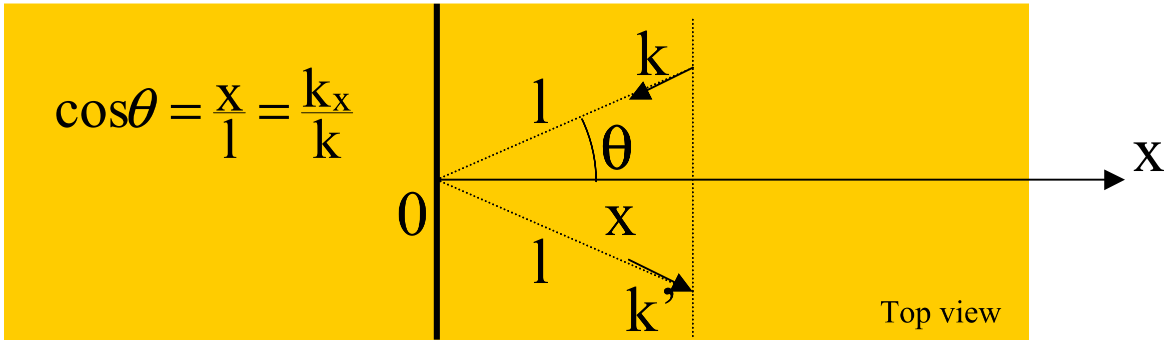
3.8 Quantum interferences – finite lifetime model

Inelastic processes **<u>on the terrace</u>** ⇨ e-e scattering, e-ph scattering



$$\psi_k(x,y) = \left(e^{ik_x x} + e^{\frac{-2x}{L_\varphi}\frac{k}{k_x}}\, r(k_x) e^{i\varphi(k_x)}\, e^{-ik_x x}\right) e^{ik_y y}$$

where L_φ is the phase relaxation length.

Numerical integration of the LDOS expression (*) (see. Transp. 3.5) gives (with $\varphi = -\pi$ and previous remarks) :

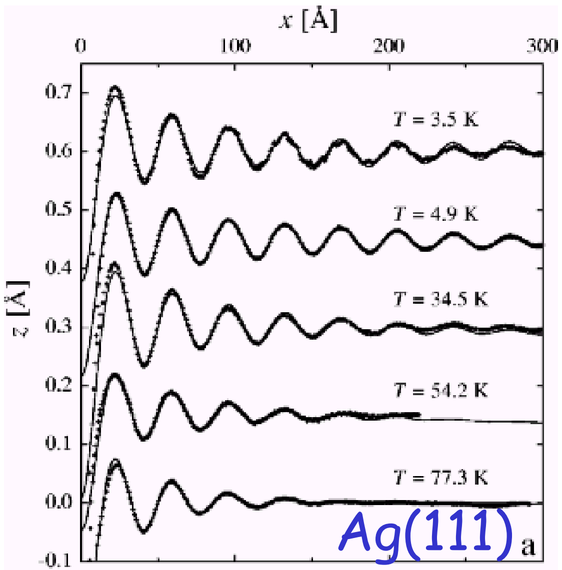
$$\rho(E,x) = L_0\left(1 - r(k)\, e^{-2\frac{x}{L_\varphi}}\, J_0(2kx)\right)$$

Inelastic processes **<u>on the terrace lead to an additional decay of the LDOS modulation !!!</u>**

From dI/dV images, $L_\varphi(E)$ and k(E) are extracted.
It is thus possible to get the lifetime of a quasiparticle (hole or electron), using the relation :

$$\tau(E) = \frac{L_\varphi}{v} = \frac{L_\varphi m^*}{k}$$

Electron – phonon interaction



Constant current z(x) line scans

Damping of the standing waves with increasing T

2. Main effect : Fermi Dirac broadening at high T

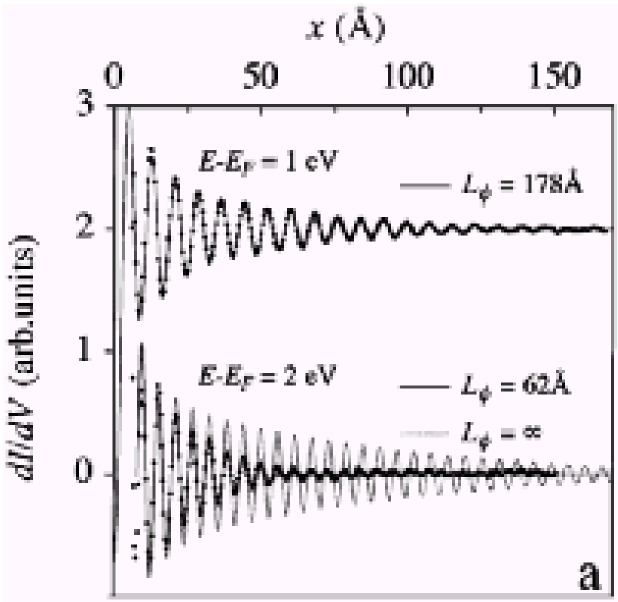
	3.5 K	77 K	178 K
Ag (111)	600	250	
Cu(111)		660	160

Lower limit for L_φ (Å)

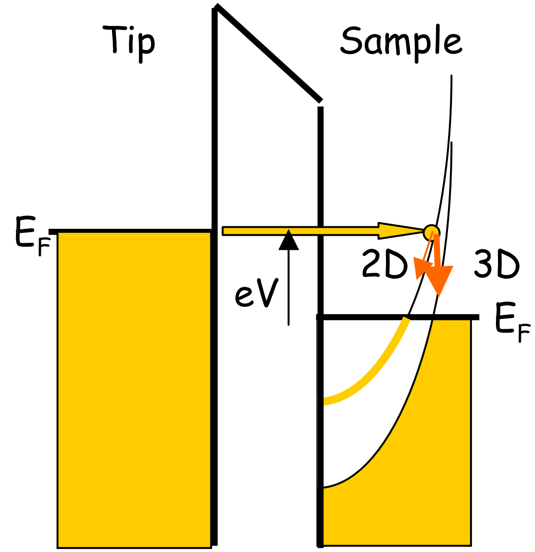
(For Cu k_F is much bigger than for Ag, thus Fermi-Dirac broadening is weak.)

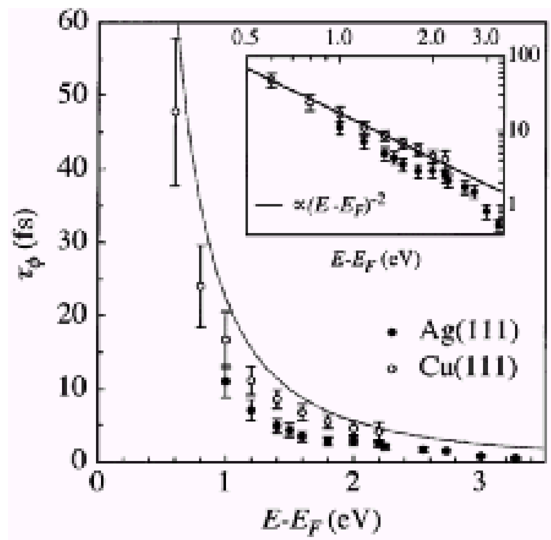
O. Jeandupeux, L. Bürgi, A. Hirstein, H. Brune and K. Kern, Phys. Rev. Lett 82, 4516 (1999)

Electron lifetime measurements



Cu(111), T = 4.9 K

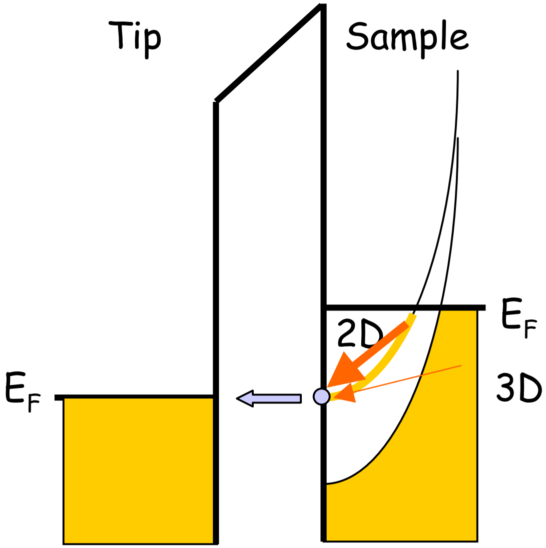


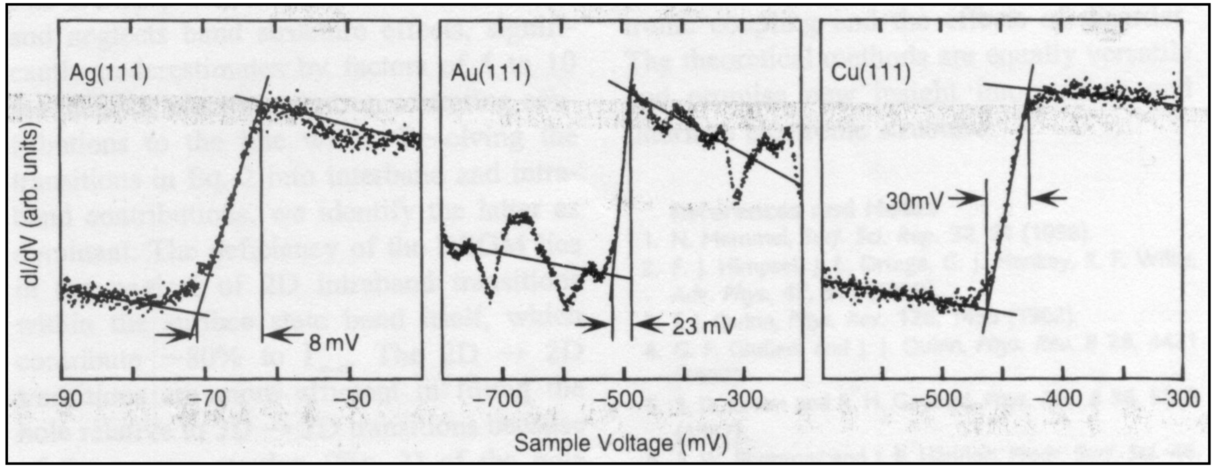


τ_φ has a $(E-E_F)^{-2}$ behaviour, which is predicted for a 3D free electron gas in the Fermi liquid theory

L. Bürgi, O. Jeandupeux, H. Brune and K. Kern, Phys. Rev. Lett 82, 4516 (1999)

Hole life-time measurements at the band edge of different surface states





The width of the onset is directly related to the lifetime of holes at the band edge:

$$\tau = \beta \frac{h}{4\Delta}$$

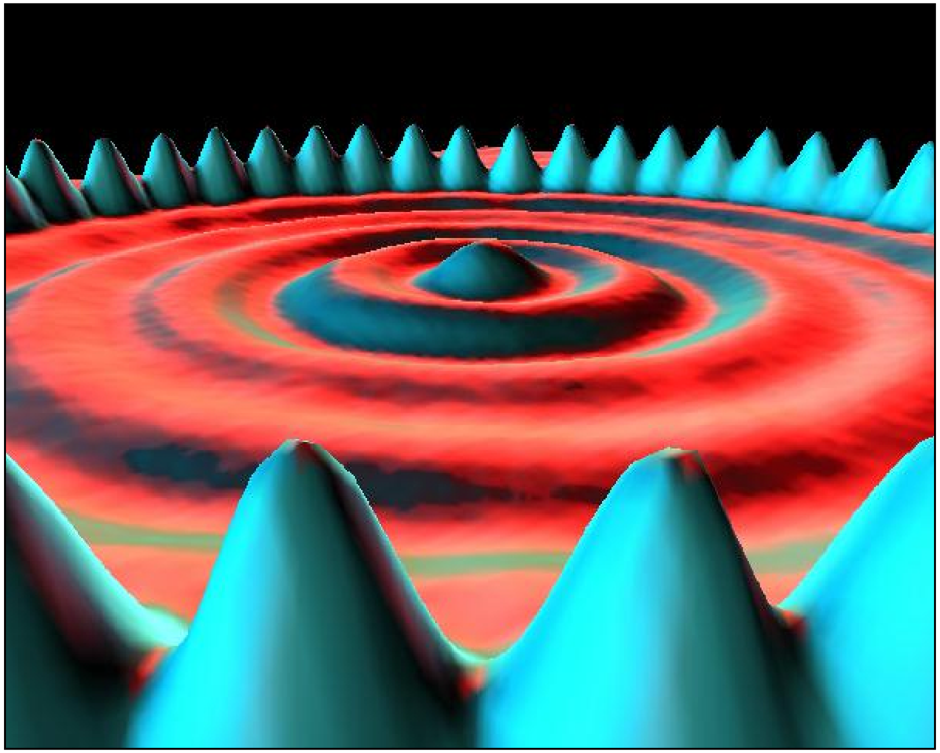
2D decay channels dominate the electron-electron interaction that contributes to the hole decay

J. Kliewer, R. Berndt, E.V. Chulkov, V.M. Silkin, P.M. Echenique, S. Crampin, Science ***288****, 1399 (2000)*

4. Quantum resonators

Quantum corrals

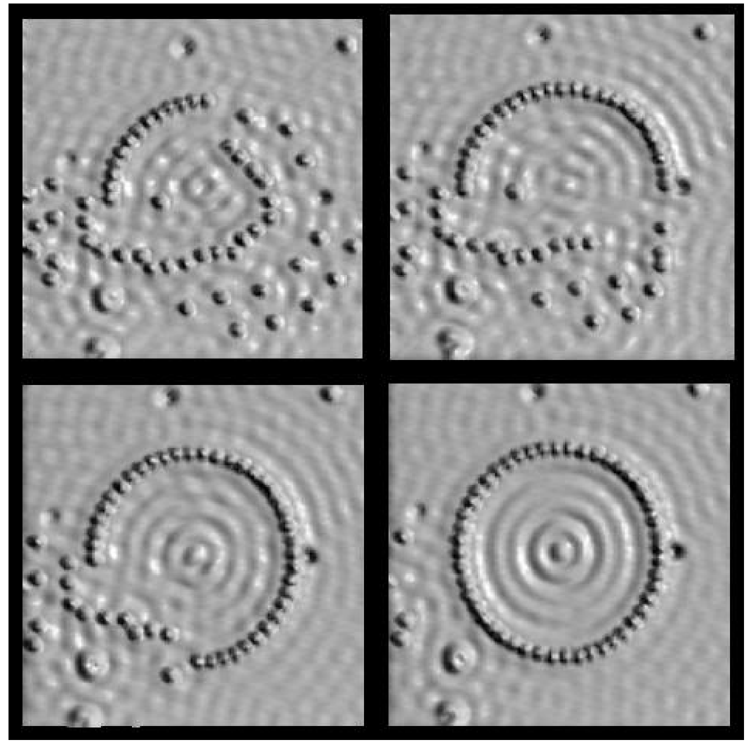
M.F. Crommie, C.P. Lutz, D.M. Eigler



Science, 262 (8 Oct. 93)

Fe/Cu(111)

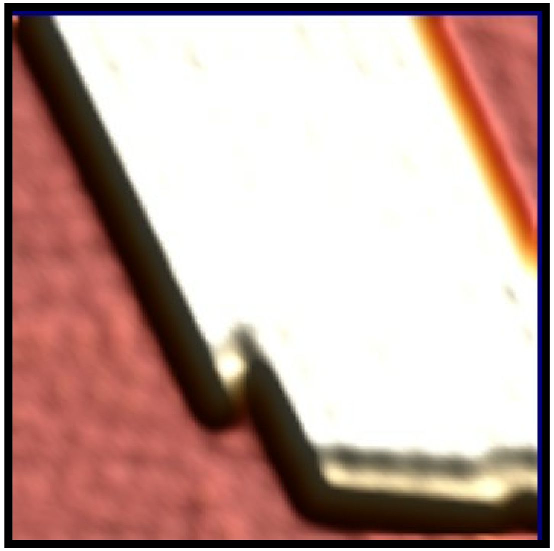
T=5K



Physics Today 46, 17-19 (1993)

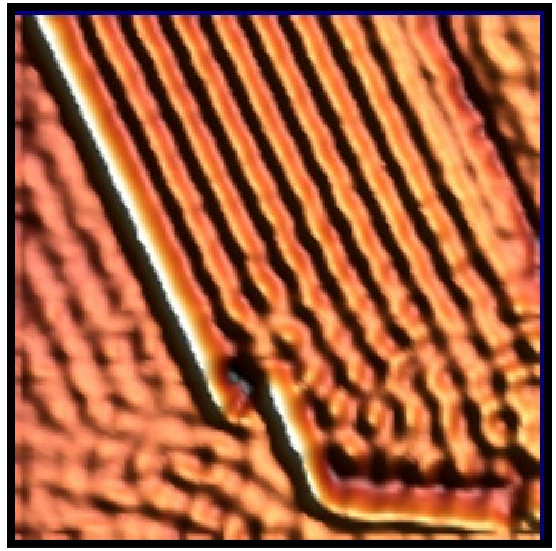
Web adress : http://www.almaden.ibm.com/vis/stm/corral.html

Cu island on Cu(111)



Topography

25x25 nm^2



dI/dV at +10 mV

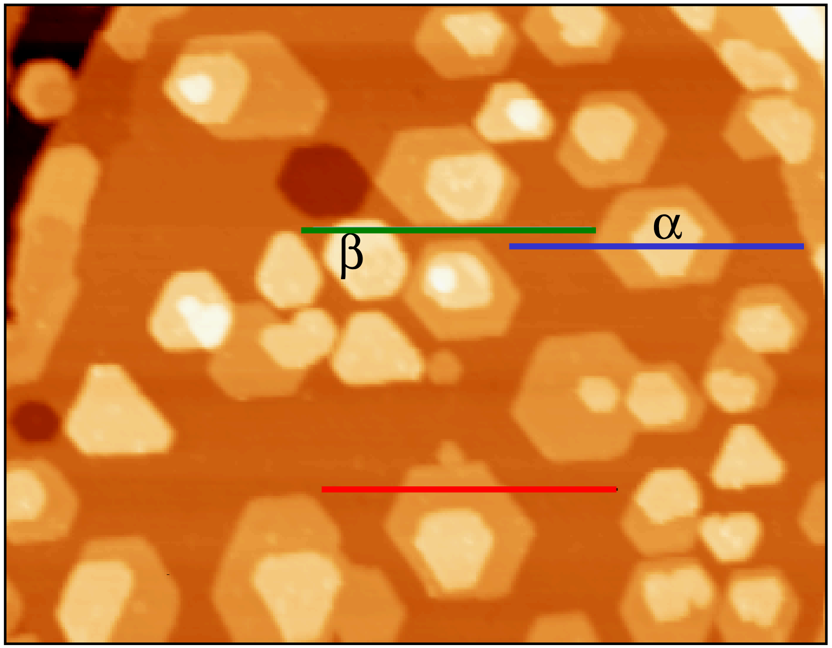
LEPES-CNRS (Grenoble)

Ni / Cu(111)

→ Cu(111) preparation (Ar etching, annealing at 650 K)

→ Room temperature deposition : ~ 0.5 monolayer of Ni

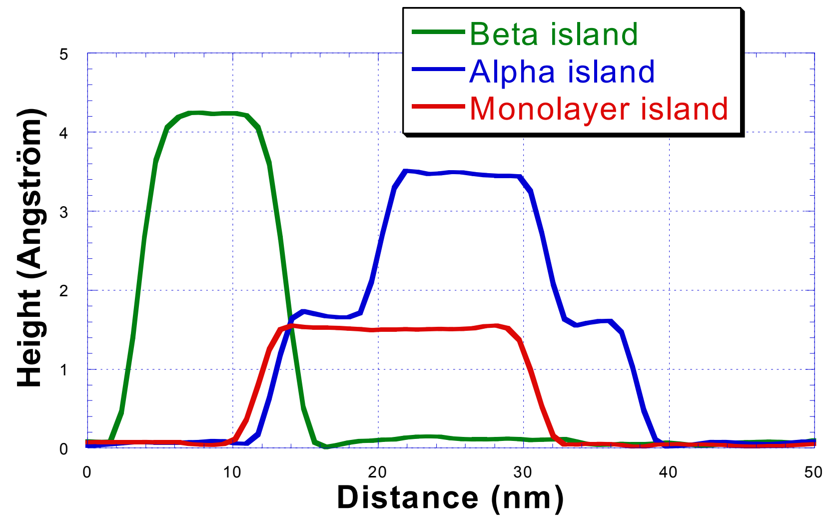
→ Cooling down at 40K, LT-STM study



Constant current STM image taken at 40 K

150 × 125 nm²

V_{sample} =150 mV, I = 1 nA

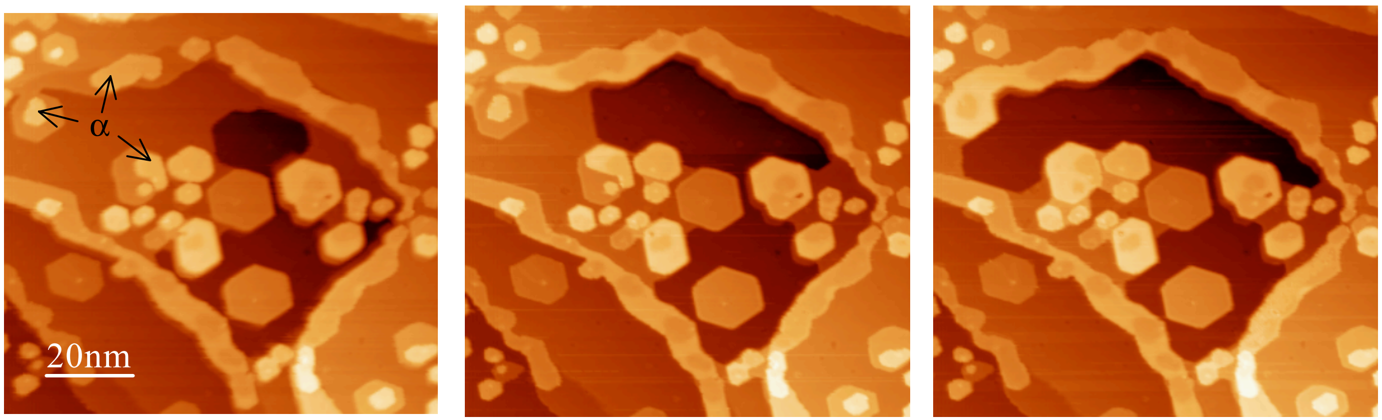


Corresponding height profiles

Two kinds of bilayer islands, with different apparent height

Room temperature STM movie (real duration 1 h)

Images extracted from the movie
(100×100 nm^2)

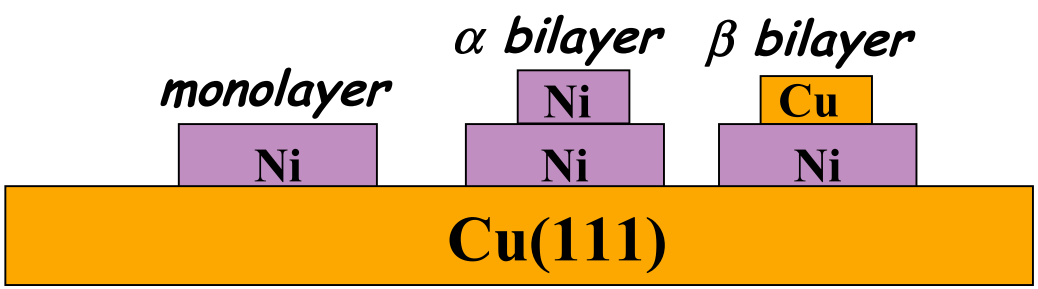


t = 0′   t = 13′   t = 26′

Cu is removed from the substrate to cover some monolayer islands

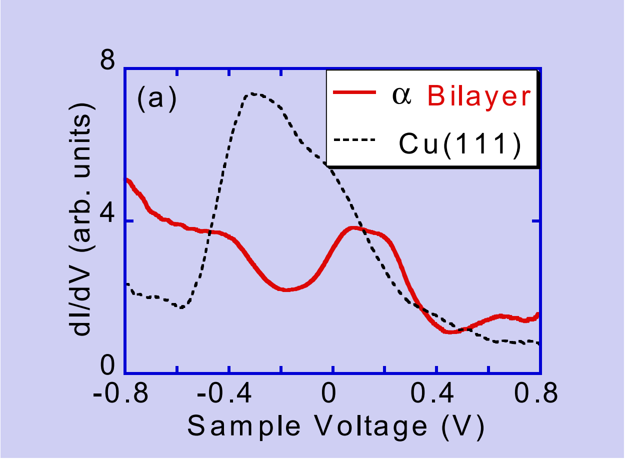
↓

Growth of β islands



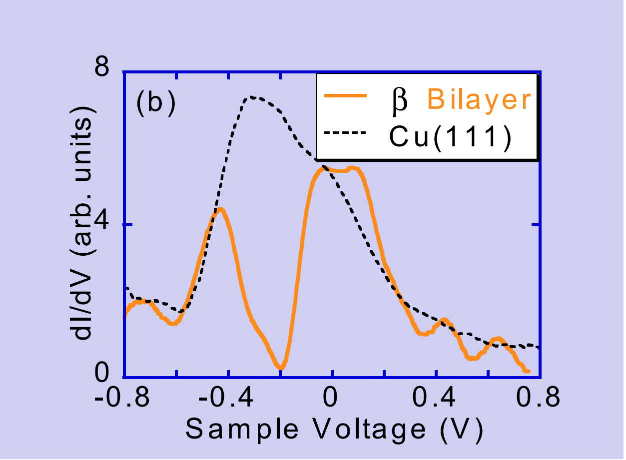
Proposed structure for the islands

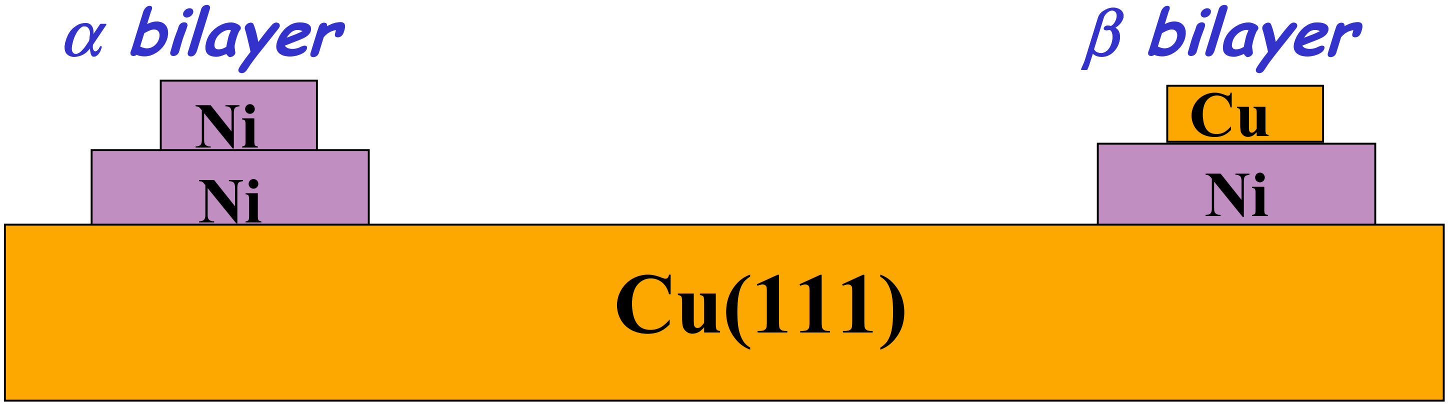
4.5 Quantum resonator – Ni/Cu(111) - STS on bilayer islands



STS

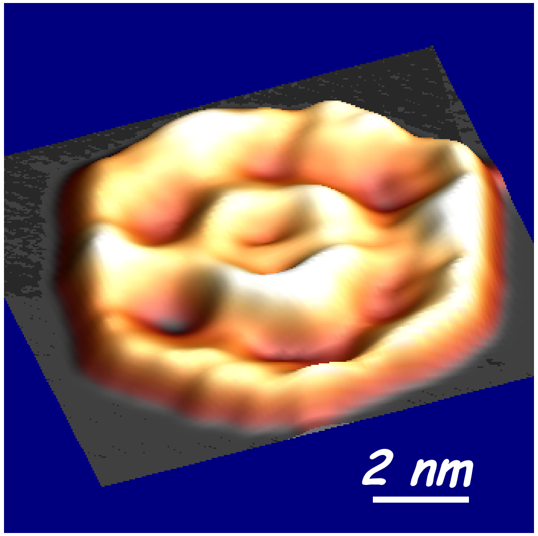
T = 40K





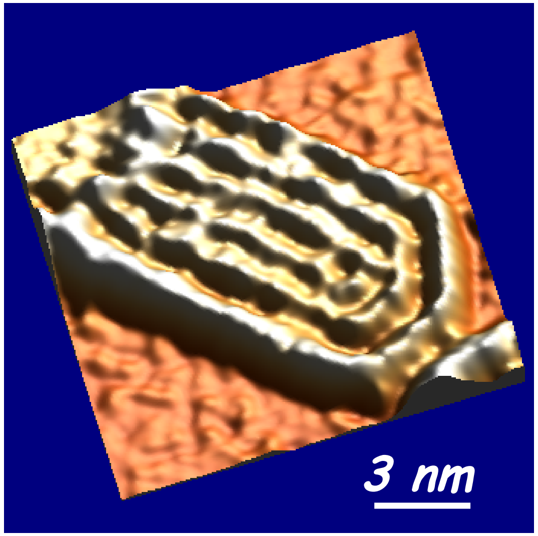
Confinement in both α and β bilayer islands

α Bilayer : Ni/Ni/Cu(111)



dI/dV (+250 mV)
image at 40K

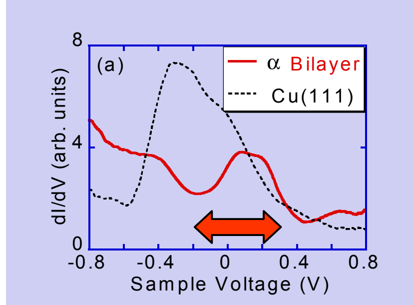
β Bilayer : Cu/Ni/Cu(111)



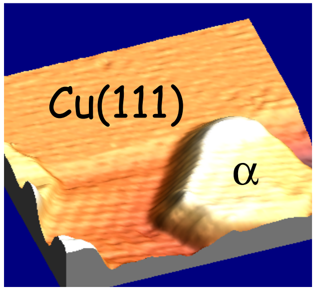
dI/dV (+450 mV)
image at 40K

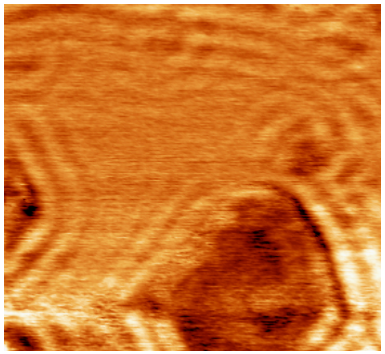
LEPES-CNRS (Grenoble)

Confinement in an Ni bilayer island (α)

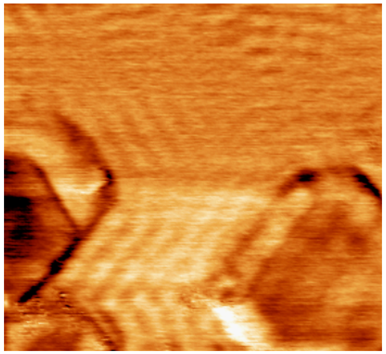


Topography :

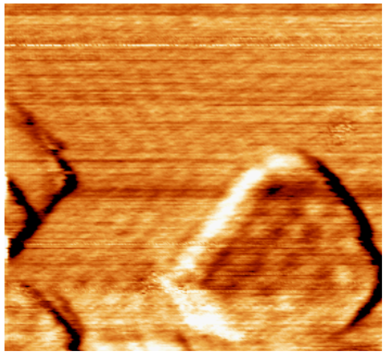




-200 mV



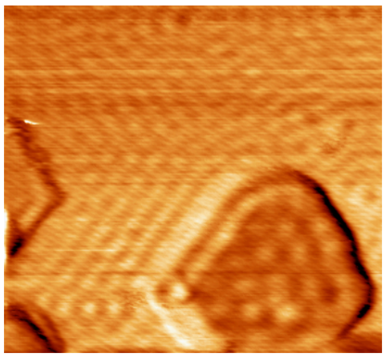
-100 mV



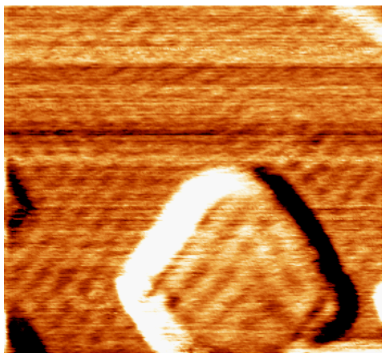
-50 mV

dI/dV images
at 40 K

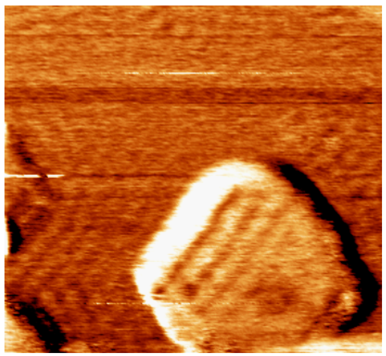
30 x 30 nm^2



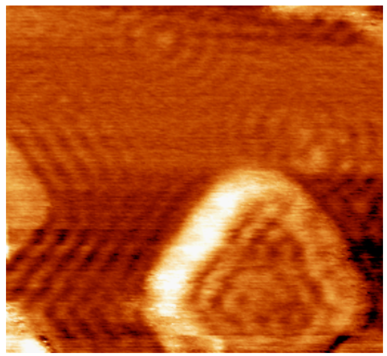
+20 mV



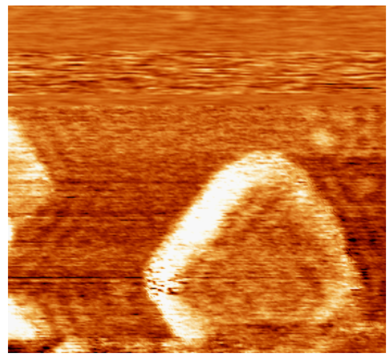
+50 mV



+100 mV

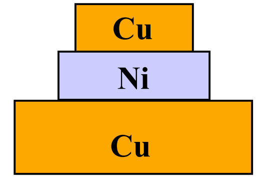


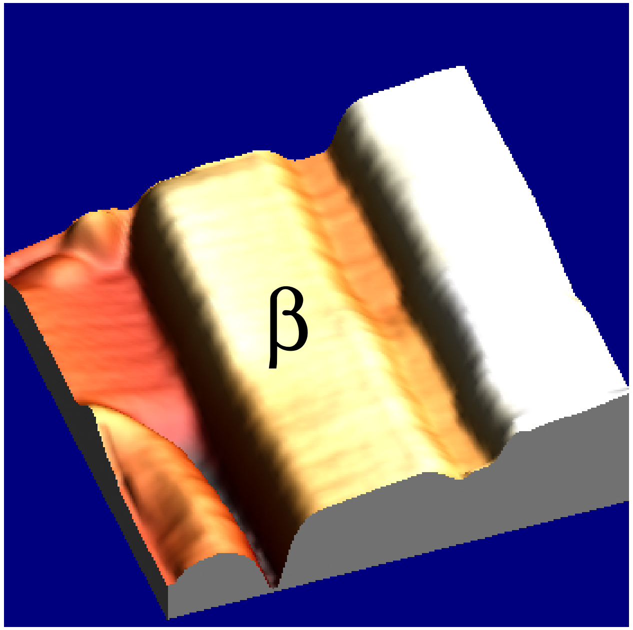
+200 mV



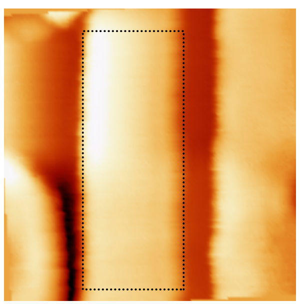
+300 mV

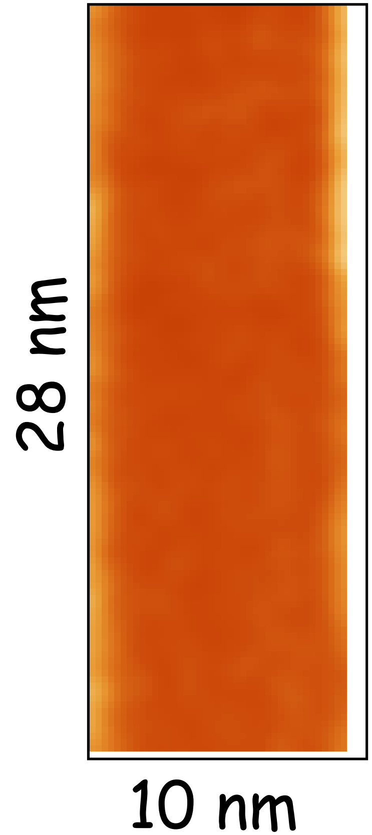
Confinement in a β bilayer island





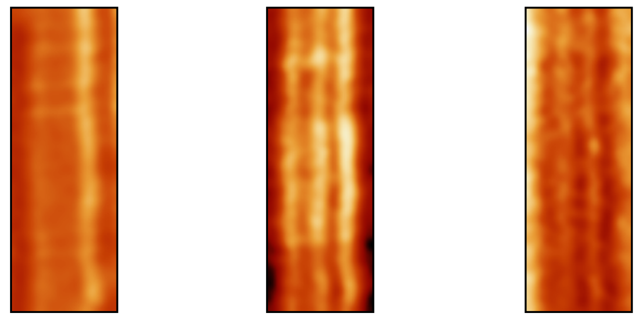
Constant current image
30 x 30 nm^2





← dI/dV (V) movie constructed from a CITS (44 images)

Energy range:
- 300 → + 400 mV

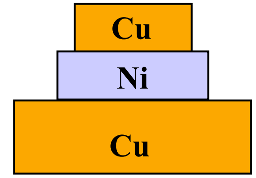


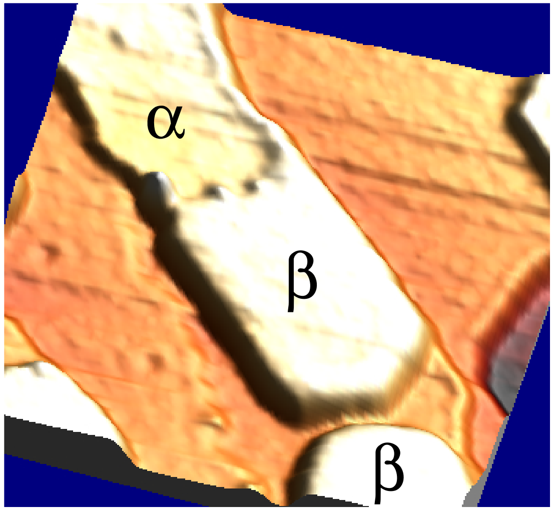
- 40 meV | +80 meV | +290 meV

T = 40 K

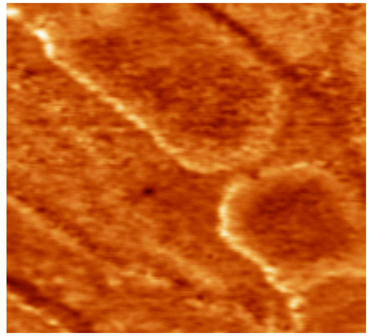
LEPES-CNRS (Grenoble)

Confinement in a β bilayer island

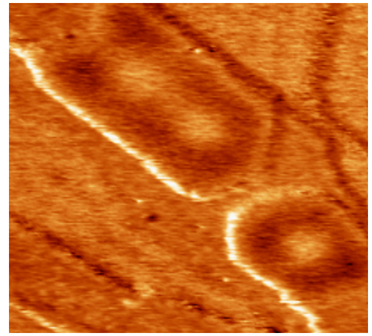




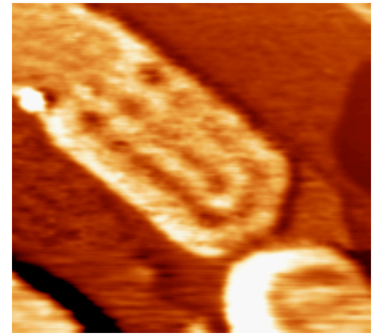
Constant current image
30 x 30 nm^2



-200 mV

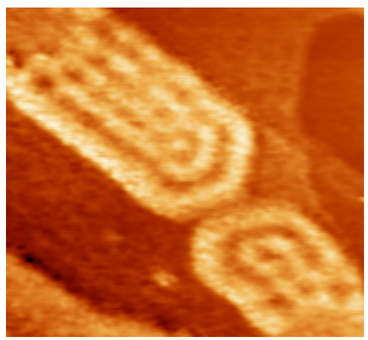


-100 mV

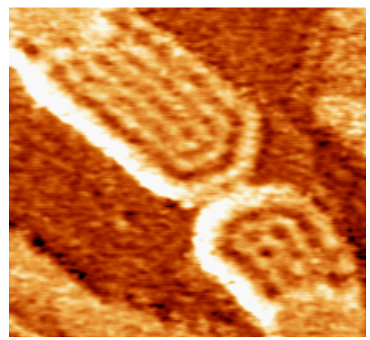


+200 mV

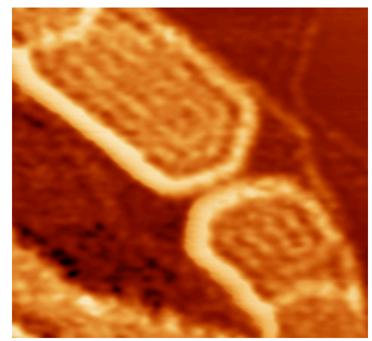
dI/dV images at 40 K
20 x 20 nm^2



+300 mV



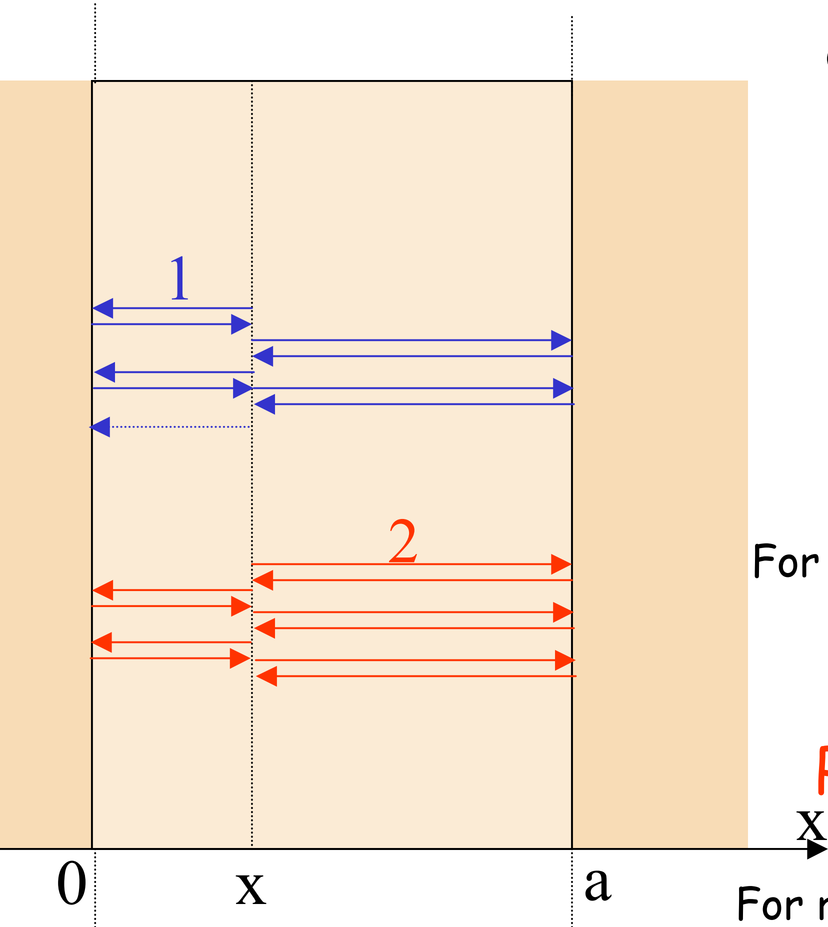
+450 mV



+620 mV

S. Pons, P. Mallet & J.Y. Veuillen, to appear in Phys. Rev. B

Model for 1D confinement in a resonator of width a



- No inelastic processes except at the boundaries !!! ($a < L_\varphi$)
- Steps at x=0 and x=a modelled by coherent reflection ($r(k_x)$,$\varphi(k_x)$)

Process 1 :

$$\psi_{1k}(x) = (e^{ik_x x} + r e^{i\varphi} e^{-ik_x x}) \times (1 + r^2 e^{2i\varphi} e^{2ik_x a} + r^4 e^{4i\varphi} e^{4ik_x a} + \dots)$$

For $r \neq 1$:

$$|\psi_{1k}(x)|^2 = \frac{1 + r^2 + 2r\cos(2k_x x - \varphi)}{1 + r^4 - 2r^2\cos(2k_x a - 2\varphi)}$$

Process 2 :

For $r \neq 1$:

$$|\psi_{2k}(x)|^2 = \frac{1 + r^2 + 2r\cos(2k_x(x-a) + \varphi)}{1 + r^4 - 2r^2\cos(2k_x a - 2\varphi)}$$

Process 1 is not coherent with respect to process 2 incoherent summation : $\rho(k_x,x) = |\psi_{1k}(x)|^2 + |\psi_{2k}(x)|^2$

$$\rho(k_x,x) = \frac{(1+r^2+2r\cos(2k_x x-\varphi))+(1+r^2+2r\cos(2k_x x-\varphi))}{1+r^4-2r^2\cos(2k_x a-2\varphi)} = \frac{N}{D}$$

N : term of interferences due to single scattering at x=0 and x=a

D : broadening term due to multiple scattering in the resonator

$\frac{1}{D}$ is maximum when $\cos(2k_x a - 2\varphi) = +1$ <==> $2k_n a = 2n\pi + 2\varphi$

Stationary phase condition

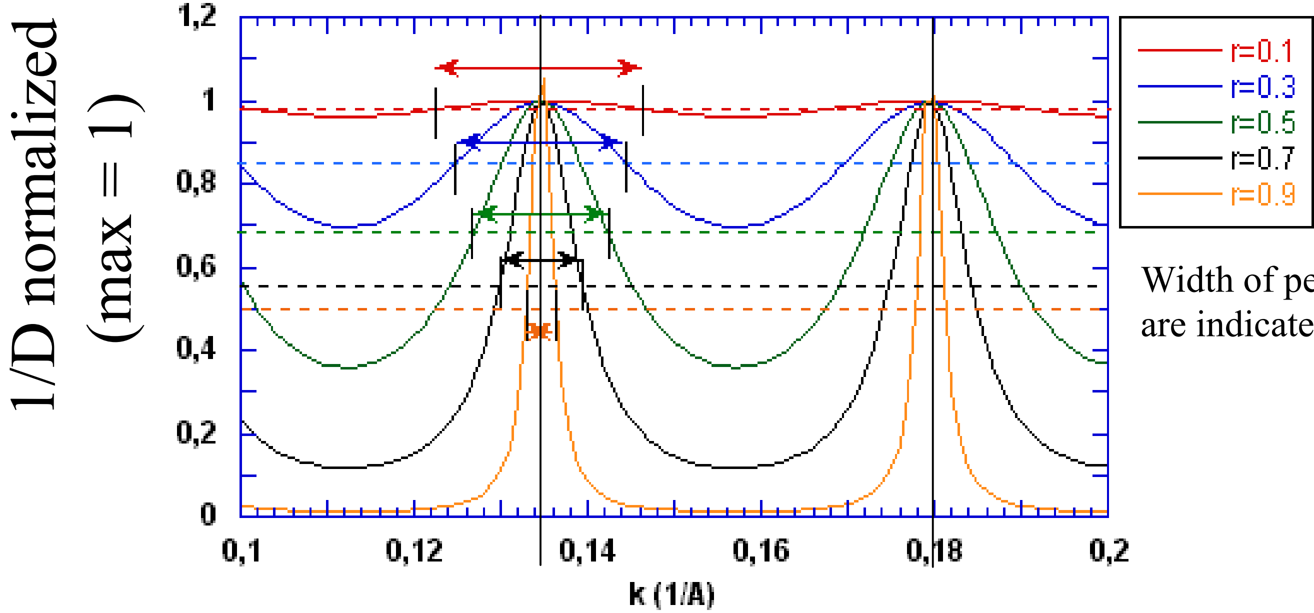
If k_x does not satisfy this condition, destructive interferences due to multiple scattering decrease N/D.
r governs the strength of the destructive interferences →

4.11 Quantum resonator – 1D confinement model

For $r \leq 1$, and $k_x - k_n \ll \pi/a$:

$$\frac{1}{D} \approx \frac{1}{(2ar)^2} \frac{1}{(k_x - k_n)^2 + \left(\frac{1-r^2}{2ar}\right)^2}$$

Lorentzians centered in k_n with HWHM $\Gamma = \frac{1-r^2}{2ar}$



Width of peaks at k_n are indicated by arrows

4.12 Quantum resonator – 1D confinement model

Calculation of $\rho(E)$ is obtained only by numerical integration:

$$\rho(E,x) = \frac{L_0}{\pi} \int_0^{k} \frac{1}{\sqrt{k^2 - k_x^2}} \, \rho(k_x,x) \, dk_x \qquad (**)$$

Particular wave numbers k_n imply maxima of ρ at energies defined by :

$$E_{0n} = E_0^{2D} + \frac{{}^{2}k_n^2}{2m^*} \qquad \textit{with} \quad 2k_n a = 2n\pi + 2\varphi$$

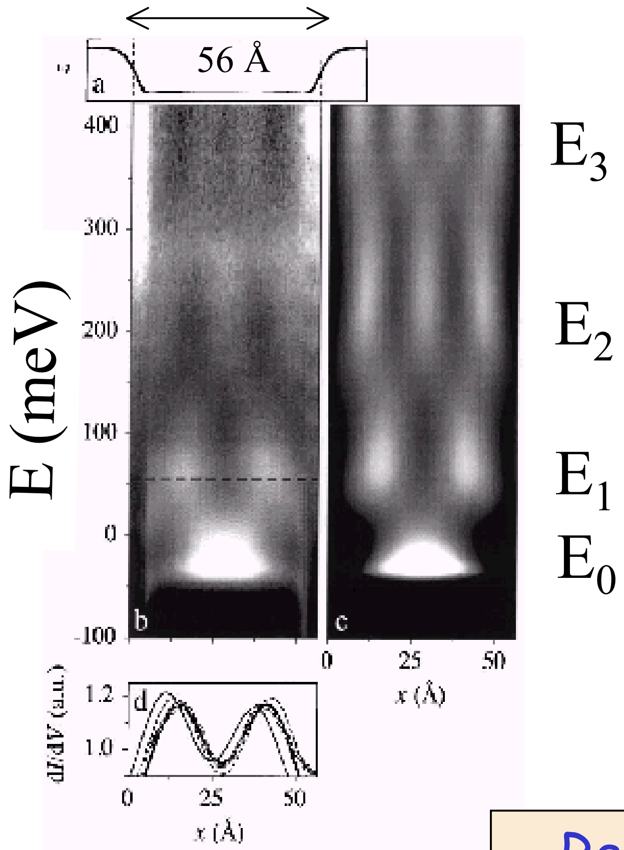
Inelastic processes at step ($r\neq1$) introduce a broadening of $\rho(E)$ at E_n ($n=0,1,2\ldots$).

What is the role of φ ?

$\varphi\neq\pi$ →shifts the energy levels of the resonator

→spatially shifts the maxima of the LDOS (toward the numerator of $\rho(k_x,x)$).

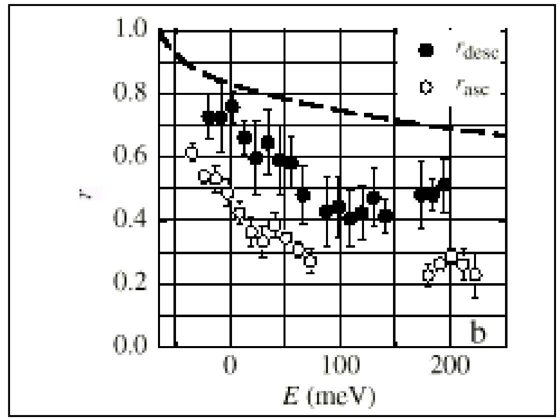
Confinement in a ~1D Ag resonator



Symmetric resonator

- Determination of $\varphi = -\pi \pm 0.3$ (independant of E)
- dI/dV (x) profile is fitted with $\rho(E,x)$ (defined by equation (**)) for each energy
  → Determination of $r_{asc}(E)$!!

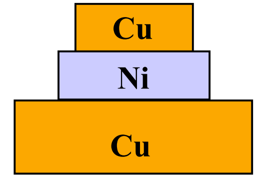
Asymmetric resonator → Determination of $r_{desc}(E)$



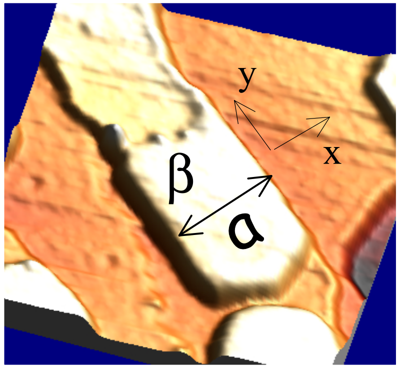
Reflection amplitude is strongly reduced at high energy
→ coupling to bulk states (absorption) becomes important

Absorption is more efficient for an ascending step

L. Bürgi, O. Jeandupeux, A. Hirstein, H. Brune and K. Kern, Phys. Rev. Lett. 81, 5370 (1998)



Model for confinement in an elongated β bilayer island



Contrary to Ag resonator, m* and E_0^{2D} are not known a priori.

hypothesis

- 1D confinement model
- Parallel steps : infinite potential walls ($r(k_x)=1$, $\varphi=\pi$)

1D : quantization of $k_x = (n+1)\pi/a$

Energy levels :

$$E_{0n} = E_0^{2D} + \frac{\hbar^2}{2m^*}\frac{(n+1)^2\pi^2}{a^2}$$

surface LDOS :

$$\rho(E,x) \propto \sum_{i=0}^{n} \sin^2\left[\frac{(i+1)\pi x}{a}\right] \times \frac{1}{\sqrt{E - E_{0i}}}$$

For $E_{0n} < E < E_{0(n+1)}$

ρ(x) shows up (n+1) maxima

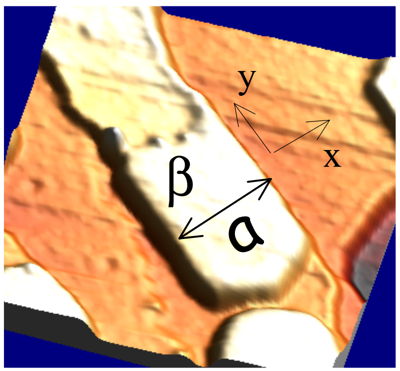
4.15 Quantum resonator – Cu/Ni 1D resonator

Parameters (independent of the island)

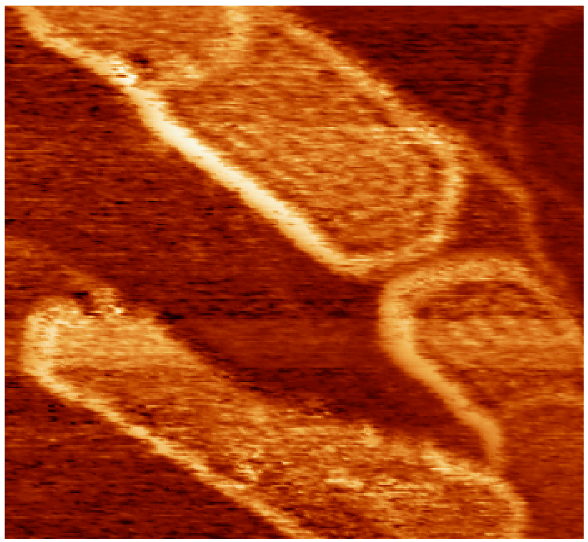
$E_0^{2D} = -140 \pm 20$ meV m* = $(0.33 \pm 0.05)\, m_e$

For this island:
$a \approx 90$ Å

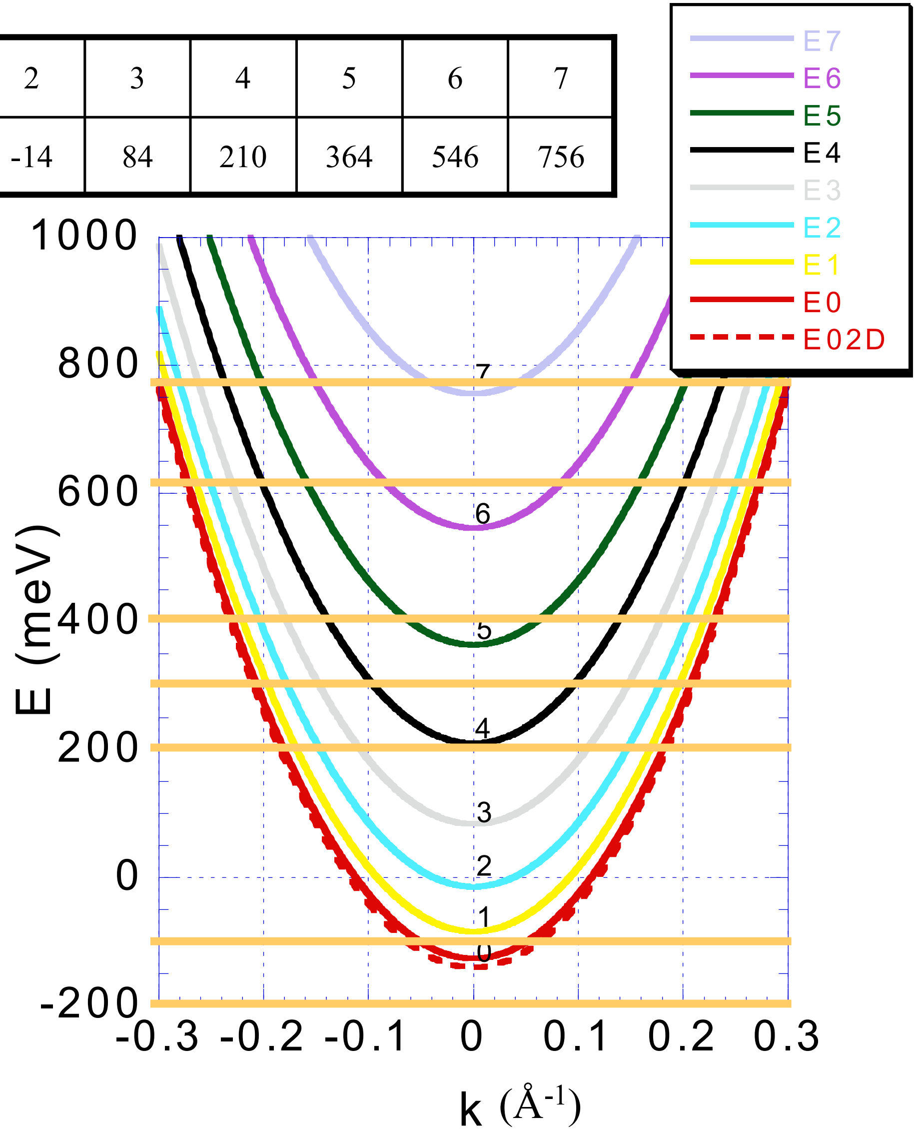
n	0	1	2	3	4	5	6	7
E_{0n} (meV)	-126	-84	-14	84	210	364	546	756



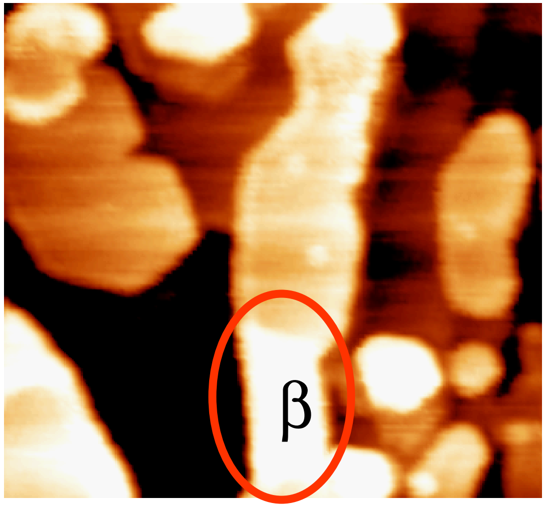
Constant current image
30 x 30 nm²
(1nA, + 0.6 V)



+ 620 mV

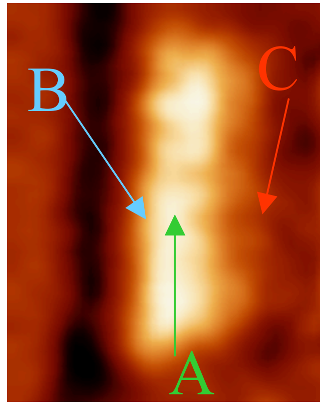


4.16 Quantum resonator - Cu/Ni 1D CITS



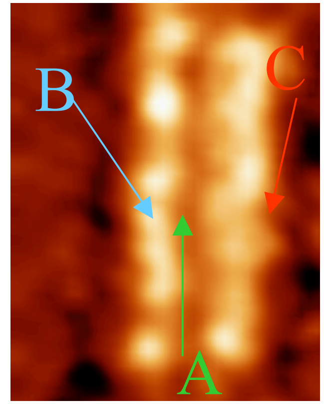
Topography 50 x 50 nm²

T = 40K



-77mV

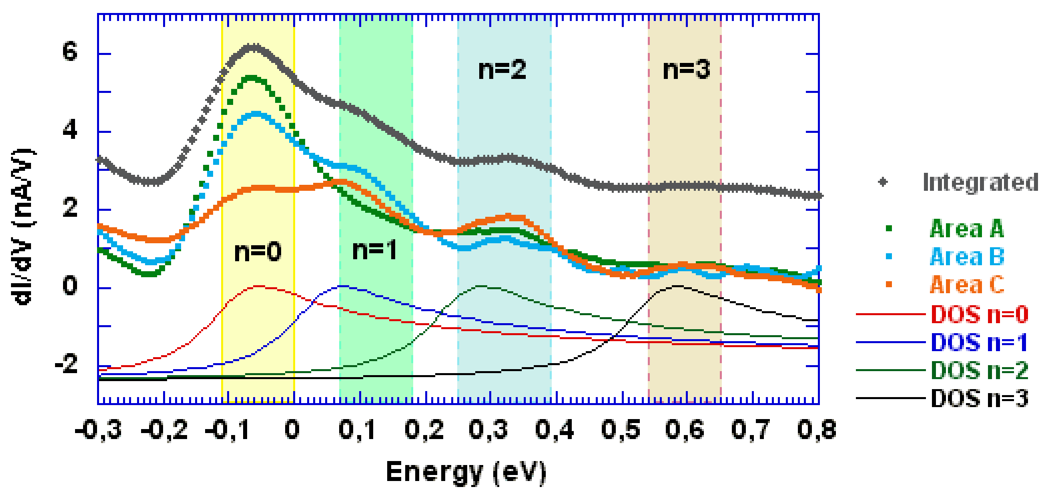
dI/dV image



106mV

dI/dV image

Spectroscopy on a β island, CITS C014.



E_0^{2D} = -135 meV

$m^* = 0.32\ m_e$

$a = 5.3$ nm

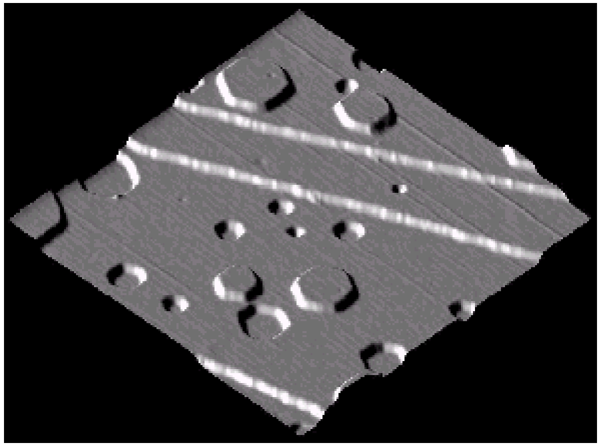
n	0	1	2	3
E_{0n} (meV)	-93	+34	+246	+542

Calculated LDOS is broadened at E_n
by a Lorentzian function with HWHM : Γ=70 meV

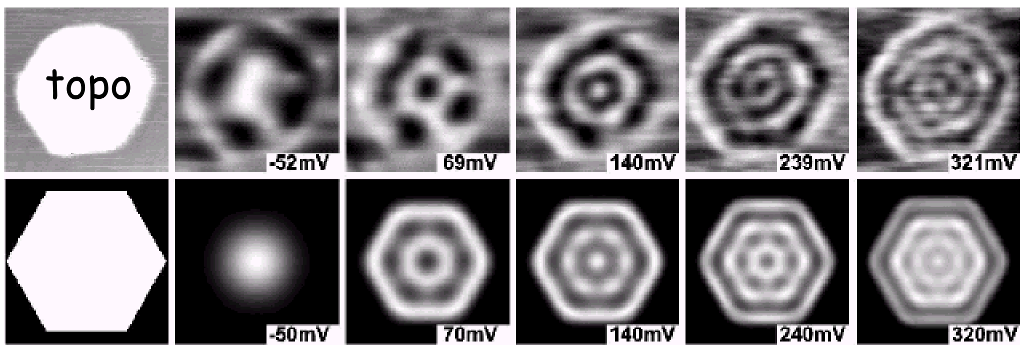
LEPES-CNRS (Grenoble)

4.17 Quantum resonator – 2D hard wall model Ag Berndt

2D confinement in Ag/Ag(111) hexagonal islands

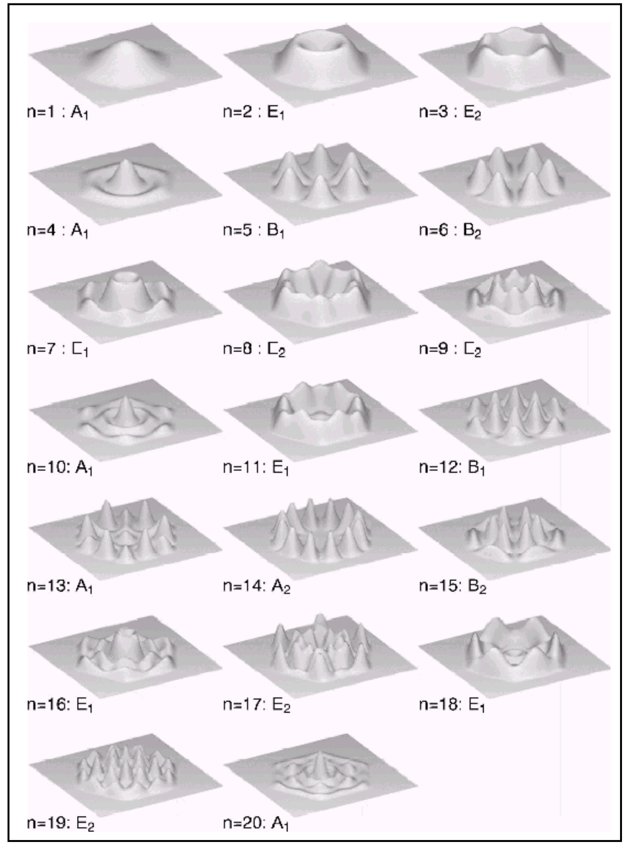


160 x 160 nm^2 constant current STM image, T = 50K



dI/dV

ρ (calcu-lation)



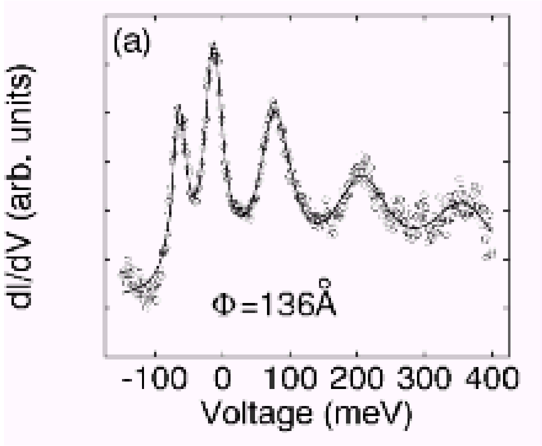
ρ(E) maps computed for the eigenvalues E_n

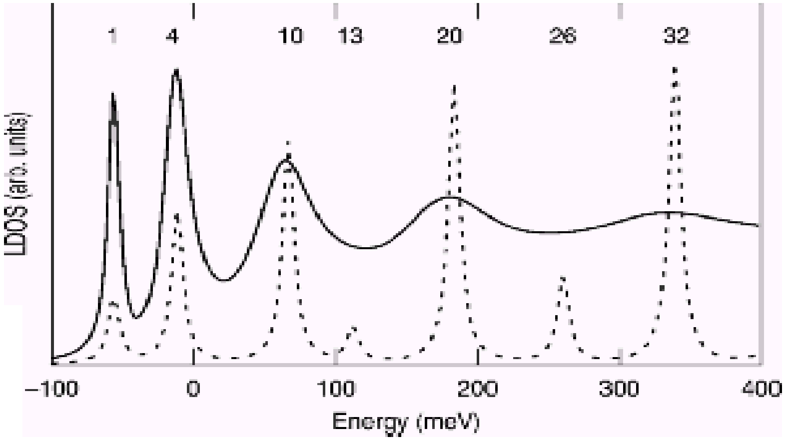
$$E_n(meV) = E_0^{2D} + 76{,}2\ \lambda_n / m^*.\Omega(nm^2)$$

J. Li, W.-D. Schneider, S. Crampin and R. Berndt, PRL ***80****, 3332 (1998) and Surface Science* ***422****, 95 (1999)*

Probing the inelastic scattering processes :

STS above the centre of a hexagonal island





Calculated spectrum

Spectra are decomposed into a series of Lorentzians with increasing linewidth :

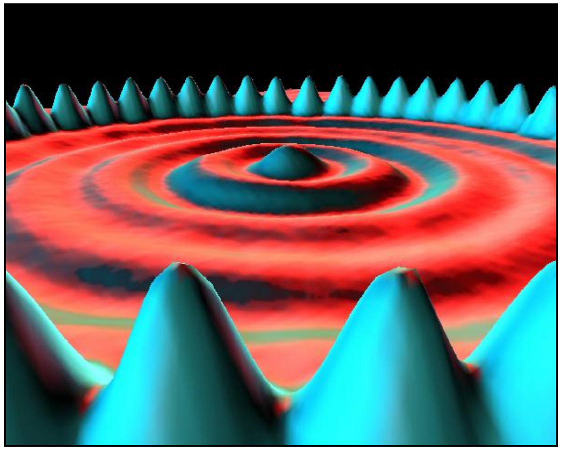
$$\Gamma_n \approx 0.2\,(E_n - E_0)$$

The width of each energy level Γ_n implies a finite lifetime for the confined electrons.

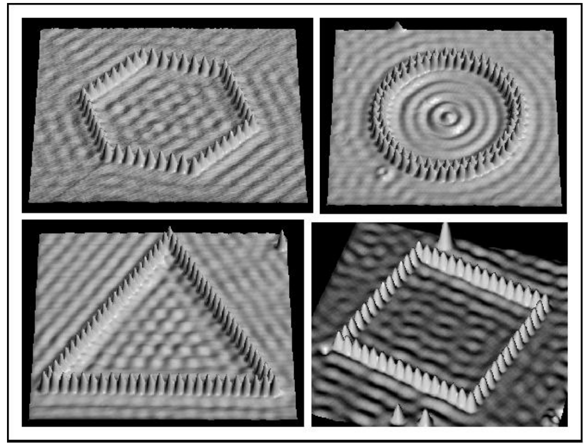
→ *Scattering at island edges into bulk states*

*J. Li, W.-D. Schneider, S. Crampin and R. Berndt, PRL **80**, 3332 (1998) and Surface Science **422**, 95 (1999)*

4.19 Models for Quantum Corrals



Science, 262 (8 Oct. 1993)



Physics Today 46 (11), 17-19 (1993)

M.F. Crommie, C.P. Lutz, D.M. Eigler, E.J. Heller

Fe atoms on Cu(111): With the hard wall model, the problem is reduced to finding the eigenstates of a particle confined in a box

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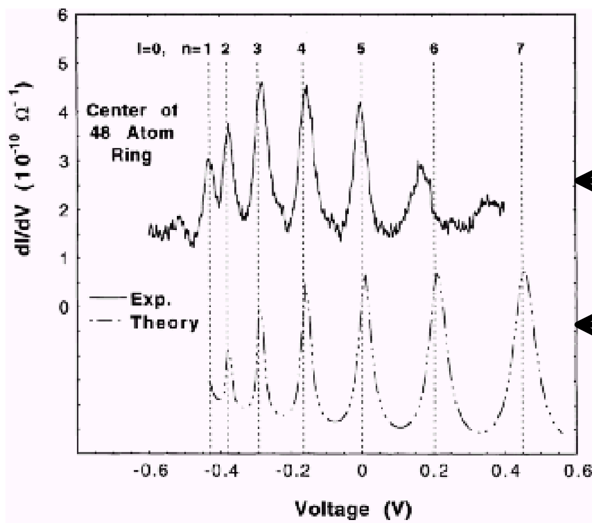
ring of 48 Fe atoms (diameter : 146 Å)

Vertical dashed lines : Eigenstates given by the hard-wall model



M.F. Crommie, J. of electron spectroscopy ***109****, 1 (2000)*

dI/dV (V) at the centre ←

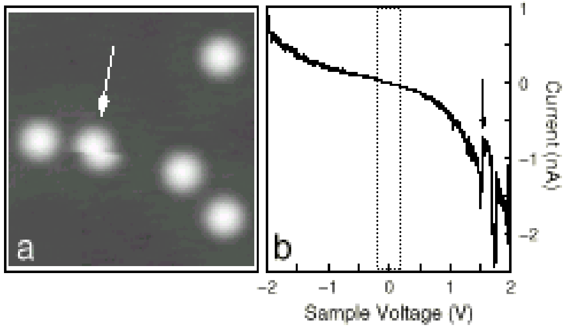
← **Black dot model :**

incoming s-wave amplitude is totally absorbed (probably coupling with bulk states) by the scatterer

The black dot model gives a fairly good account of the broadening of the measured dI/dV peaks !!!

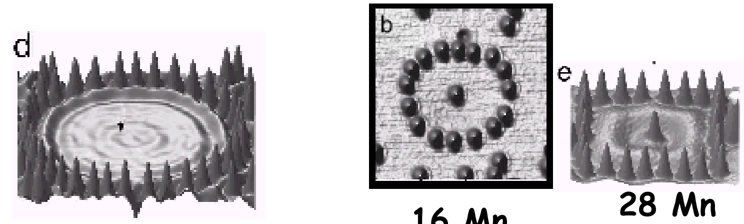
5. Interaction adsorbate – surface state

LDOS of an adsorbate centered to a quantum corral



60 x 60 Å² topo Mn/Ag(111)

I/V spectrum on single Mn atom



35 Mn atom ring

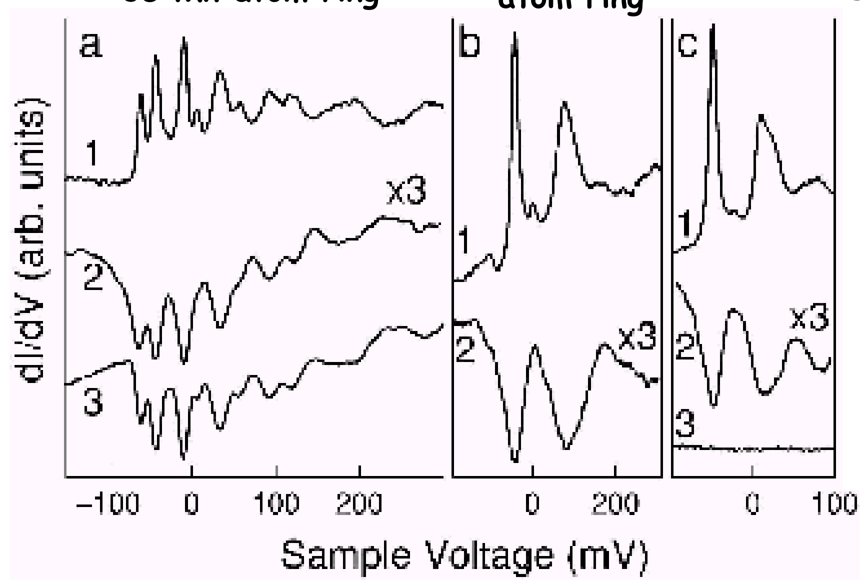
16 Mn atom ring

28 Mn atom rectangle

1. Without central Mn →

2. With central Mn →

3. Without, inverted and scaled →

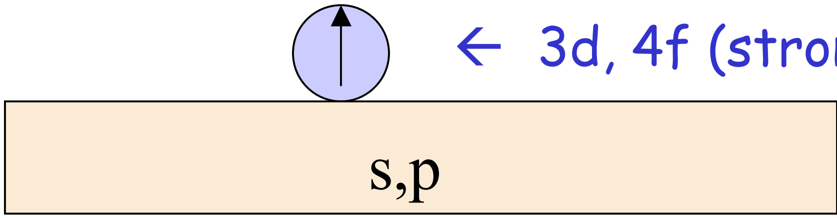


Spectra 2: inverted structure characteristic of a strongly coupled adsorbate level, à priori s level (cf calculations)

Controlled modification of adsorbate electronic structure !!!

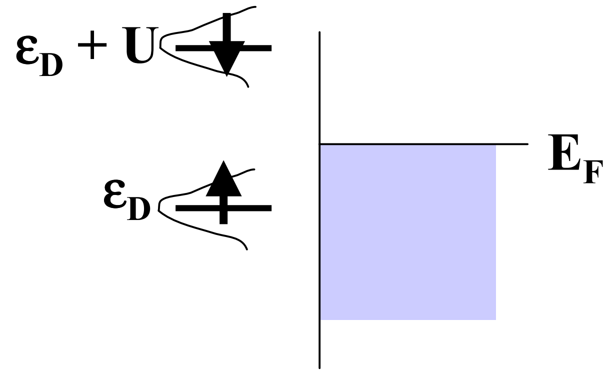
J. Kliewer, R. Berndt and S. Crampin, Phys. Rev. Lett. ***85****, 4936 (2000)*

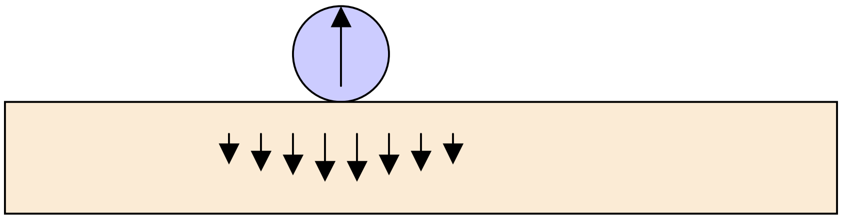
Kondo effect



← 3d, 4f (strong Coulomb repulsion)

$T > T_K$





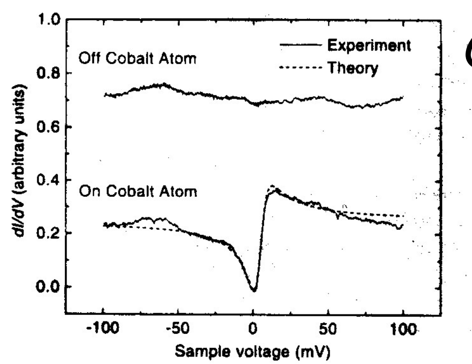
$T < T_K$

Spin dependant scattering
(with spin flip)

Highly correlated ground state in the electron gas, with **screening the adsorbate spin**.

⇒ narrow resonance located at E_F, HWHM ~ T_K

Kondo effect probed by STS



Co / Au(111) : T_K = 70K

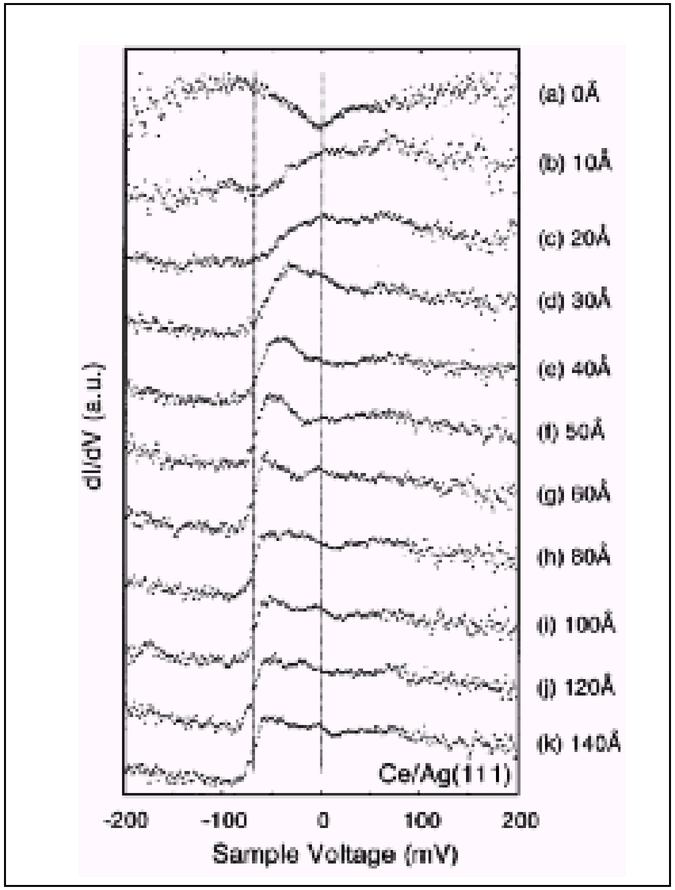
V. Madhavan, W. Chen, T. Jamneala, M.F. Crommie, N.S. Wingreen

Science 280, 567 (1998)

$$kT_K \approx D|3\rho(E_F)Jv|^{1/3} \exp\left(\frac{1}{3\rho(E_F)Jv}\right)$$

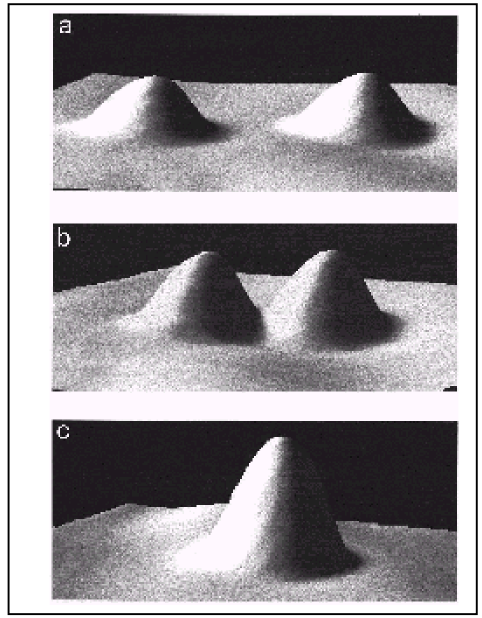
A.C. Hewson, The Kondo Problem to heavy fermions, Cambridge University Press, NY 1985)

Kondo effect probed by STS

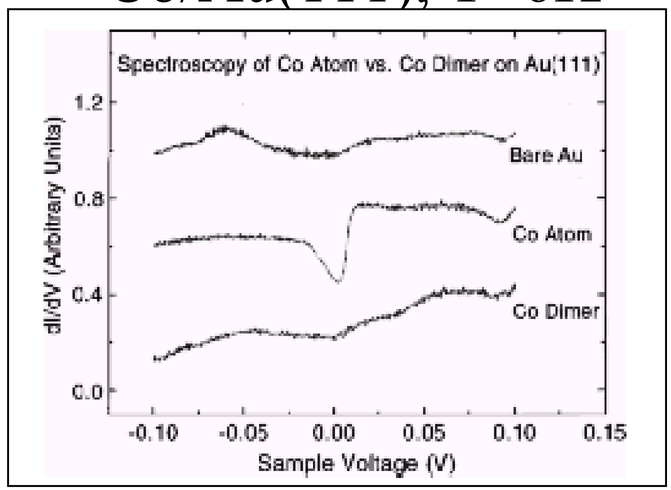


Ce/Ag(111), T=5K

J. Li, W-D Schneider, R. Berndt & B. Delley,
Phys. Rev. Lett 80, 2893 (1998)

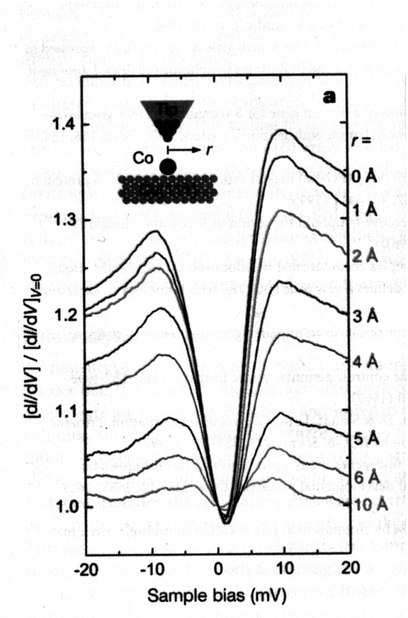


Co/Au(111), T=6K

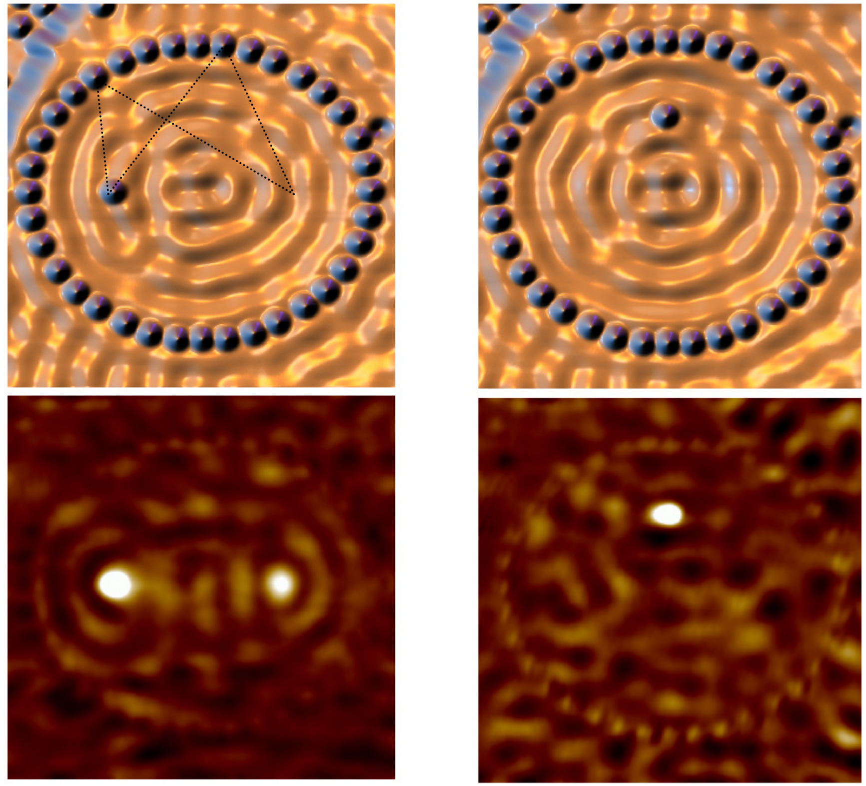


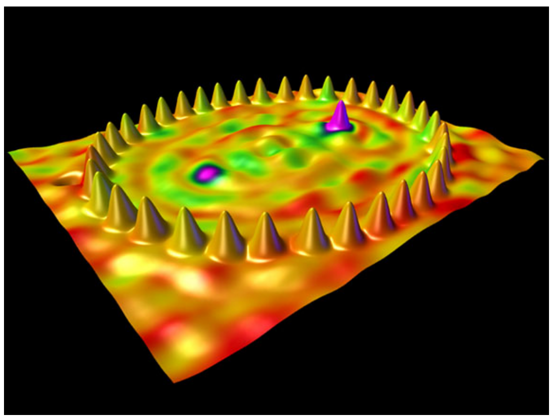
W. Chen, T. Jamneala, V. Madhavan & M.F. Crommie
Phys. Rev. B 60, R8529 (1999)

Quantum mirage



36 + 1 Co atoms / Cu(111), T=4K





H.C. Manoharan, C.P. Lutz and D. Eigler Nature, 3 Feb. 2000

Conclusion

Scattering of surface states electrons :
low temperature STM study

- Determination of 2D shockley-like surface state parameters
- Study of inelastic processes (e-e and e-phonons interactions)
- Confinement in nanostructures:
  quantitative study of scattering processes at defects (steps, adsorbates)

- Interaction adsorbate – confined electron gas :
  construction game with atoms
  + driving of the electronic properties at atomic scale !!!