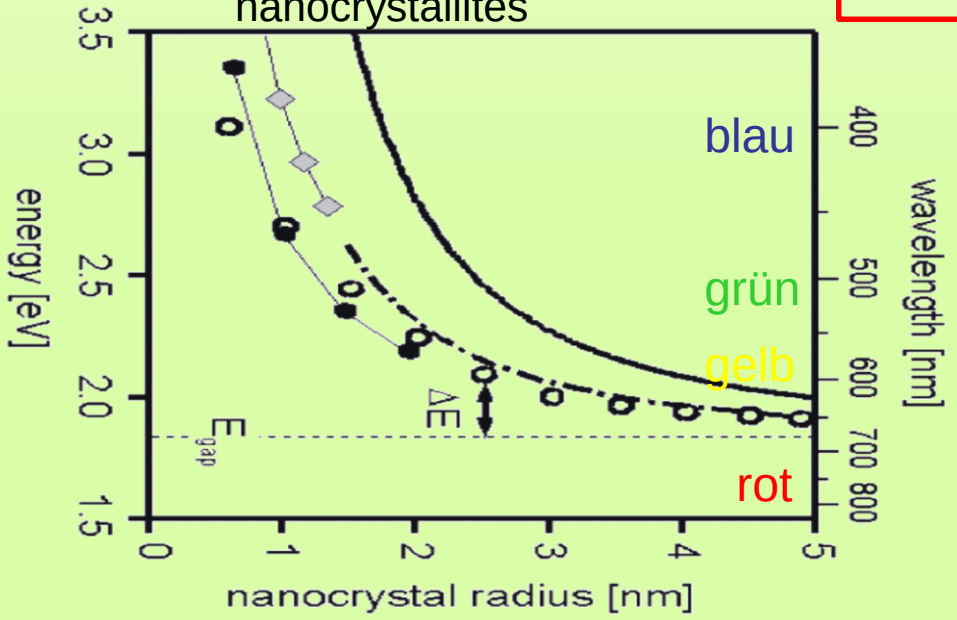
Quantum size effects

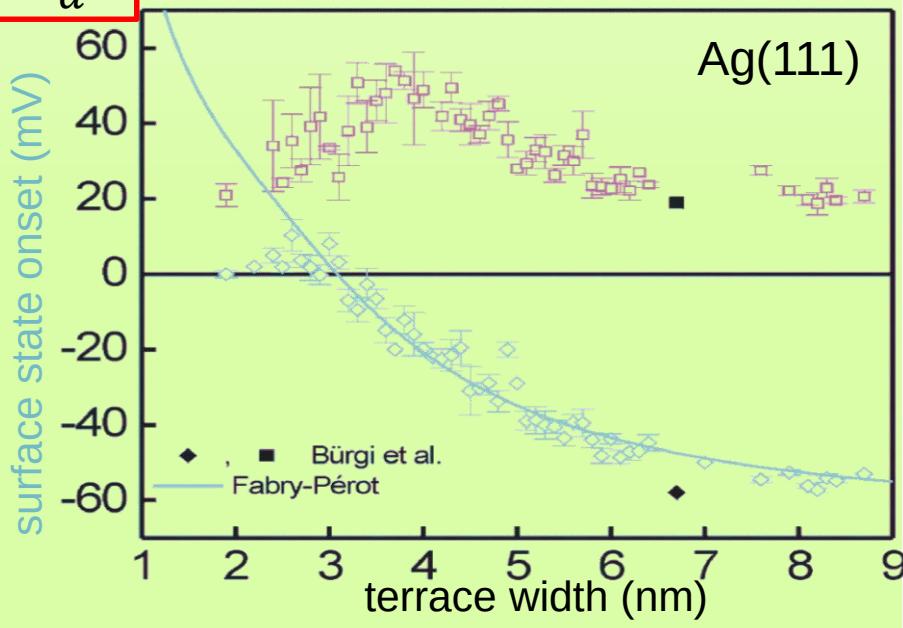


colloidal cadmium selenite nanocrystallites

$$\Delta E(d) \propto \frac{1}{d^2}$$

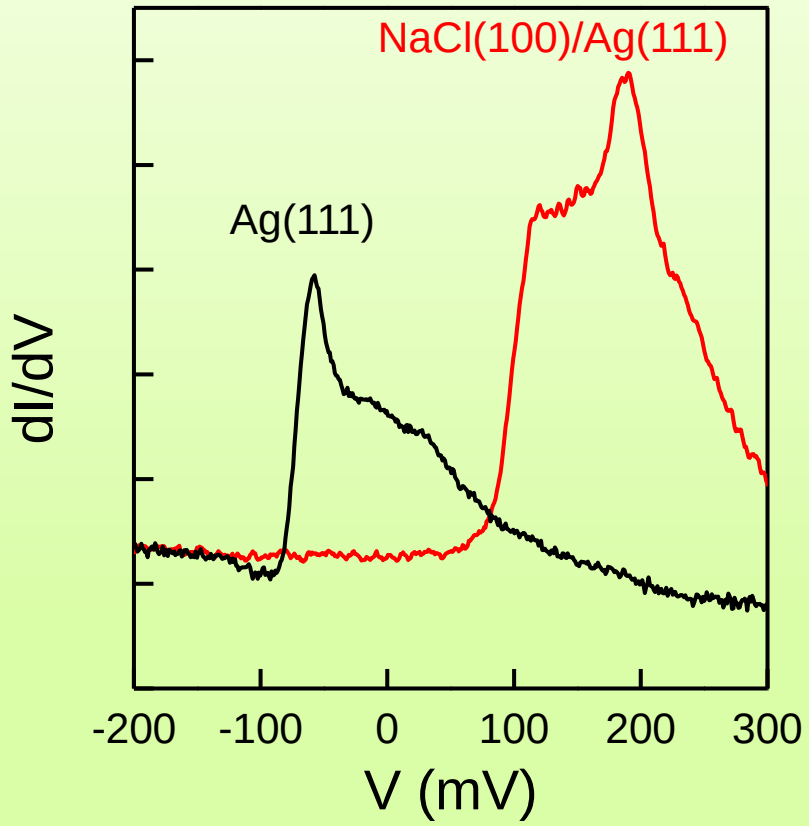
K. Morgenstern et al.
Phys. Rev. Lett. 89, 226801 (2002)



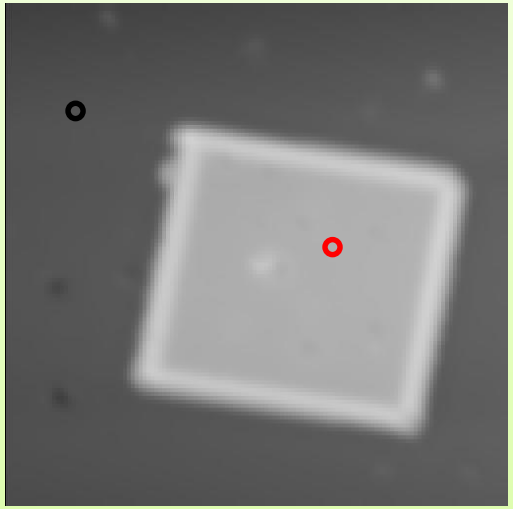


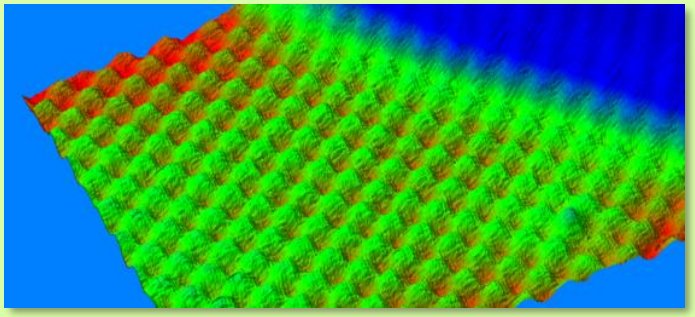
STS of insulator on fcc(111) metal

J Phys. Chem. C. 117, 16094 (2013)



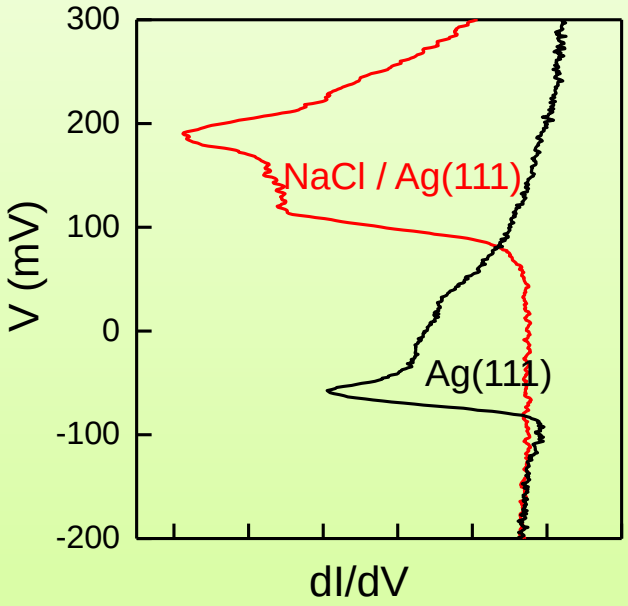
NaCl(100) on Ag(111)

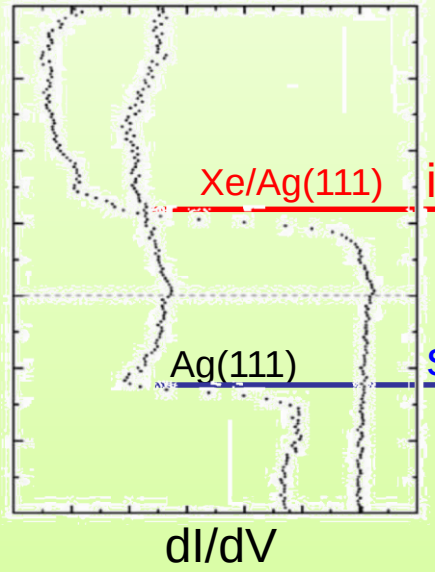




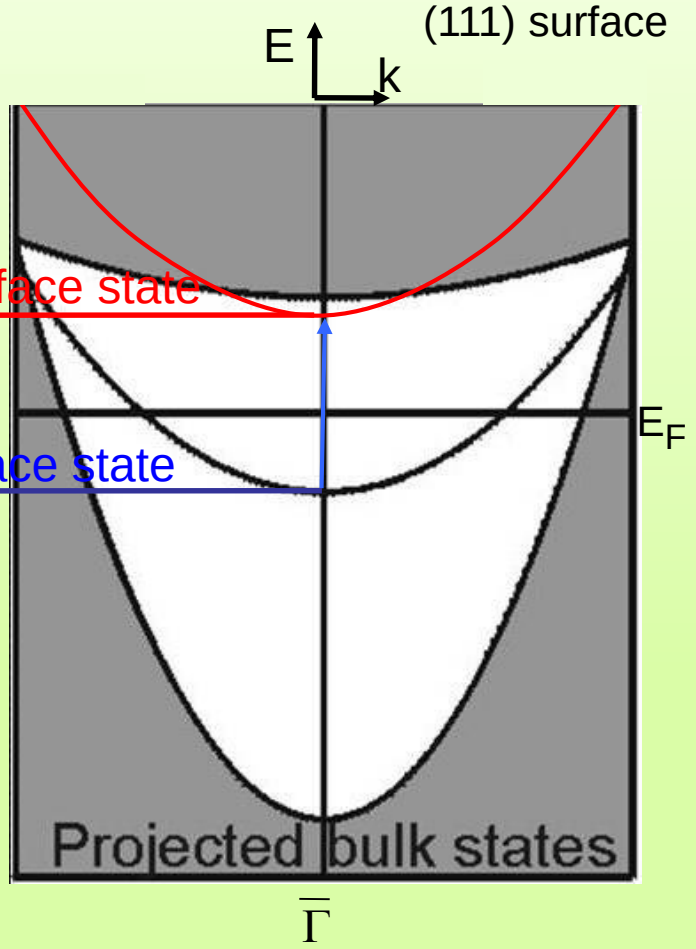
Surface vs. interface state

J Phys. Chem. C. 117, 16094 (2013)





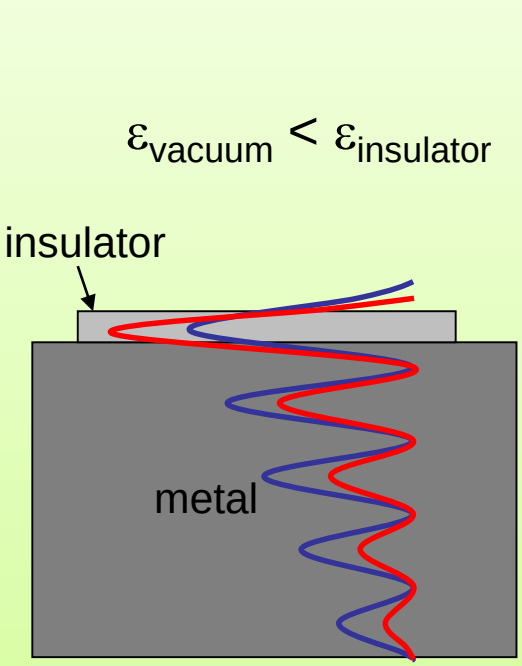
H. Hövel et al.
Surf. Sci. 477, 43, 2001
Ag(111) c.f. Bürgi et al.
Phys. Rev. Lett. 81 (1998) 5370

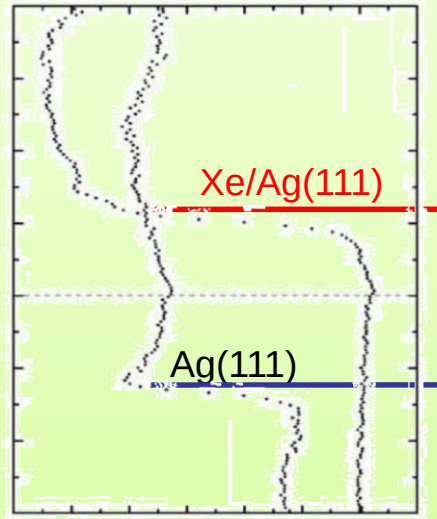


J. Li et al., Phys. Rev. Lett., 80(15), 3332 (1998)
H. Jensen et al., Phys. Rev. B, 71(15), 155417 (2005)

Surface vs. interface state

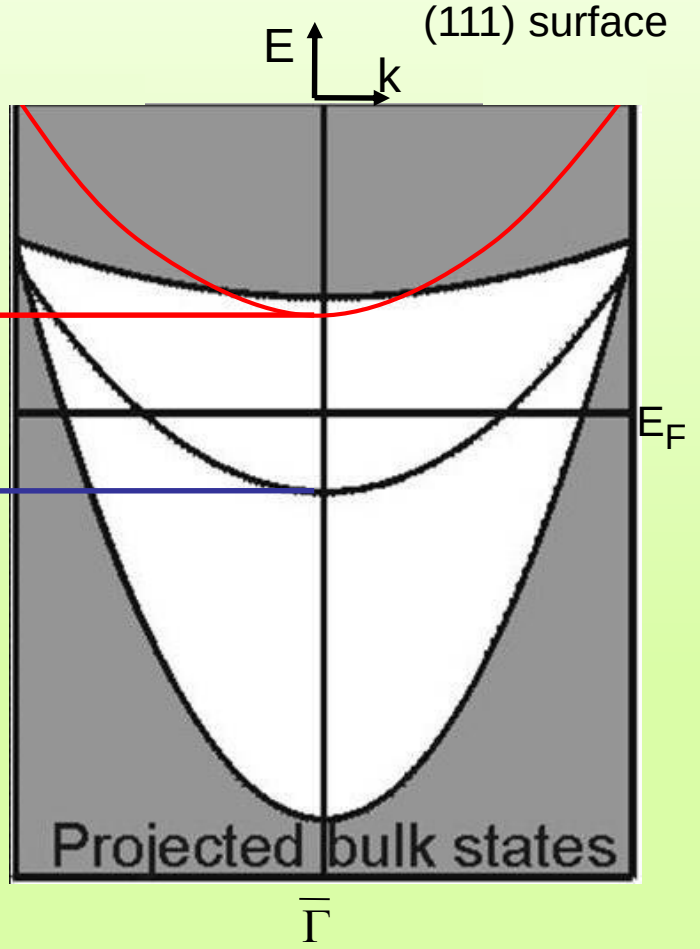
J Phys. Chem. C. 117, 16094 (2013)





H. Hövel et al.
Surf. Sci. 477, 43, 2001

>

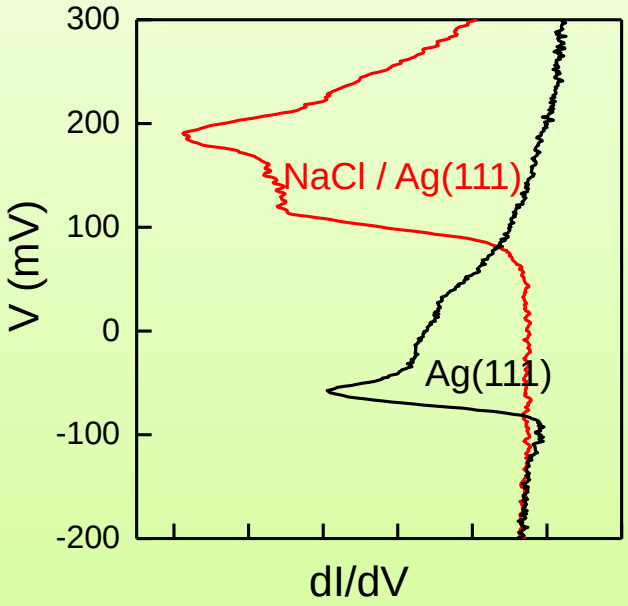


J. Li et al., Phys. Rev. Lett., 80(15), 3332 (1998)

H. Jensen et al., Phys. Rev. B, 71(15), 155417 (2005)

Surface vs. interface state

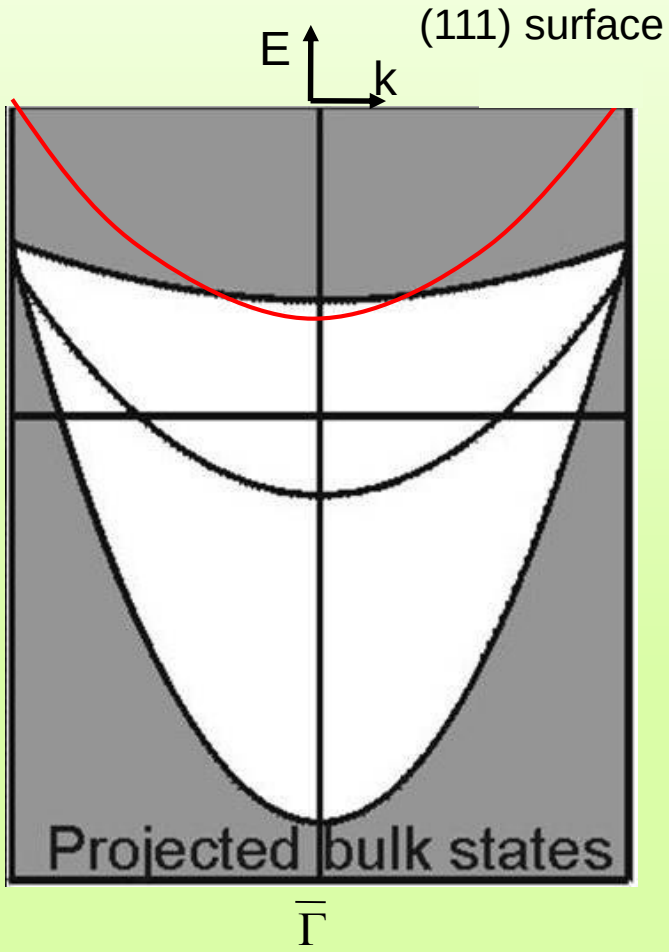
J Phys. Chem. C. 117, 16094 (2013)



⇒interface state
@ +(90 ± 4) meV

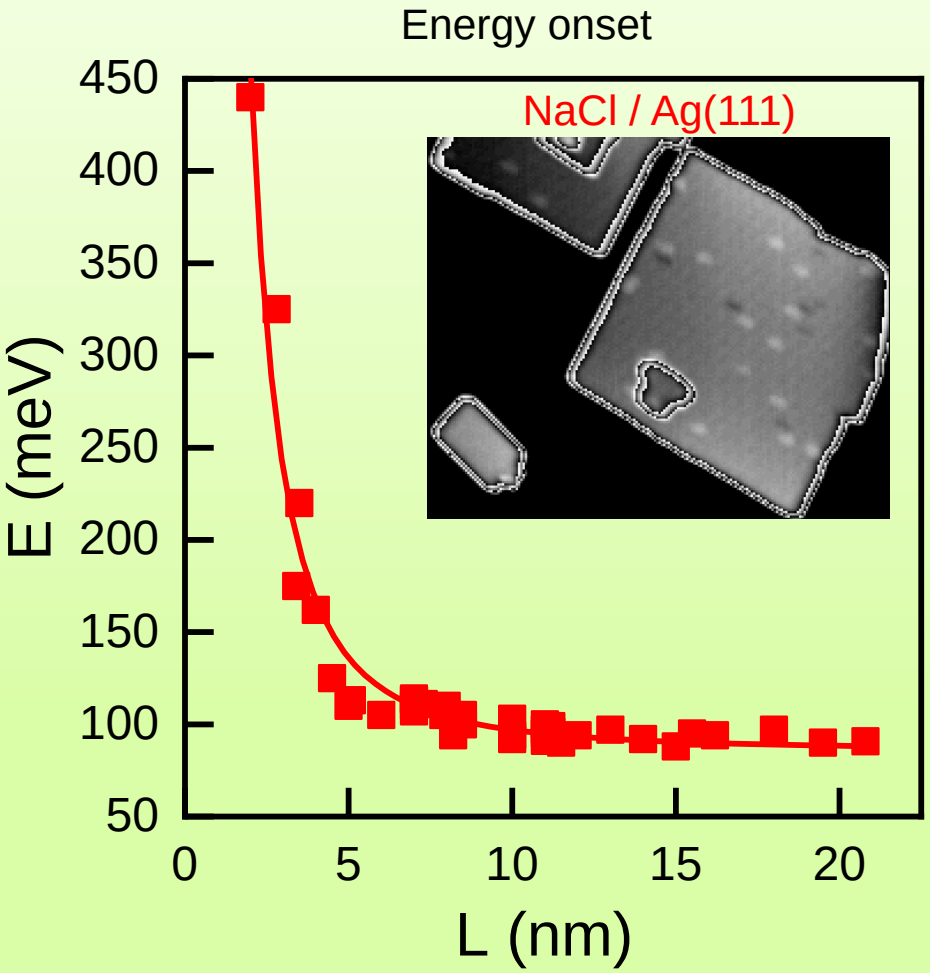
⇒ surface state
@ -(65 ± 3) meV

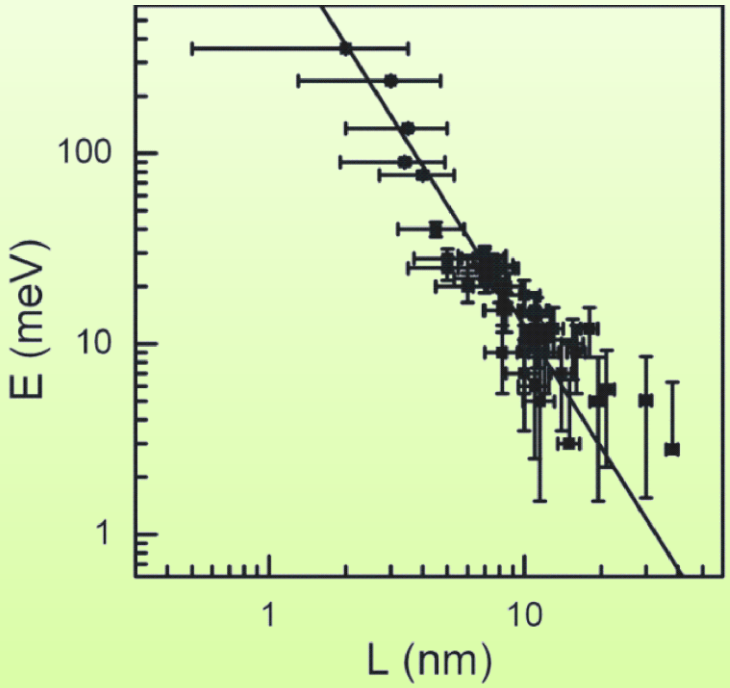
⇨~150 meV shift for NaCl layers



Quantum confinement

Nano Lett. 14, 13 (2014)



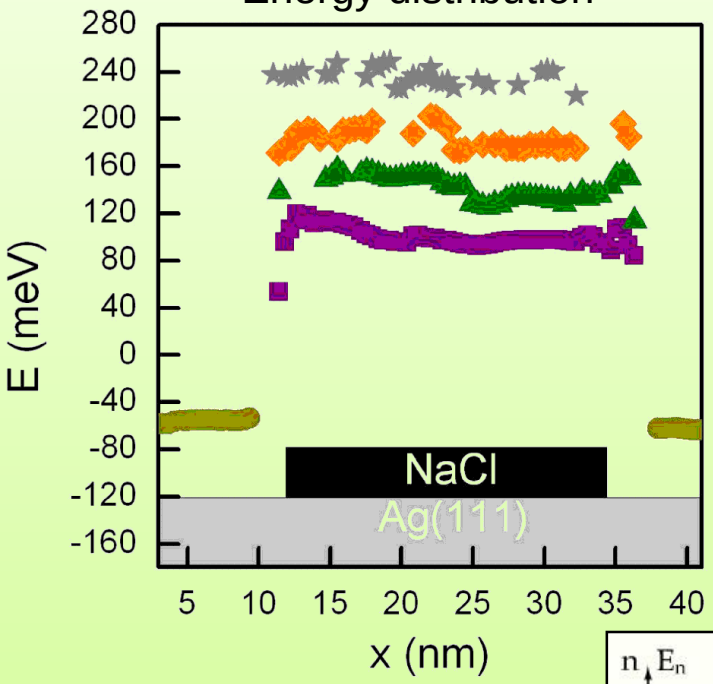


$E \propto 1/L^2$

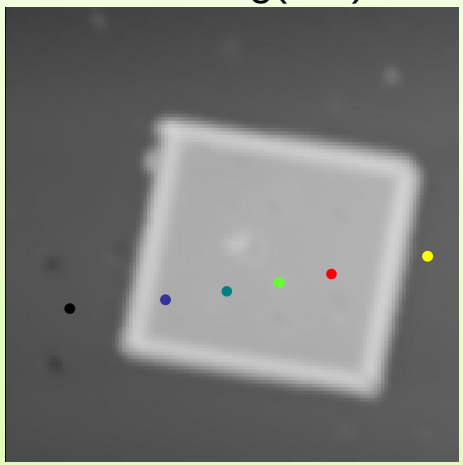
⇨quantum confinement < 8 nm

Particle in a box

Energy distribution



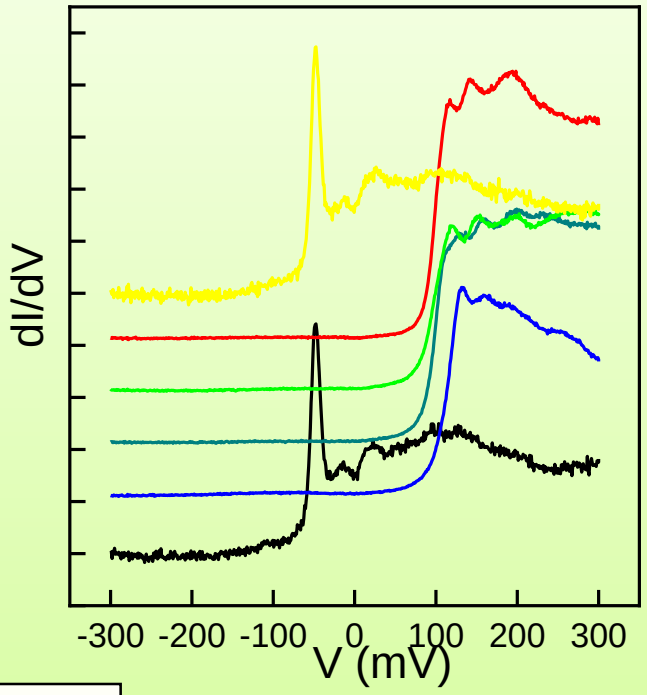
NaCl/Ag(111)

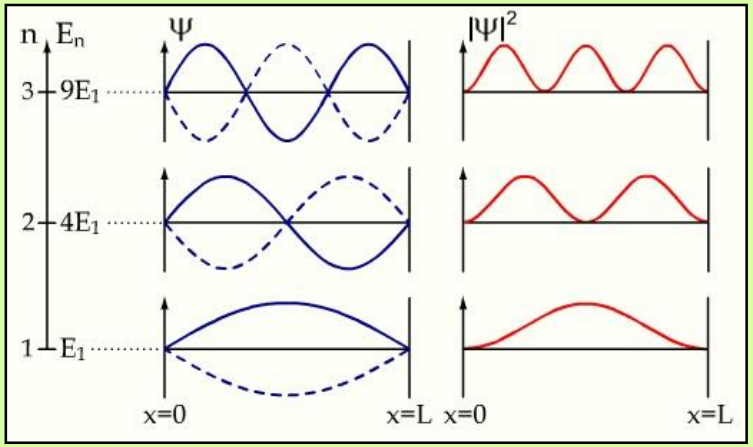


Island size 22.9 x 42.3 nm^2

76 pA, -300 mV

Nano Lett. 14, 13 (2014)

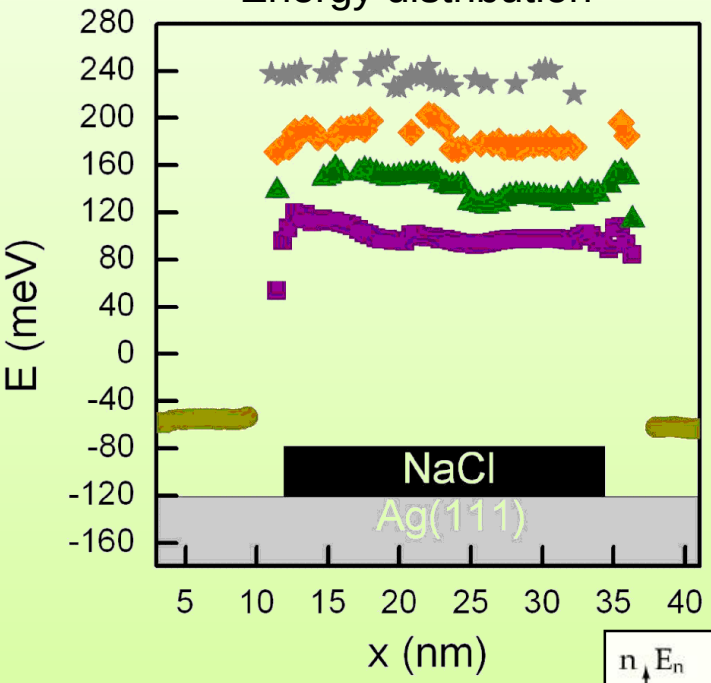




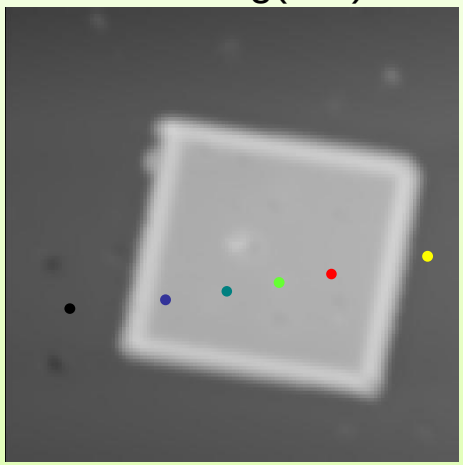
Particle in a box

Nano Lett. 14, 13 (2014)

Energy distribution



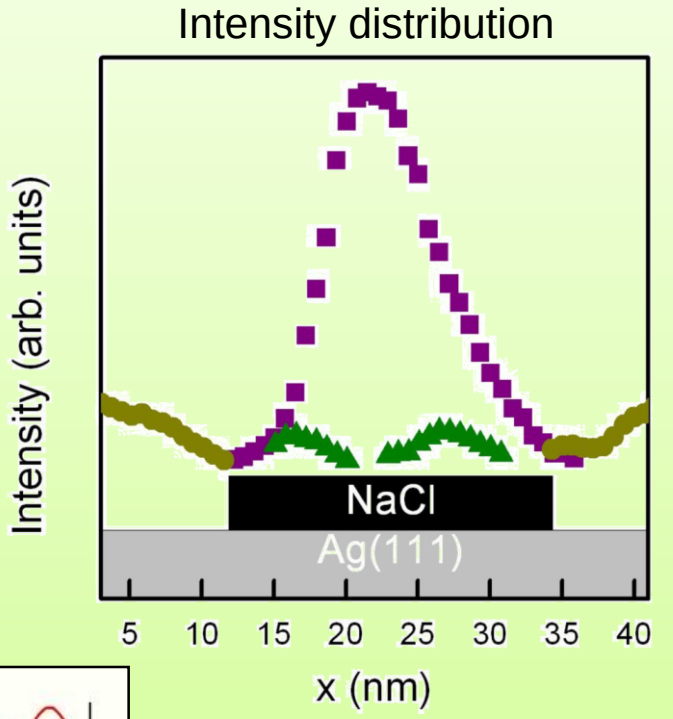
NaCl/Ag(111)

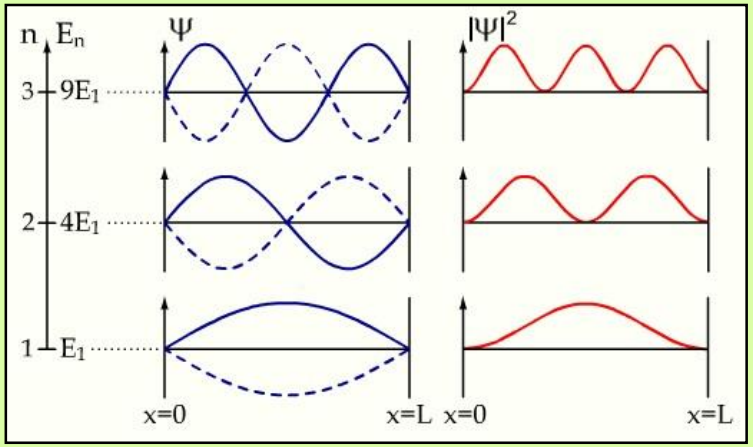


Island size 22.9 x 42.3 nm^2

76 pA, -300 mV

Intensity distribution



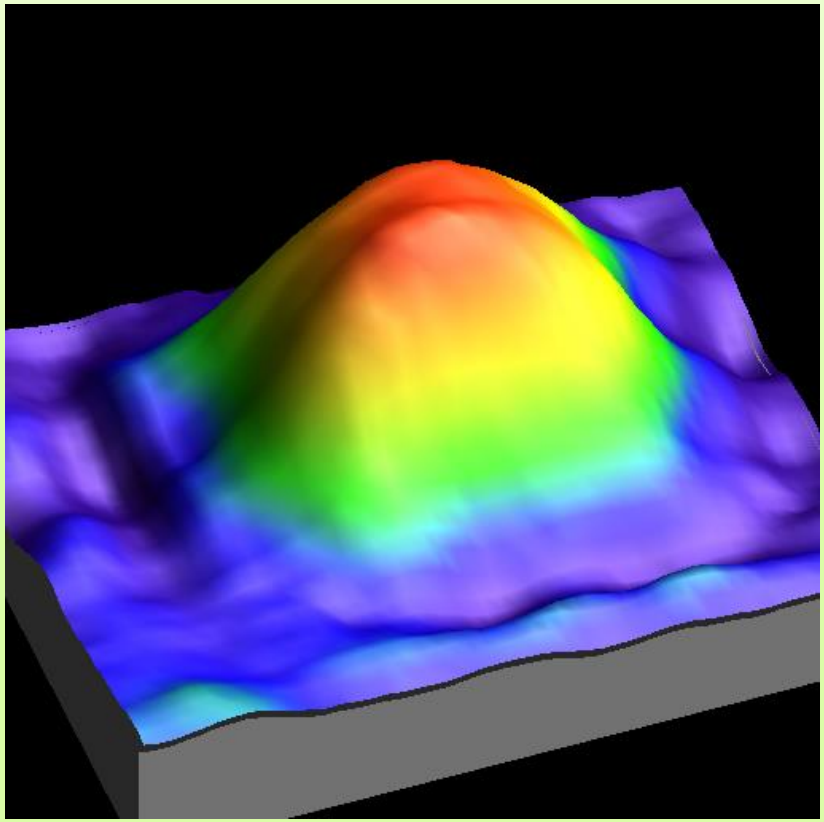


Particle in a box

Nano Lett. 14, 13 (2014)

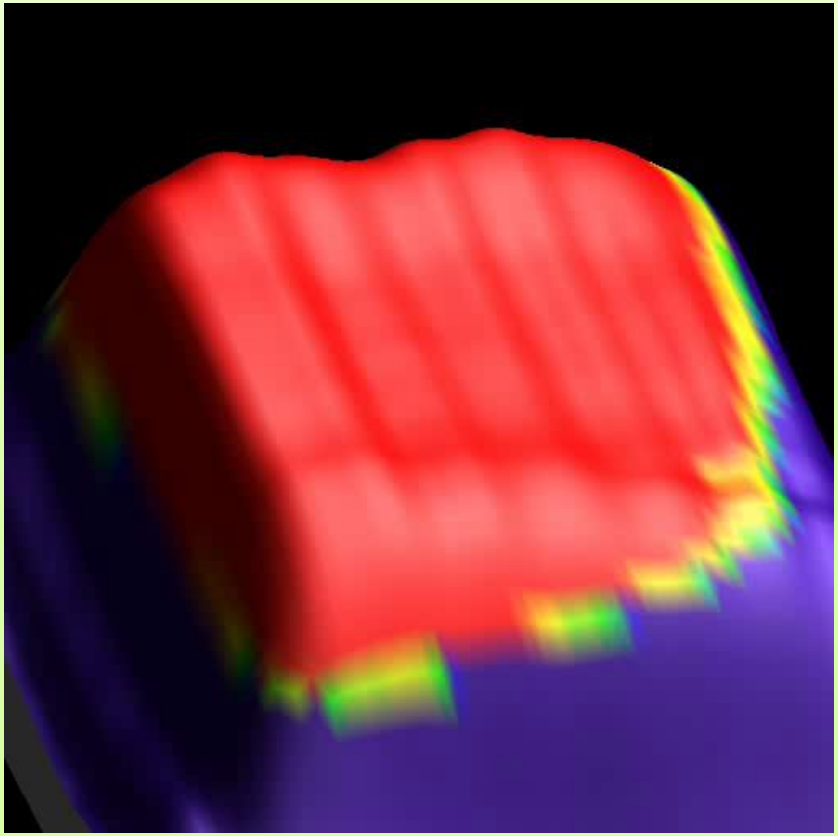
STS maps

from 70 to 300 meV
Island: 12 x 10 nm^2
voltage steps: 6 meV



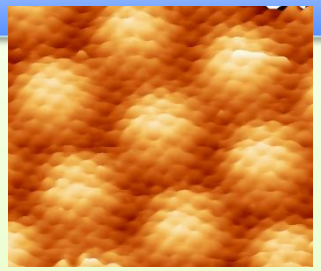
0.1 nA
modulation: 5 meV

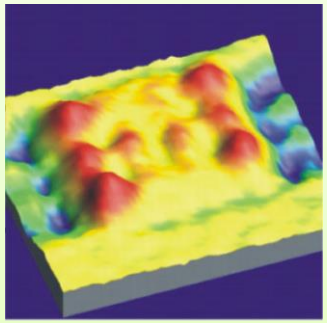
from 83 to 300 meV
Island: 21 x 22 nm^2
voltage steps: 7 meV



0.1 nA
modulation: 7 meV

Outline





1) STM, STS, IETS, and manipulation

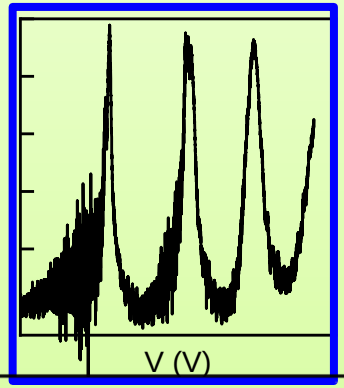
   An extended introduction

2) Quantum effects on surface imaged by STM

   Electron in a box I

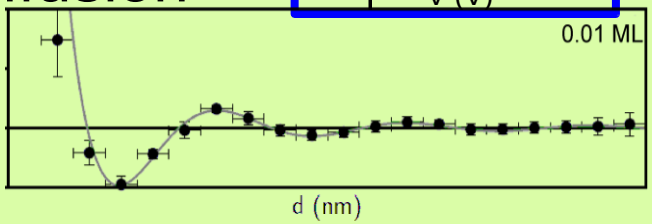
3) Quantum effects on surfaces measured by STS

   Electron in a box II skip



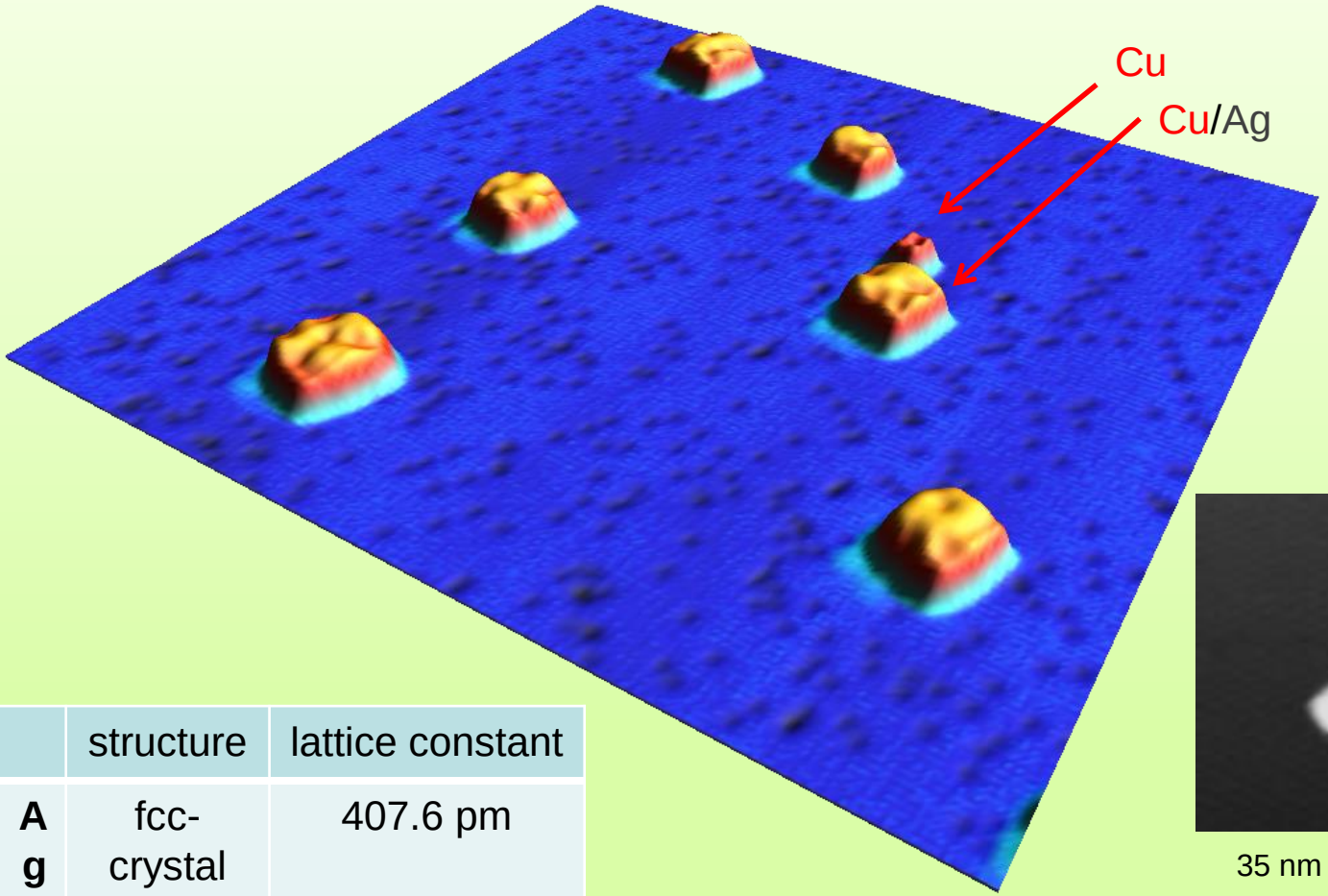
4) Electron interference effects surface diffusion

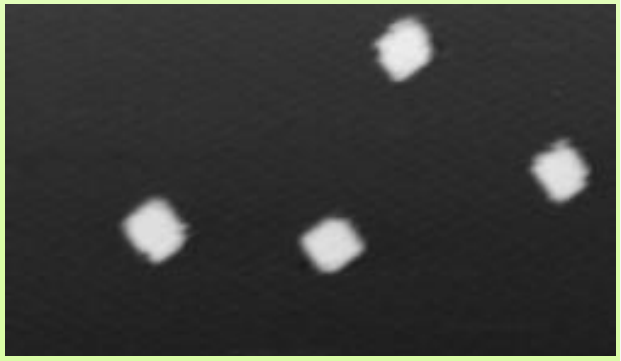
   Influence of Friedel oscillations on diffusivity



Grain size stability of a complex surface: Cu on Ag(100)

PRL 107, 046101 (2011)
PRB 90, 165418 (2014)
PRB 92, 045422 (2015)





35 nm x 21 nm, 0.79 nA, 0.61 V, 300 K

	structure	lattice constant
Ag	fcc-crystal	407.6 pm
Cu	fcc-crystal	361.5 pm

13% lattice mismatch

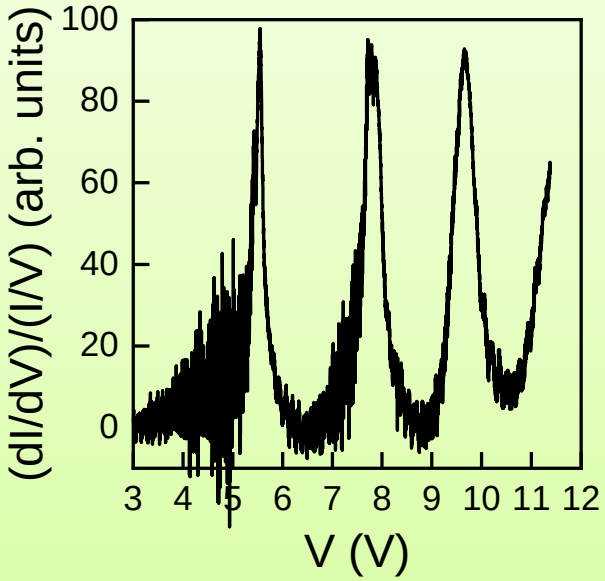
- large strain
- quadratic islands of monatomic height

Image potential states

Cu/Ag(100)

Phys. Rev. B 90, 165418 (2014)

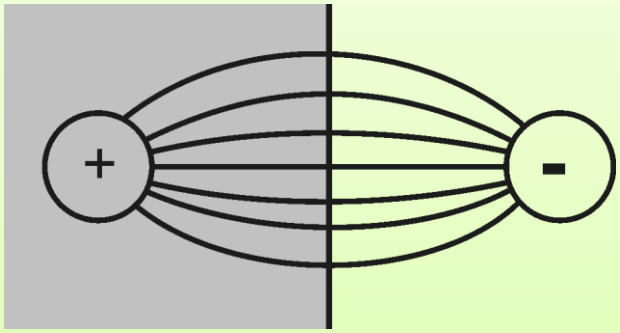
dI/dV with z increase



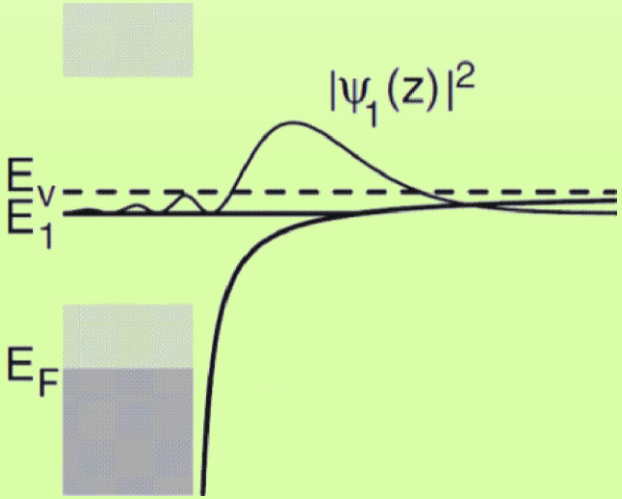
n=1 n=2 n=3

$$E_n = E_V - \frac{13.6eV}{[4(n+a)]^2}$$

Image potential



metal vacuum



see: P.M. Enchenique, e.g. Chem. Rev. 106, 4160 (2006)

sketch from Crampin PRL 95 046801 (2005)

Image potential states

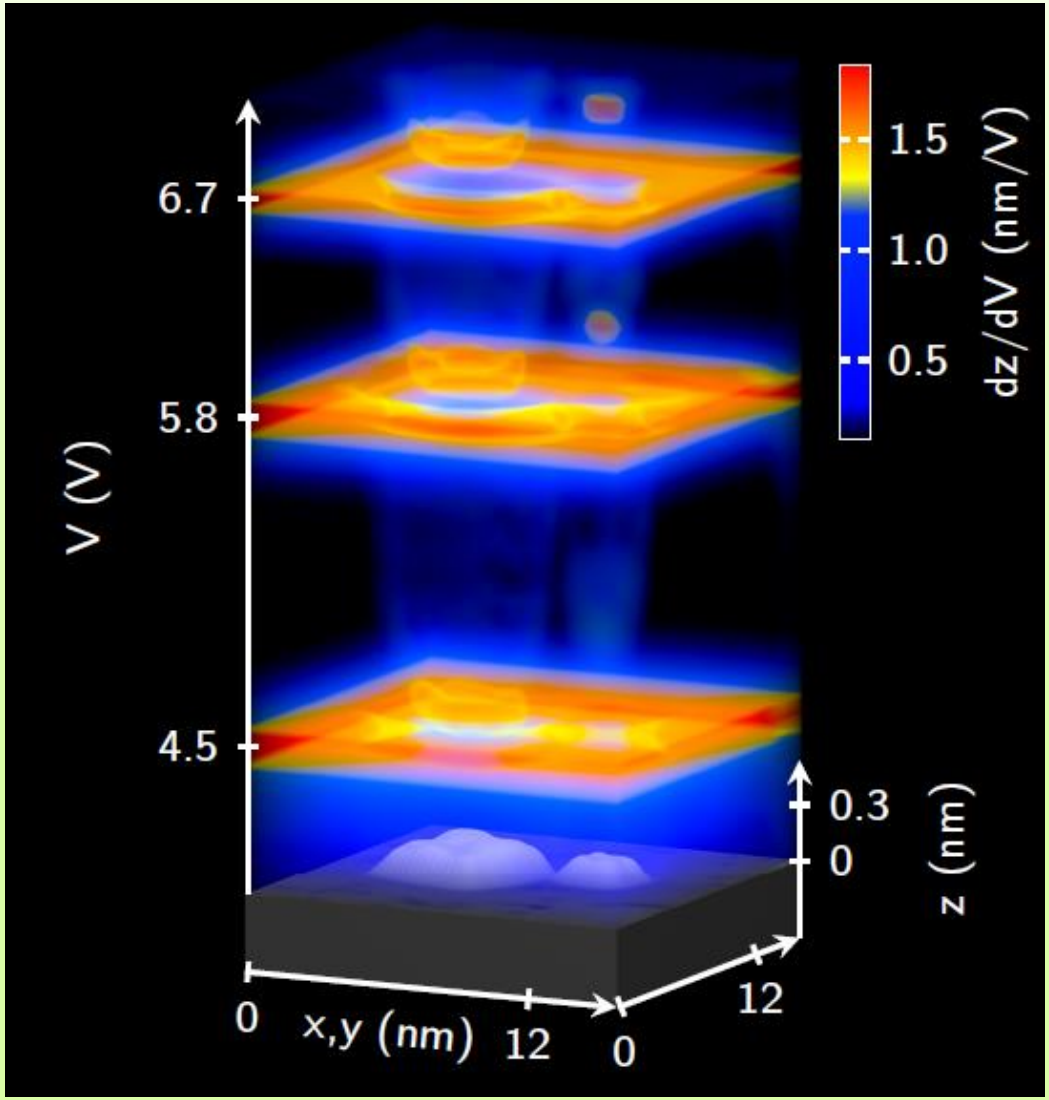
Phys. Rev. B 90, 165418 (2014)

n=3

n=2

n=1

STM

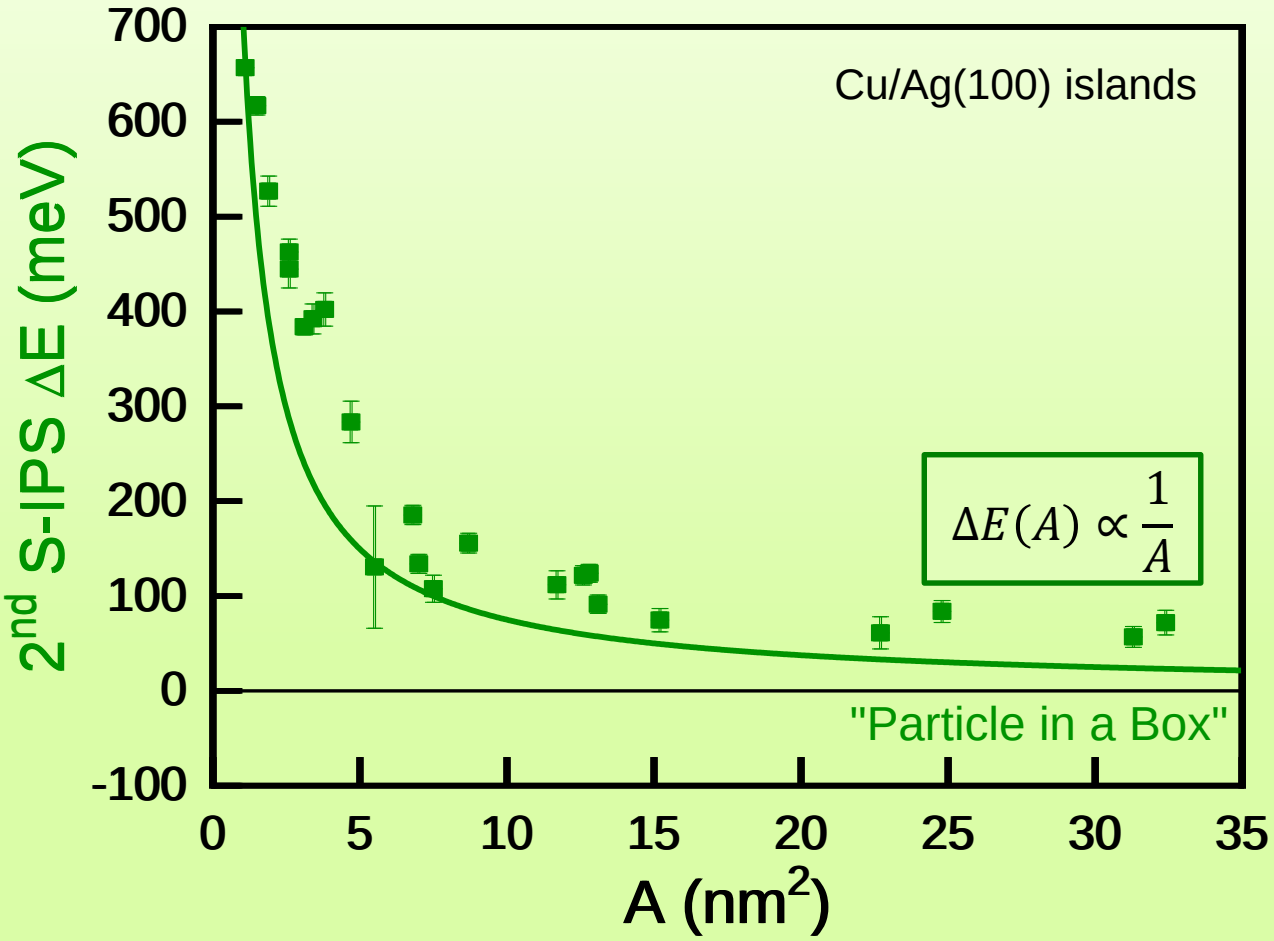


Cu/Ag(100) islands

Cu/Ag Cu

Image potential states

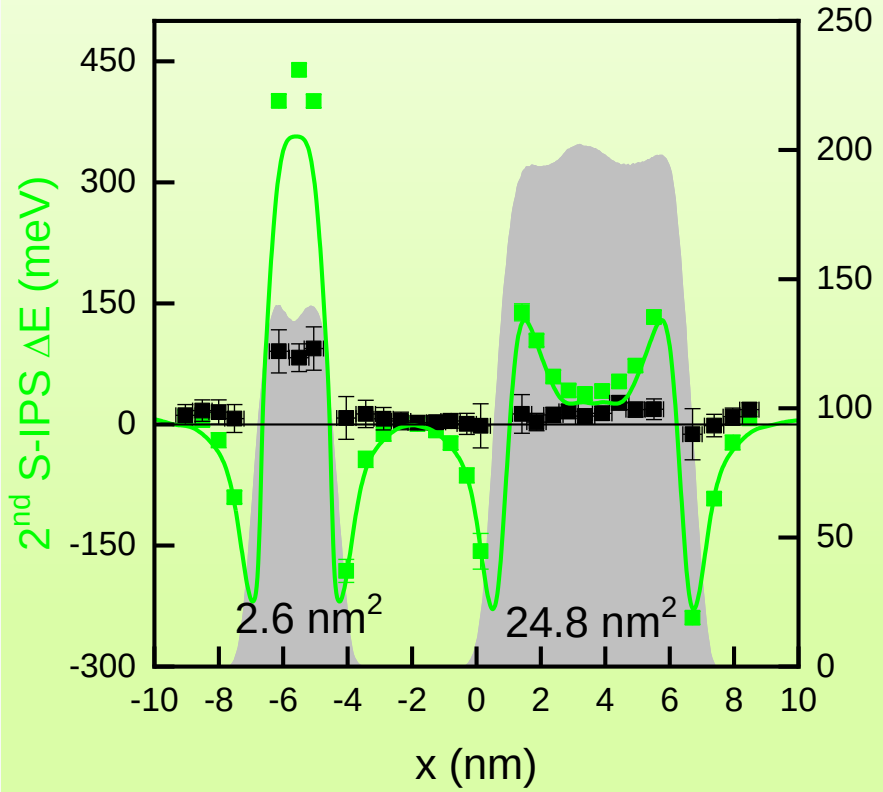
Phys. Rev. B 90, 165418 (2014)



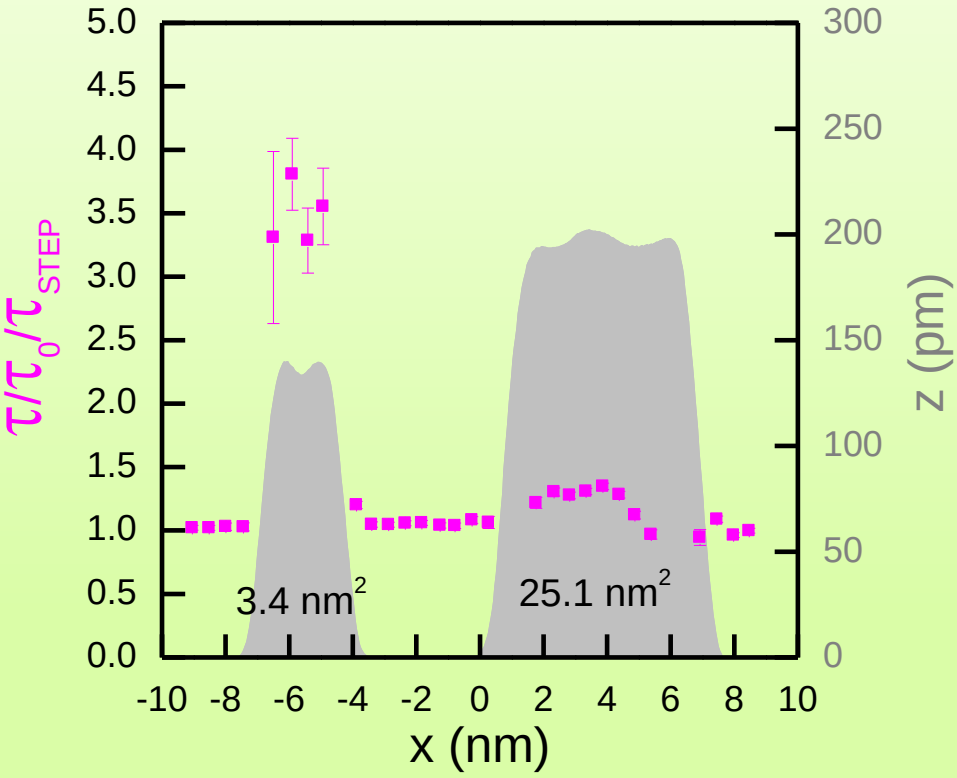
Local dependence of image potential states

Phys. Rev. B 90, 165418 (2014)

Energy shift



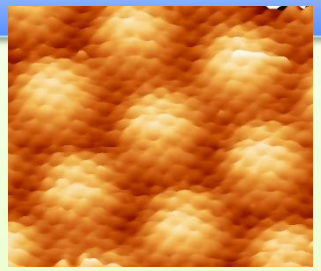
Change in life time

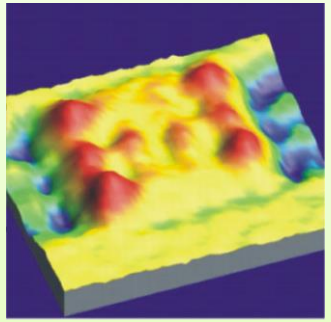


⇨quantum interference effect at step edge

⇨ size-dependent lifetime of electrons in image potential states

Outline



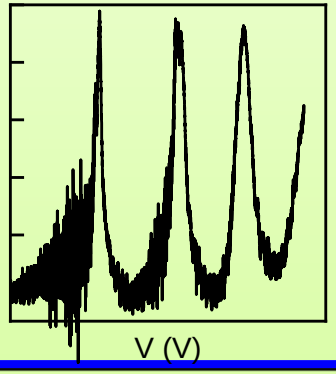


1) STM, STS, IETS, and manipulation

   An extended introduction

2) Quantum effects on surface imaged by STM

   Electron in a box I

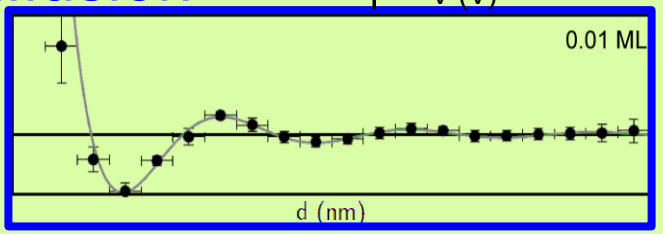


3) Quantum effects on surfaces measured by STS

   Electron in a box II

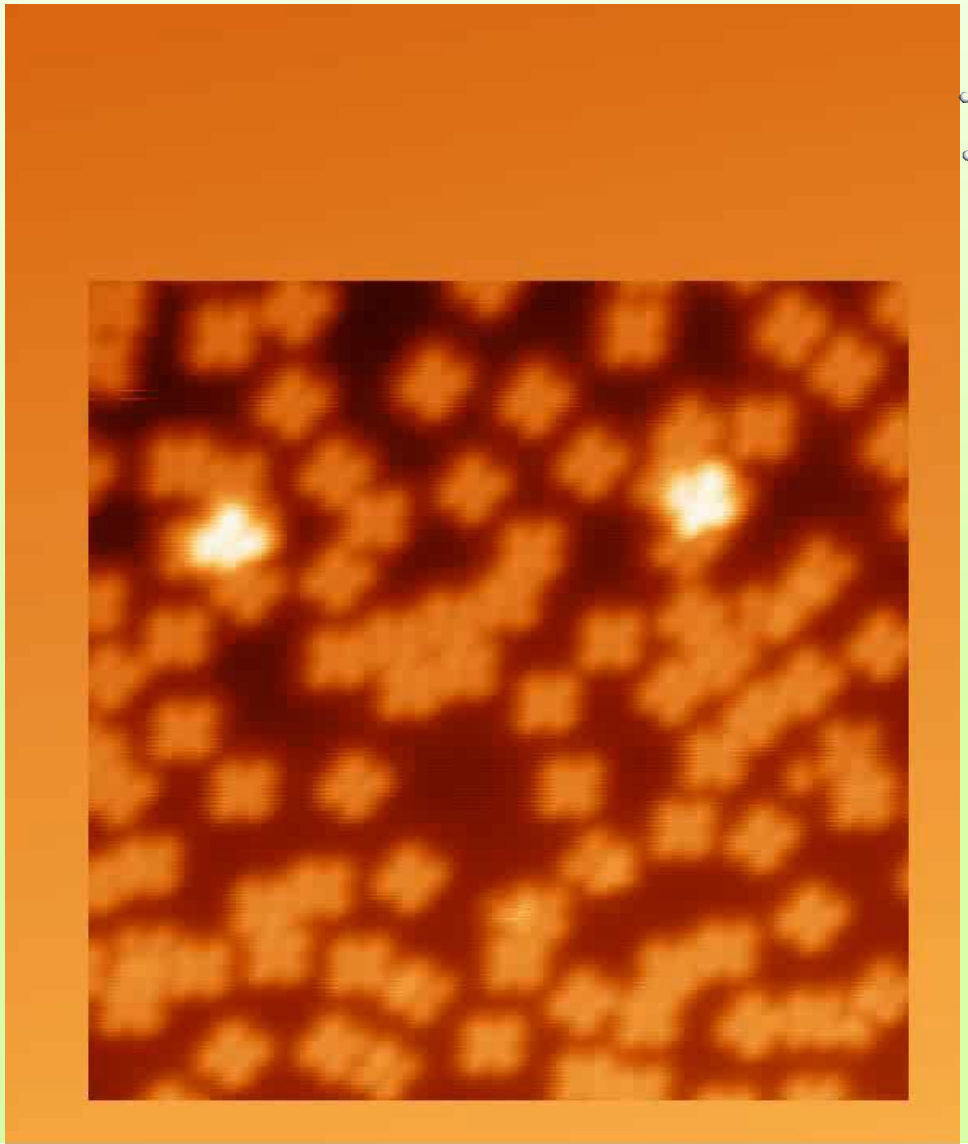
4) Electron interference effects surface diffusion

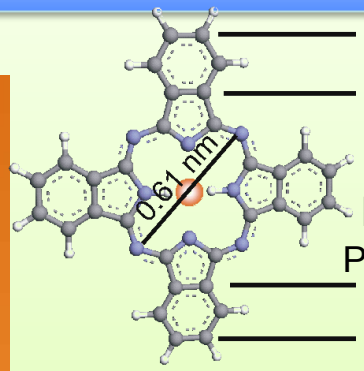
   Influence of Friedel oscillations on diffusivity skip



Diffusion of molecules on surfaces

Phtalocyanine / Ag(100)





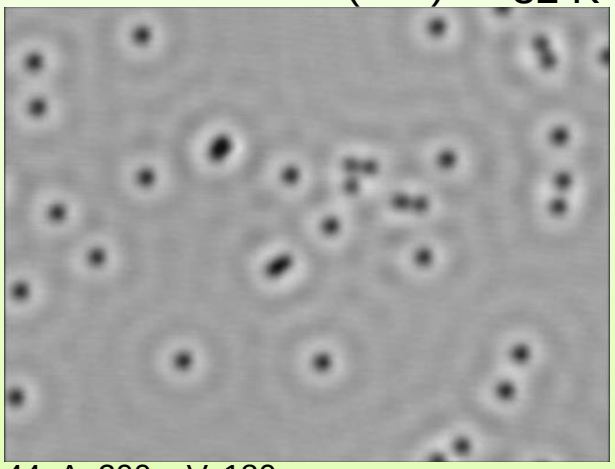
T = 75 K
Δt = 135 s
V = 289 mV
I = 51 pA

Diffusion studies (KM et al.):

Phys. Stat. Sol. B 242, 773 (2005)
Nano Lett. 23, 4793 (2023)
Angew. Chem. Int. Ed. 61 (2022) e202212245
Nano Lett. 22, 340 (2022)
Nano Lett. 19, 710 (2019)
Nano Lett. 16, 3001 (2016)
J. Phys. Chem. Lett. 6, 4165 (2015)
J. Am. Chem. Soc. 137, 14920 (2015)
ACS Nano 9, 3572 (2015)
Phys. Rev. Lett. 114, 146104 (2015)
Phys. Rev. Lett. 107, 046101 (2011)
Phys. Rev. Lett. 104, 076101 (2010)
Phys. Rev. Lett. 100, 116104 (2008)
Phys. Rev. Lett. 94, 166104 (2005)
Phys. Rev. Lett. 93, 056102 (2004)
Phys. Rev. Lett. 86, 5739 (2001)
Phys. Rev. Lett. 83, 1613 (1999)
Phys. Rev. Lett. 80, 556 (1998)
Phys. Rev. Lett. 76, 2113 (1996)
Phys. Rev. Lett. 74, 2058 (1995)

Diffusion of molecules on surfaces

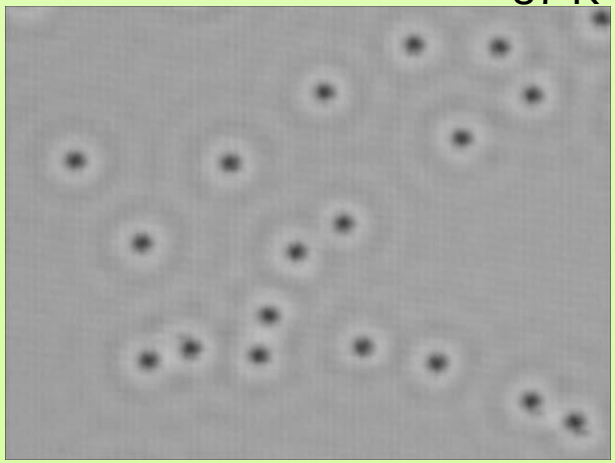
CO / Cu(111) 32 K



44pA, 200 mV, 180 s

5 nm

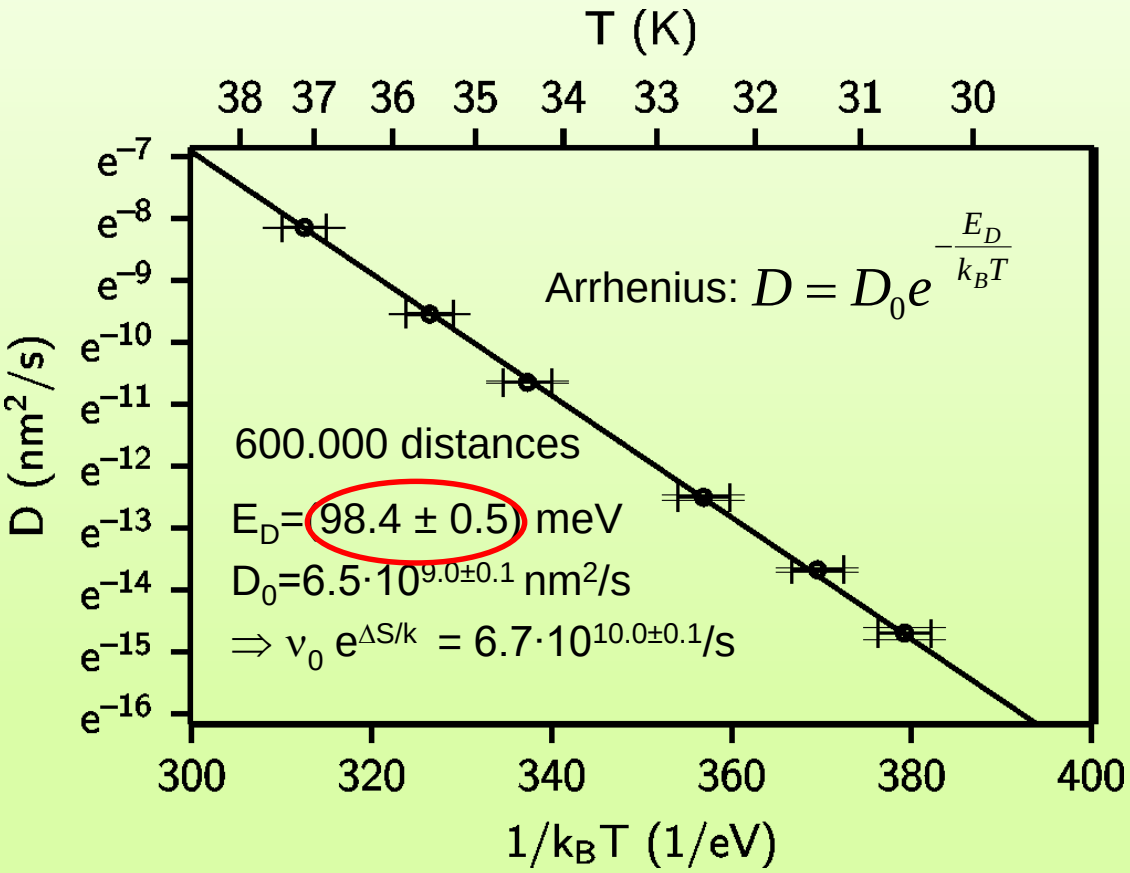
37 K



44pA, 200 mV, 180 s

5 nm

Phys. Rev. Lett.114, 146104 (2015)

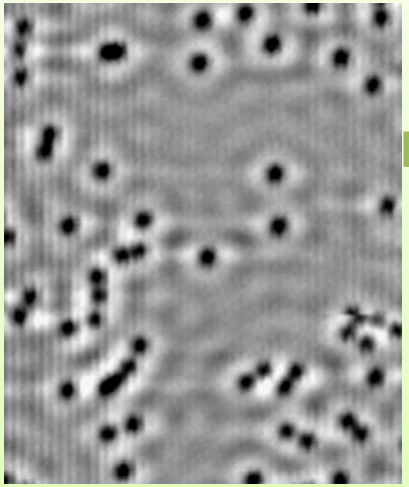


Helium-Spin Echo spectroscopy:

E_D = (98 ± 5) meV

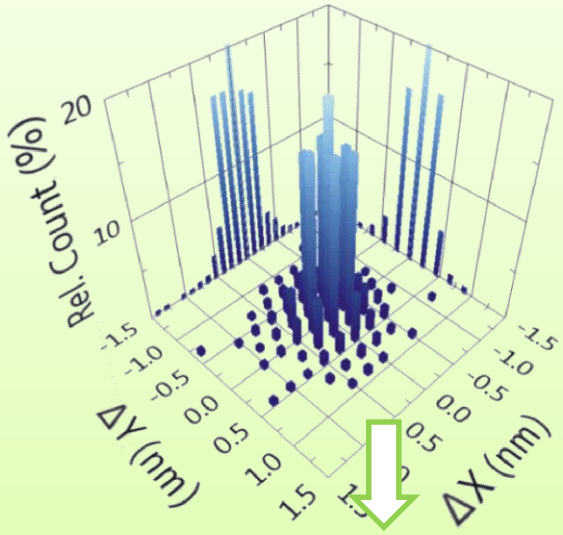
P. R. Kole et al., J. Phys. Condens. Matter 24, 104016 (2012).

Influence of neighbors on diffusion



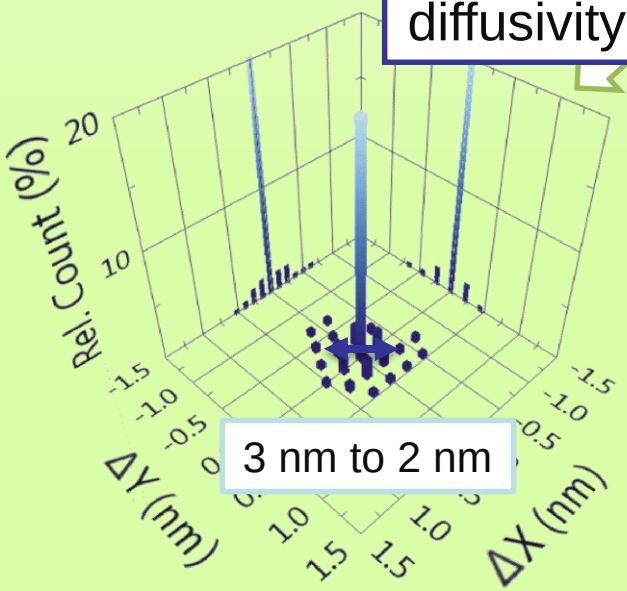
16 nm x 13 nm, 50pA, 230mV
Δt = 140 s

T = 42 K

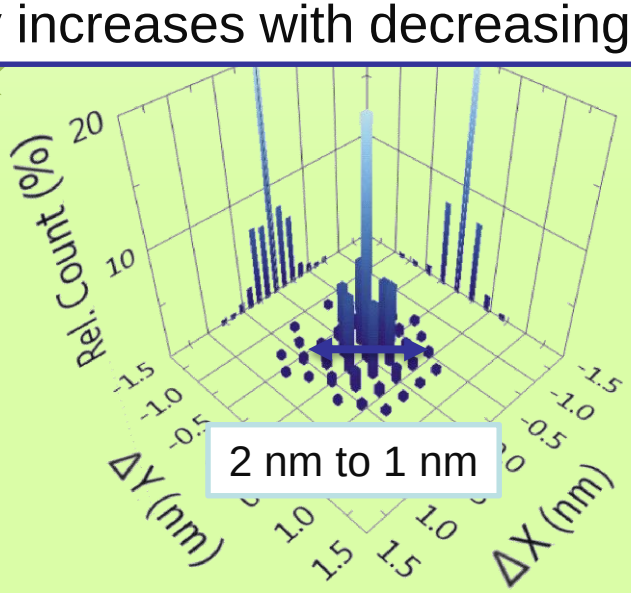


Phys. Rev. Lett.114, 146104 (2015)
CO / Cu(111)

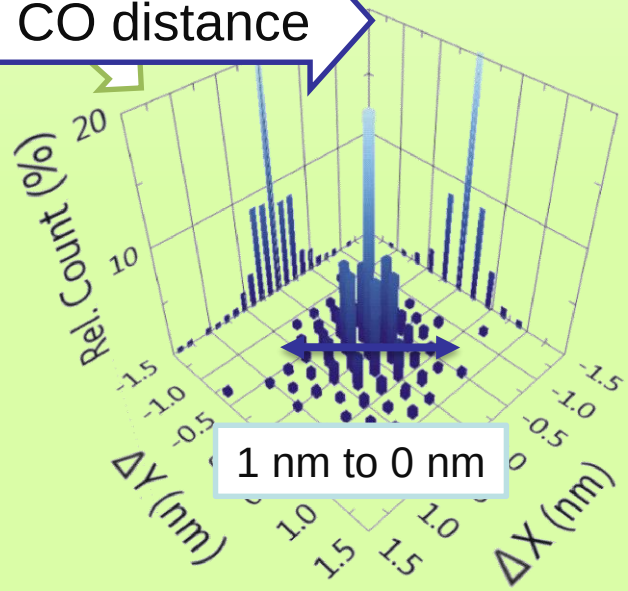
diffusivity increases with decreasing CO distance



3 nm to 2 nm



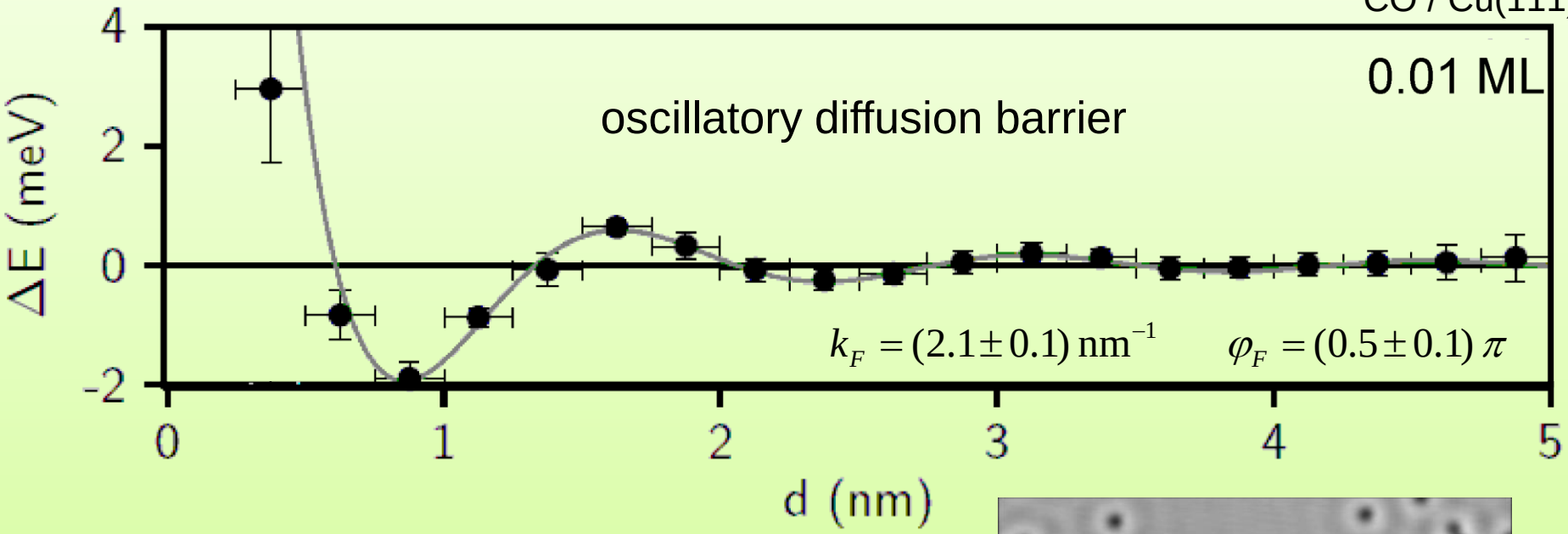
2 nm to 1 nm



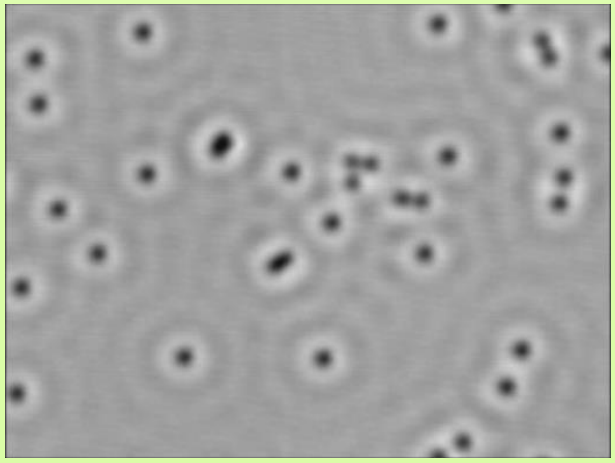
1 nm to 0 nm

Diffusion of CO on Cu(111)

Phys. Rev. Lett.114, 146104 (2015)
CO / Cu(111)



$$\Delta E(R) = -\alpha \cdot \frac{\sin(2k_F R + 2\phi)}{(k_F R)^2}$$



⇨ Friedel oscillations in diffusivity
⇨ long-range interaction mediated by surface state electrons

Thanks to

Experiments:
Grazyna Antzcak
Yunjun Cao
Heiko Gawronski
Sarah Heidorn
Jörg Henzl
Ting-Chieh Hung
Karsten Lucht
Michael Mehlhorn
Violeta Simic-Vilosevic
Kai Volgmann
Christopher Zaum

Theory:
Javier Carrasco, Angelos Michaelides, UCL, UK
Galina Rusina, Svetlana Borisova, Tomsk, Russia
Evgueni Chulkov, San Sebastian
Joel Mieres-Perez, Elsa Sanchez-Garcia, UDE, TUD, D
Dave Austin, Eric Switzer, Talat Raman, UCF, USA

Molecules:
Julien Rowen, Wolfram Sander, R.U.B., D

cost
EUROPEAN COOPERATION IN SCIENCE & TECHNOLOGY

GIF

VolkswagenStiftung

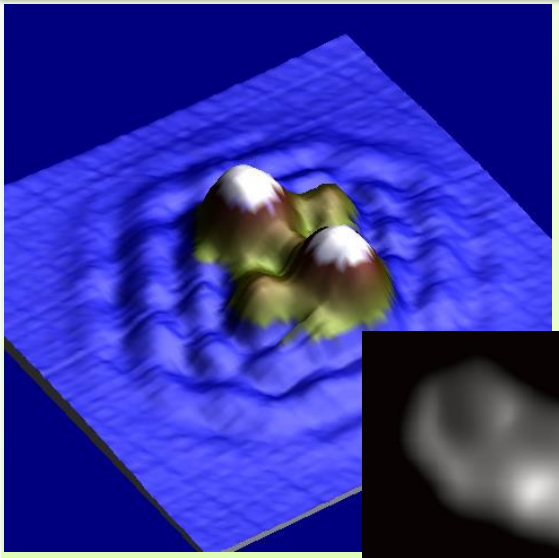
RESOLV
RUHR EXPLORES SOLVATION
CLUSTER OF EXCELLENCE - EXC 2033

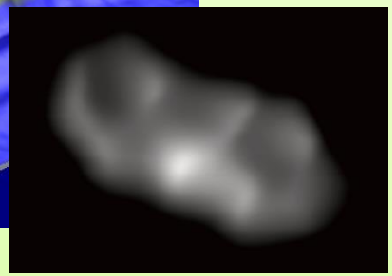
GRK 2376

DFG
Deutsche Forschungsgemeinschaft

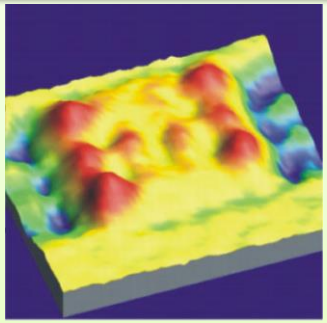
FP-RESOMUS
a Fellowship Program of the NCCR MUST and the Cluster of Excellence - RESOLV

Summary

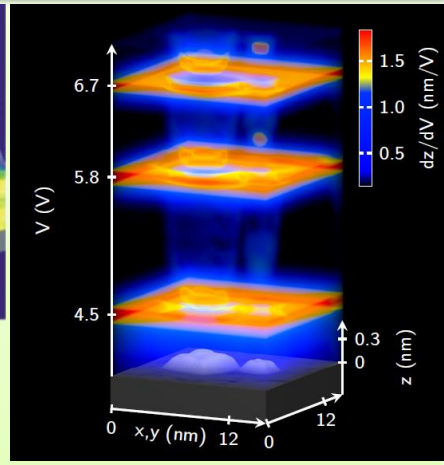




STM images present a convolution of topography, electronic density of states, and Pauli repulsion

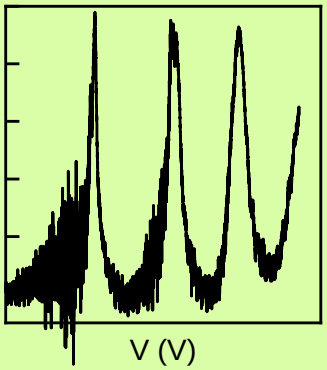


Particles in a box

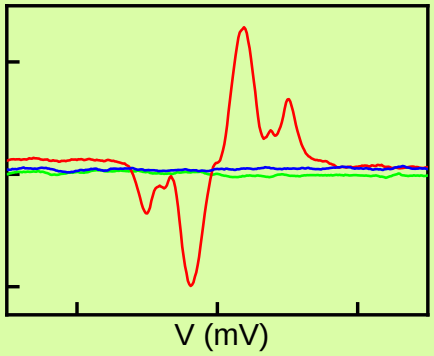


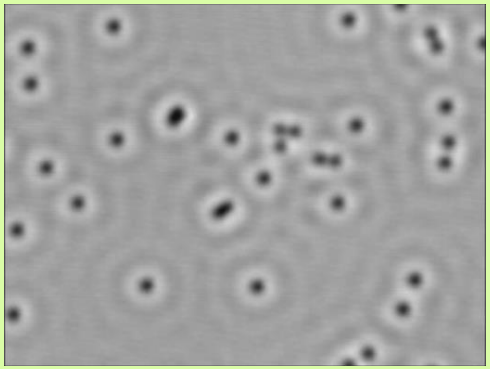
⇨ fascinating view of the nanoworld by quantum mechanics based STM

STS measures electronic states



IETS measures phonons and vibrations





Friedel-like oscillations influence surface processes