

# Spin polarized Scanning Tunneling Microscopy

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# Outline

## **Theoretical and technical background**

Tunnel magneto-resistance

Scanning Tunneling Spectroscopy

Magnetic tips and surfaces

## **SP-STM : a tool to study nanomagnetism**

Background of magnetism

Domain wall, vortex

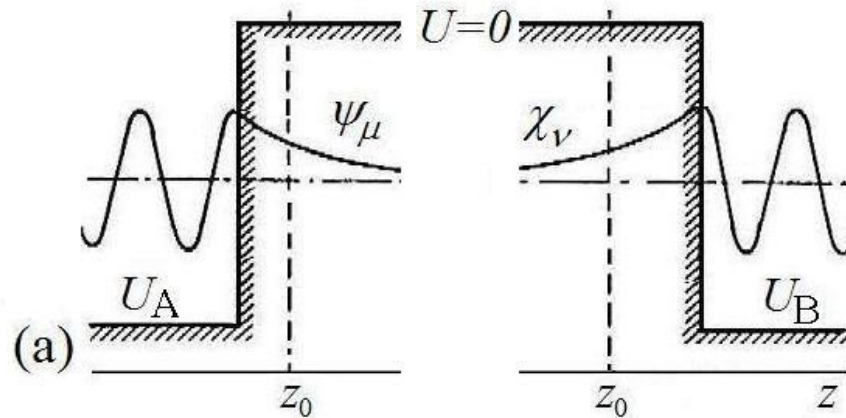
Skyrmions

## **Towards nanospintronics**

Molecular spintronics

Atomic spin logic

# Background of tunneling



$$M = -\frac{\hbar^2}{2m} \int_{z=0} \left[ \chi^* \frac{\partial \psi}{\partial z} - \psi \frac{\partial \chi^*}{\partial z} \right] dx dy$$

J. Bardeen, Phys. Rev. Lett. 6, 57 (1961)

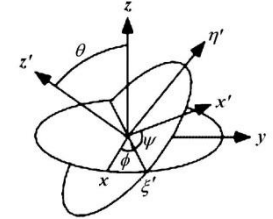
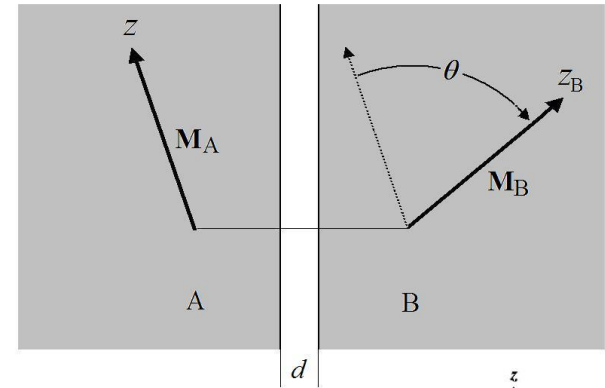
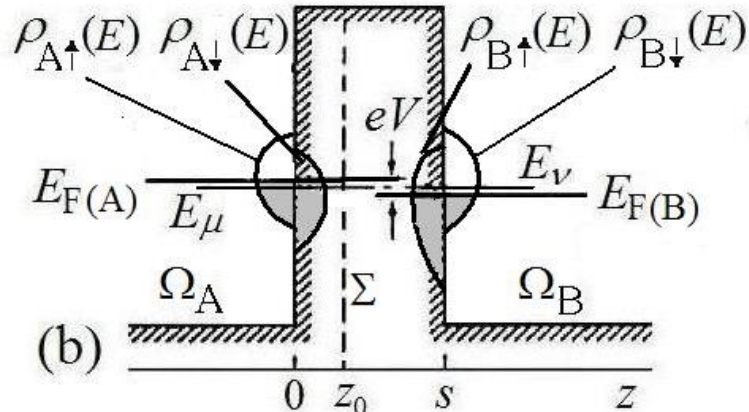
$$I = \frac{2\pi e^2}{\hbar} |M_{\mu\nu}|^2 \rho_S(E_F) \rho_T(E_F) V$$

$$\propto |\psi(\mathbf{r}_0)|^2 \rho_S(E_F)$$

J. Tersoff and D.R. Hamann, Phys. Rev. B 31, 805 (1985)

Measure of the Local Density of State (LDOS)

# Tunneling between magnetic electrodes



**Spinor in electrode A, along  $z_A$ :**

$$\Psi_{A\uparrow} = \psi(\mathbf{r}) \begin{pmatrix} 1 \\ 0 \end{pmatrix}, \quad \Psi_{A\downarrow} = \psi(\mathbf{r}) \begin{pmatrix} 0 \\ 1 \end{pmatrix}$$

**Spinor in electrode B, along  $z_B$ :**

$$\Psi_{B\uparrow} = \chi(\mathbf{r}) \begin{pmatrix} 1 \\ 0 \end{pmatrix}, \quad \Psi_{B\downarrow} = \chi(\mathbf{r}) \begin{pmatrix} 0 \\ 1 \end{pmatrix} \quad \rightarrow \quad \begin{pmatrix} M_{\uparrow\uparrow} & M_{\uparrow\downarrow} \\ M_{\downarrow\uparrow} & M_{\downarrow\downarrow} \end{pmatrix} = M_0 \begin{pmatrix} e^{i(\phi+\psi)/2} \cos(\theta/2) & ie^{i(\phi-\psi)/2} \sin(\theta/2) \\ ie^{i(-\phi+\psi)/2} \sin(\theta/2) & e^{-i(\phi+\psi)/2} \cos(\theta/2) \end{pmatrix}$$

$$G = 2\pi^2 G_0 \left( \rho_{A\uparrow} \rho_{B\uparrow} |M_{\uparrow\uparrow}|^2 + \rho_{A\uparrow} \rho_{B\downarrow} |M_{\uparrow\downarrow}|^2 + \rho_{A\downarrow} \rho_{B\uparrow} |M_{\downarrow\uparrow}|^2 + \rho_{A\downarrow} \rho_{B\downarrow} |M_{\downarrow\downarrow}|^2 \right)$$

$$\rho_A = \rho_{A\uparrow} + \rho_{A\downarrow}, \quad \rho_B = \rho_{B\uparrow} + \rho_{B\downarrow};$$

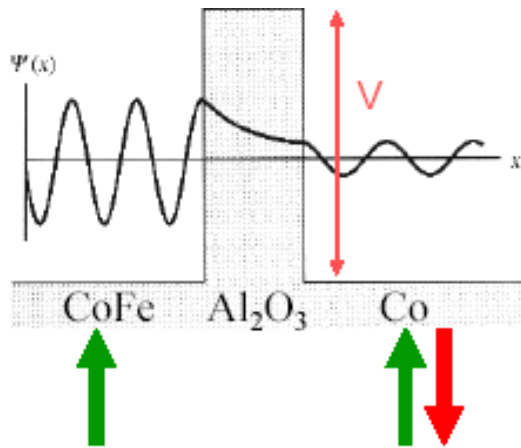
$$m_A = \rho_{A\uparrow} - \rho_{A\downarrow}, \quad m_B = \rho_{B\uparrow} - \rho_{B\downarrow}.$$

$$P_A \equiv \frac{m_A}{\rho_A}, \quad P_B \equiv \frac{m_B}{\rho_B}.$$

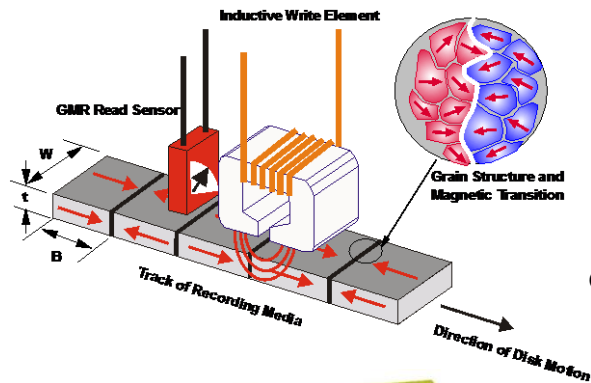
$$G = 2\pi^2 G_0 |M_0|^2 \rho_A \rho_B (1 + P_A P_B \cos \theta)$$

$$= G_{sa} + G_{sp} \cos \theta.$$

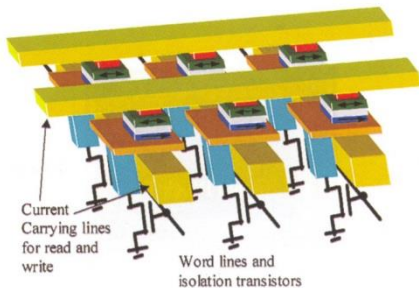
# Tunnel magneto-resistance



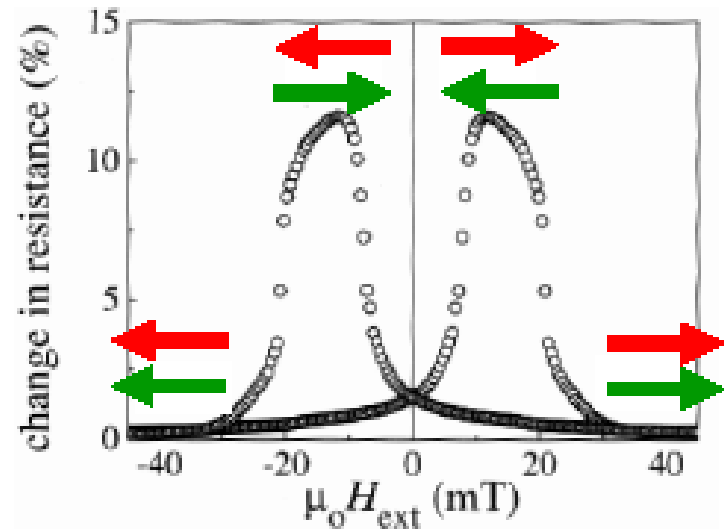
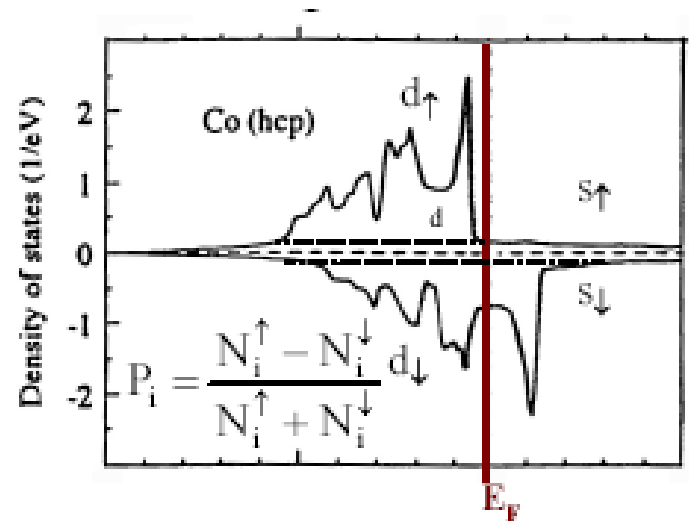
CoFeB/MgO/CoFeB : 600 % at room temperature



in read head  
of hard disk drive

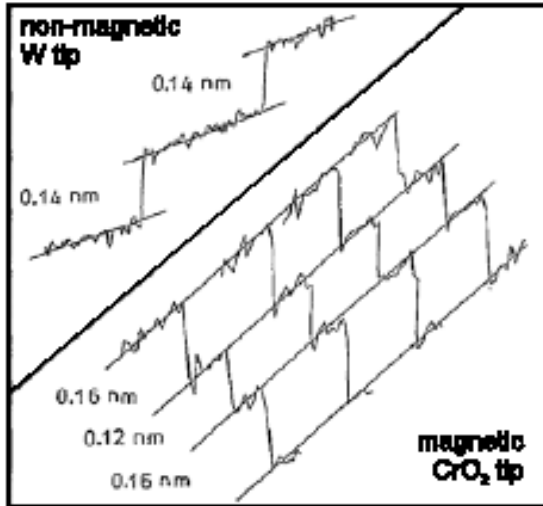


in magnetic random  
access memory  
< 200 nm



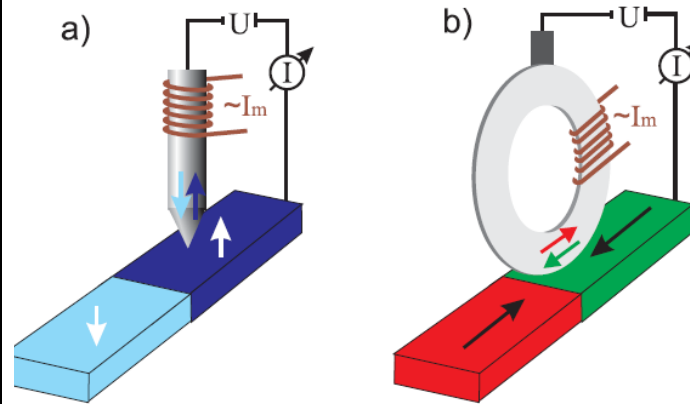
# SP-STM : experimental techniques

## Constant current topography



R. Wiesendanger et al,  
Phys. Rev. Lett. 65 (1990) 247

## Lock-in on magnetization modulation



W. Wulfhekel et al,  
Appl. Phys. Lett. 75 (1999) 1944

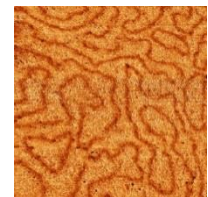
## STS, conductance image



Typical setup : LT STM,  
tip preparation,  
MBE for Cr, Fe, Co...

Other related techniques : ● Optically pumped spin polarized GaAs tip  
cf. A. Rowe, LMC, Polytechnique

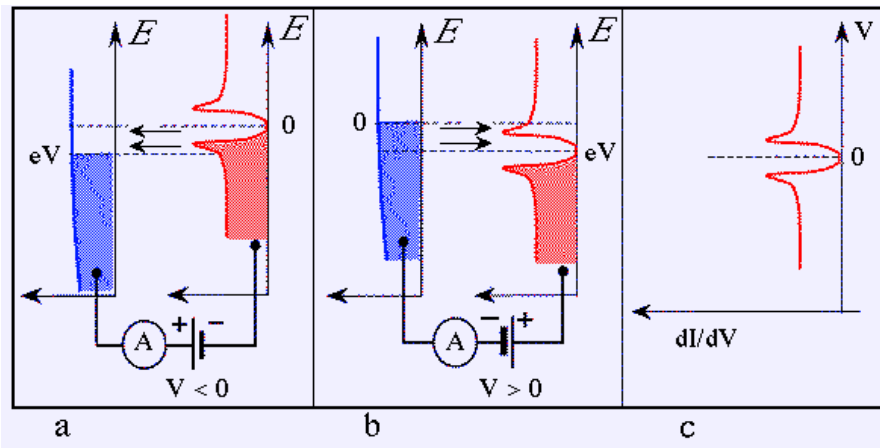
● Spin-polarized Ballistic Energy Electron Microscopy



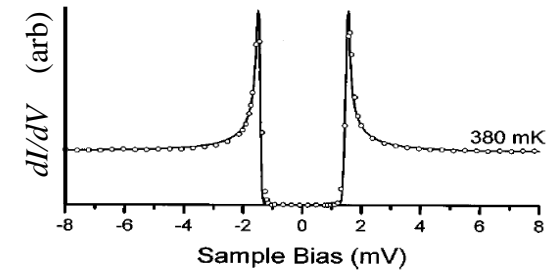
A. Bellec et al. EuroPhys. Lett. **91** (2010) 17009

# Spin polarized Scanning Tunneling Spectroscopy

STS :

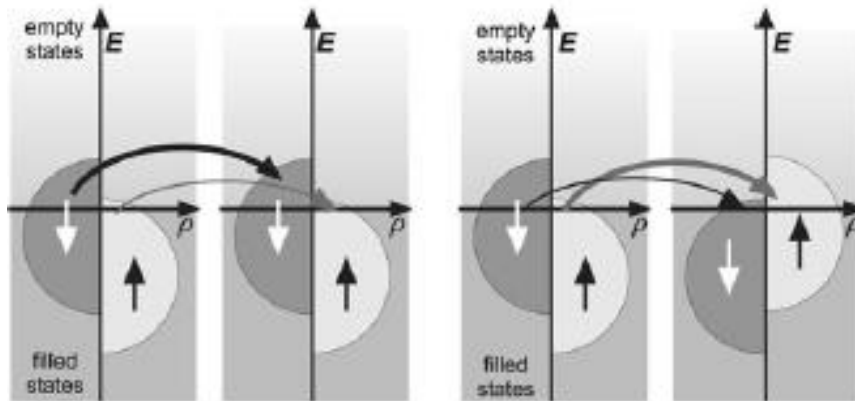


$$\left. \frac{\partial I_T}{\partial V} \right|_{V_T} \propto \rho_t \int_{-\infty}^{\infty} \rho_s(\epsilon) \delta(\epsilon - eV_T) d\epsilon = \rho_t \rho_s(eV_T)$$

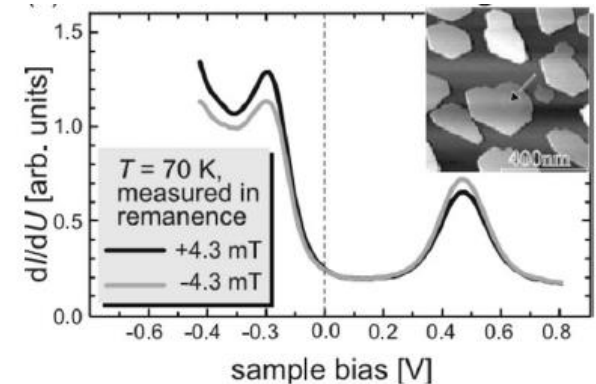


S.H. Pan et al., Appl. Phys. Lett. **73** (1998) 2992

SP-STS :



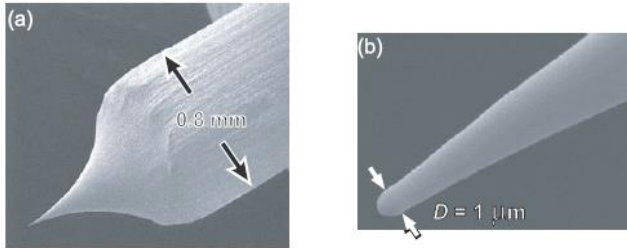
$$\frac{dI^P}{dV} \propto \rho_1^M \cdot \rho_2^M + \rho_1^m \cdot \rho_2^m > \frac{dI^{AP}}{dV} \propto \rho_1^M \cdot \rho_2^m + \rho_1^m \cdot \rho_2^M$$



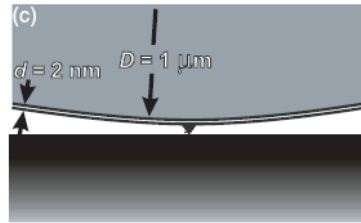
M. Bode et al., Phys. Rev. Lett. **81** (1998) 4256

# The magnetic tip

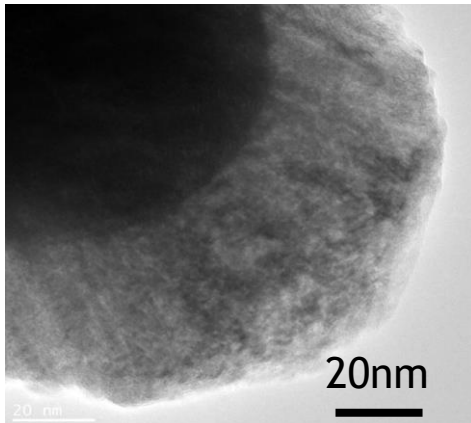
W tip, flashed at 2200 K



coated with Cr, Co, Fe...



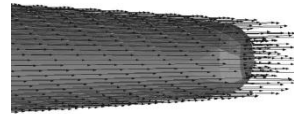
R. Wiesendanger,  
Rev. Mod. Phys. 81 (2009) 1495



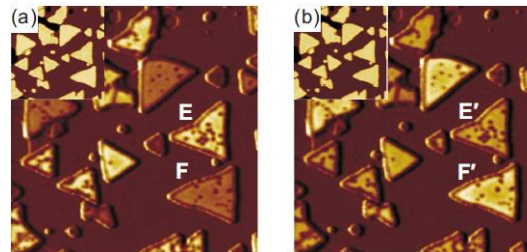
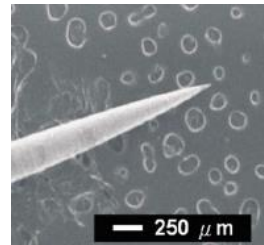
G. Rodary et al,  
Appl. Phys. Lett. 98 (2011) 82505

Bulk tips

Fe, Co, Ni, Cr,  
FeMnC, FeCoNiSiB...

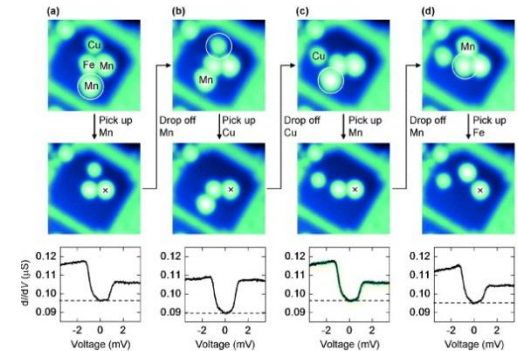
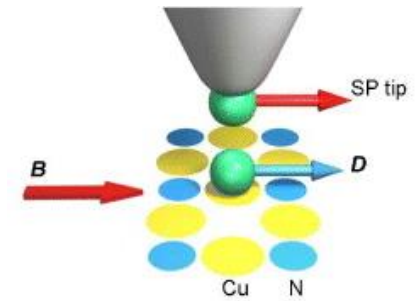
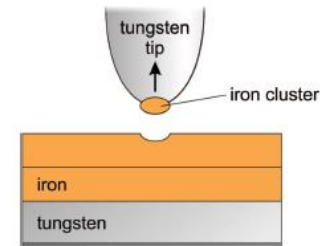


Magnetic stray field !



P-J. Hsu et al,  
Appl. Phys. Lett. 96 (2010) 142515  
A. Bassi et al,  
Appl. Phys. Lett. 91 (2007) 173120

Nano-indentation  
or manipulation

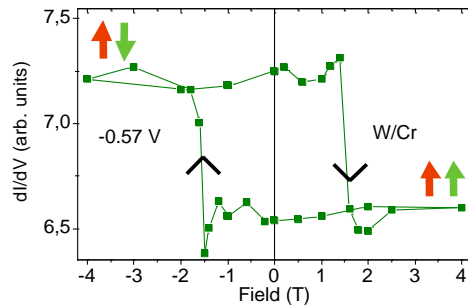
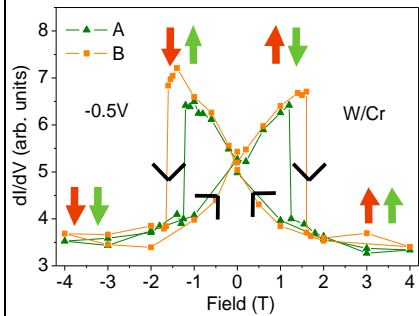
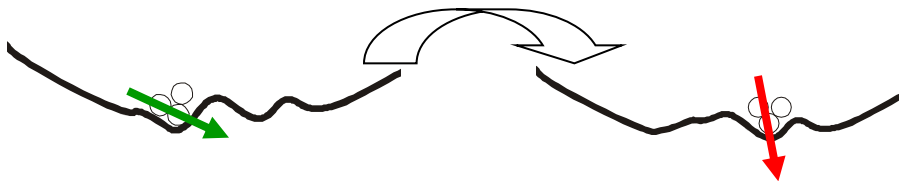


S. Loth et al,  
New J. Phys. 12 (2010) 125021

# The magnetic tip

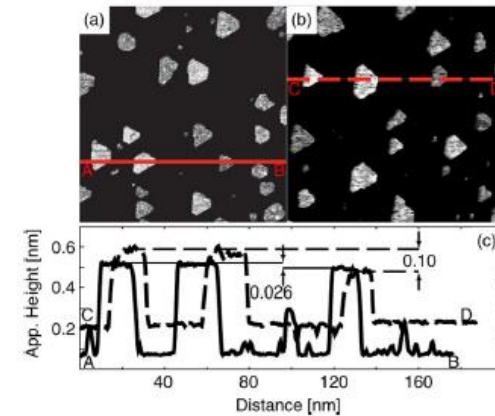
Poor control of the tip spin quantization axis

Voltage pulse

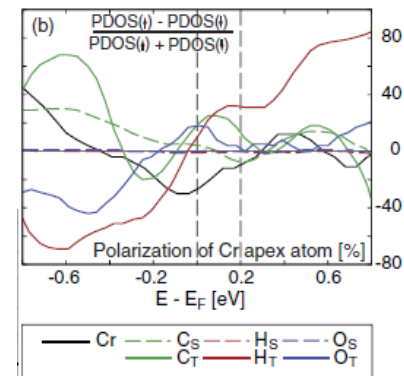


G. Rodary et al, Appl. Phys. Lett. 95 (2009) 152513

Poor control of the the tip spin polarization



TMR variations from 50% to 850% !



Extreme sensitivity to adsorbates

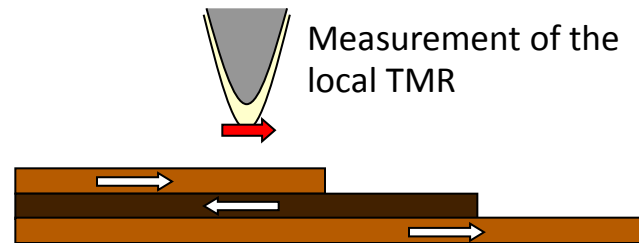
W. Hofer et al, Phys. Rev. Lett. 100 (2008) 26806



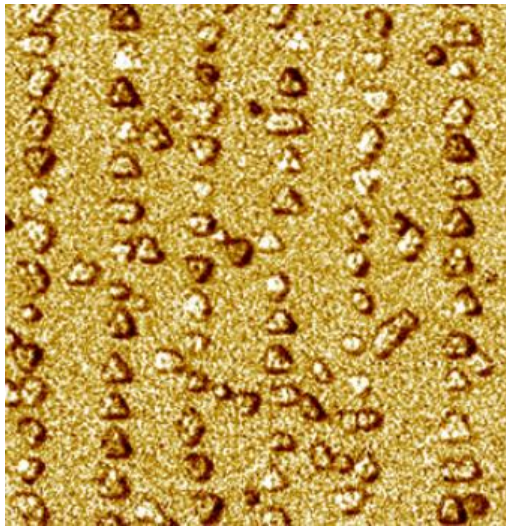
A good SP-STM tip should have a sharp resolution, a flat density of states, a spin quantization axis parallel to the one of the sample, a high spin polarization !

# Model magnetic surfaces

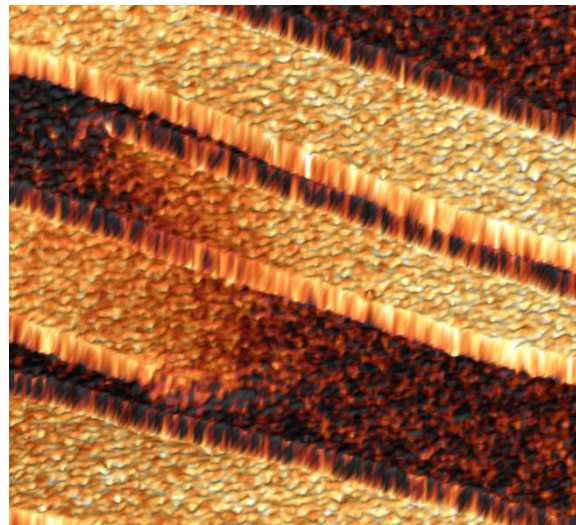
## Spin polarized conductance images



Fe/Au(111)



Cr(001)



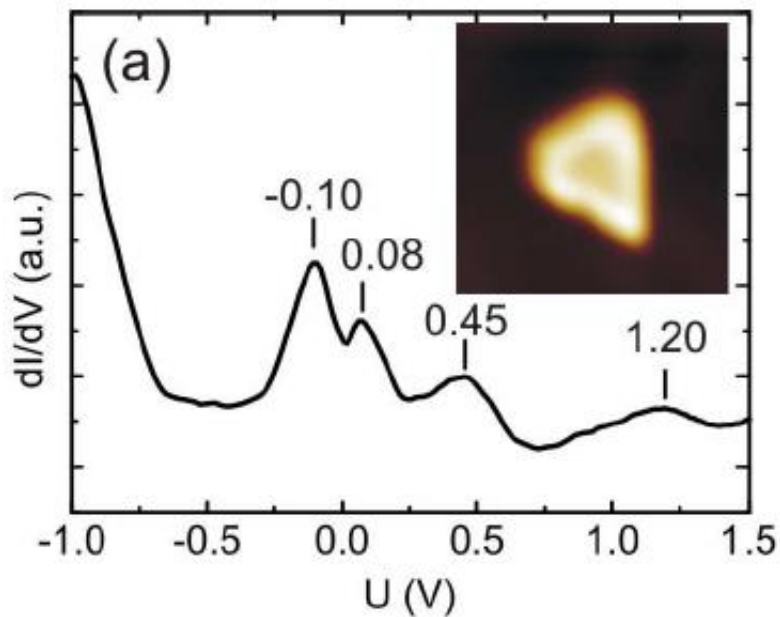
Co/Pt(111)



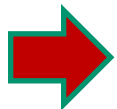
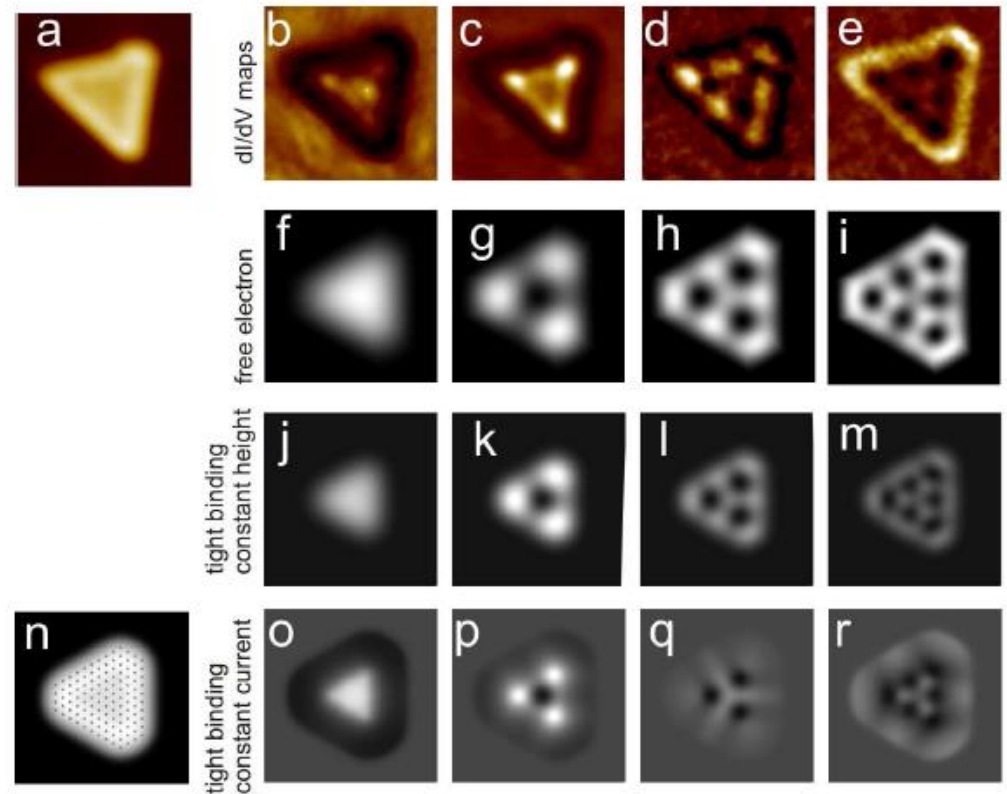
Magnetic tips : Fe film on W (~20 ML)

# Electronic properties of Fe/Au(111)

Confined two-dimensional electron gas in the Fe dots :



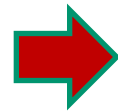
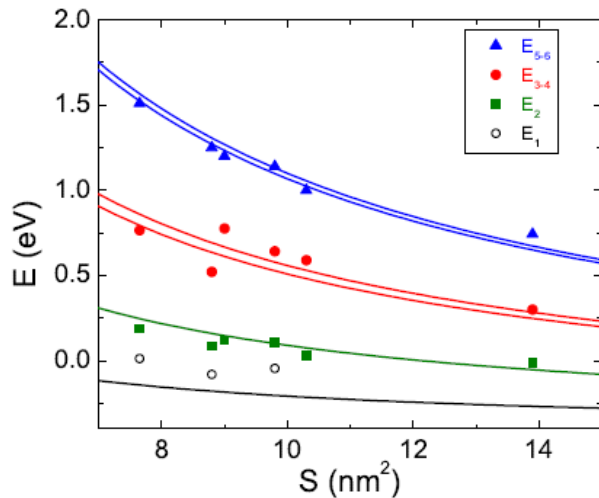
STs spectrum above a Fe island



Strong variation of the spin averaged local conductance with the island size

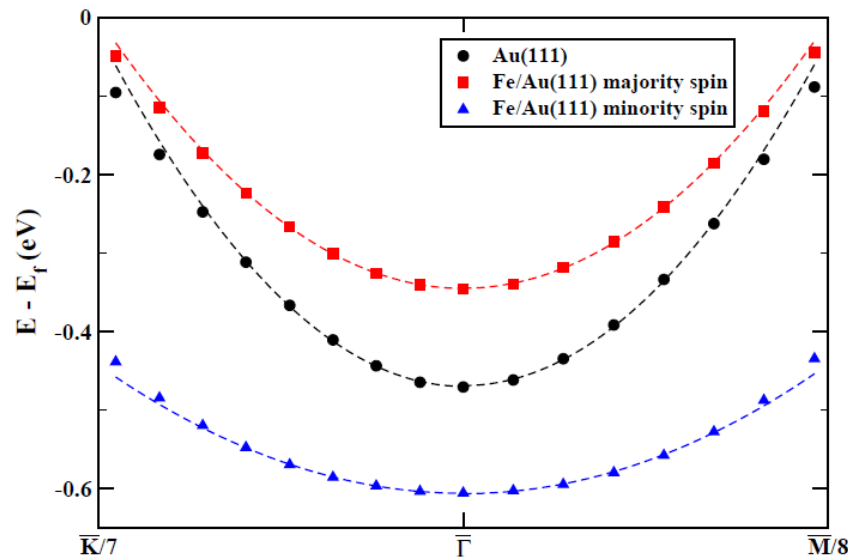
# Electronic properties of Fe/Au(111)

A fully spin polarized surface state :

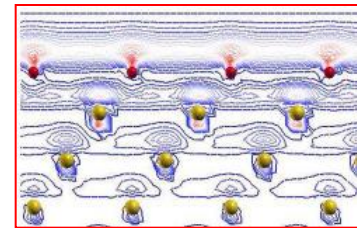


$$m^* = 0.39 m_e \quad E_0 = -420 \text{ meV}$$

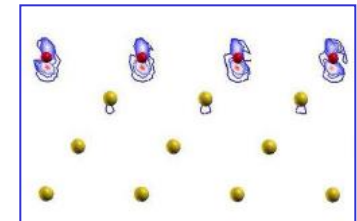
Comparison with ab-initio calculations  
(S. Narasimhan, Bangalore) :



Spin up



Spin down



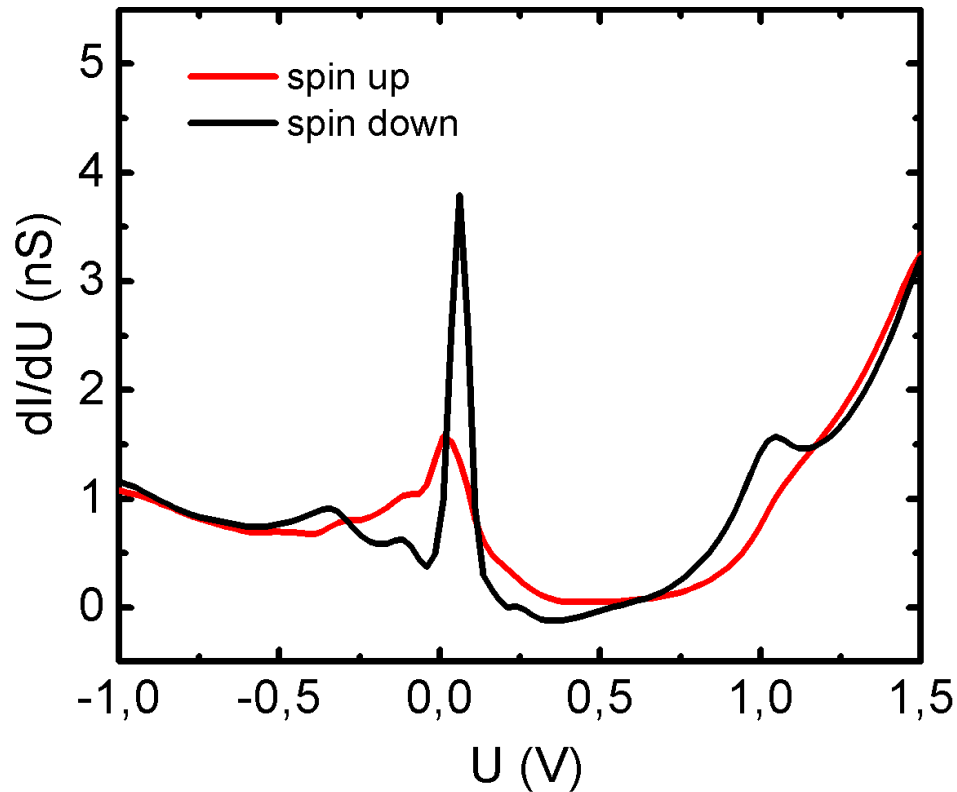
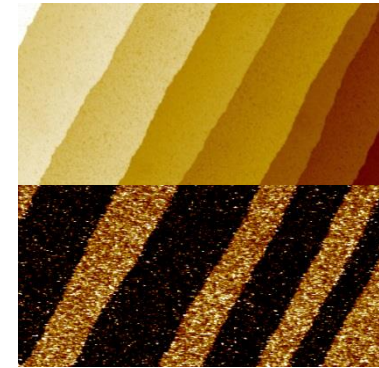
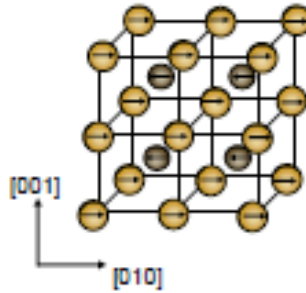
In STM, we measure only the spin up state which is sp-like

# Electronic properties of Cr(001)

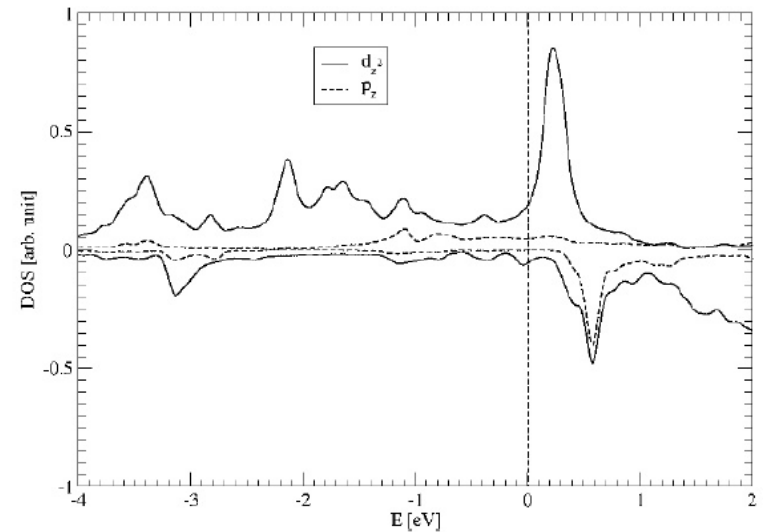
Antiferromagnetic

Spins in the plane at low T

Bulk spin density wave



Ab initio density of states :



Dispersive minority spin surface state  
close to the Fermi level

# A world tour



R. Wiesendanger, Hambourg



# Outline

## Theoretical and technical background

Tunnel magneto-resistance

Scanning Tunneling Spectroscopy

Magnetic tips and surfaces

## **SP-STM : a tool to study nanomagnetism**

Background of magnetism

Domain wall, vortex

Skyrmions

## **Towards nanospintronics**

Molecular spintronics

Atomic spin logic

# Background of magnetism


A typical magnetic hamiltonian :

$$E = \underbrace{-\mu_0\mu\mathbf{H} \sum_i \mathbf{m}_i}_{\text{Zeeman}} - \underbrace{J \sum_{\langle i,j \rangle} \mathbf{m}_i \cdot \mathbf{m}_j}_{\text{Exchange}} - \underbrace{\sum_i k_i (\mathbf{m}_i \cdot \mathbf{e}_i)^2}_{\text{Anisotropy}} - \underbrace{\frac{\mu_0\mu^2}{8\pi} \sum_{i,j \neq i} \left[ \frac{3(\mathbf{m}_i \cdot \mathbf{r}_{ij})(\mathbf{m}_j \cdot \mathbf{r}_{ij})}{r_{ij}^5} - \frac{\mathbf{m}_i \mathbf{m}_j}{r_{ij}^3} \right]}_{\text{Dipolar}}$$

Microscopic view :

**Intra-atomic exchange, electron correlation effects:**

**LOCAL (ATOMIC) MAGNETIC MOMENTS**



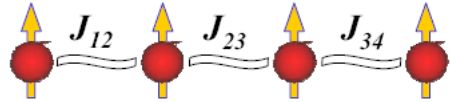
$\vec{m}$

$d$  or  $f$  electrons

Hund's rules

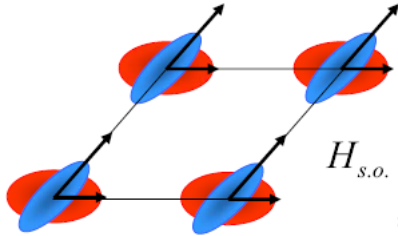
**Inter-atomic exchange:**

**MAGNETIC ORDER**

$$H_{exc} = -\sum_{i \neq j} J_{ij} \mathbf{S}_i \cdot \mathbf{S}_j$$


**Spin-Orbit Coupling:**

**MAGNETOCRYSTALLINE ANISOTROPY**

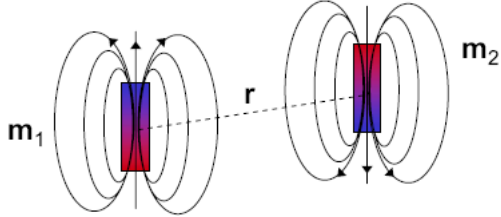


$$H_{s.o.} = \lambda \mathbf{L} \cdot \mathbf{S}$$

$$= \sum \xi \mathbf{s}_i \cdot \mathbf{l}_i$$

**Dipolar Interaction:**

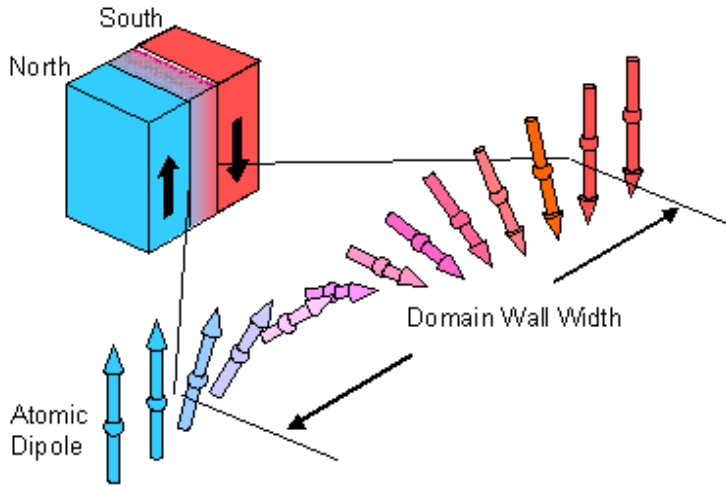
**SHAPE ANISOTROPY**



$$H_{dip} = \frac{1}{4\pi} \left[ \frac{\mathbf{m}_1 \cdot \mathbf{m}_2}{r^3} - 3 \frac{(\mathbf{m}_1 \cdot \mathbf{r})(\mathbf{m}_2 \cdot \mathbf{r})}{r^5} \right]$$

# Magnetic length scales

## Domain wall width

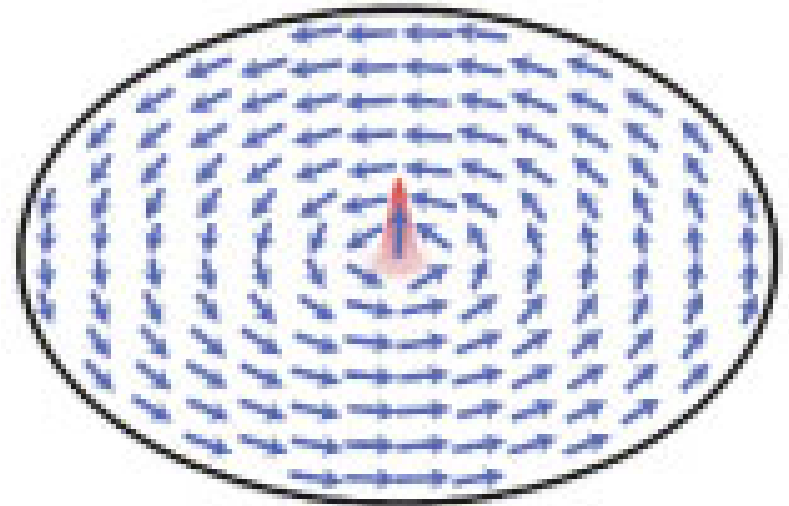


$$e = \underbrace{A \left( \frac{d\theta}{dx} \right)^2}_{\text{Exchange } J/m} + \underbrace{K \sin^2 \theta}_{\text{Anisotropy } J/m^3}$$

$$\Delta = \sqrt{\frac{A}{K}} \quad \Delta = 1 \text{ to } 100 \text{ nm}$$

$$A = 10^{-11} \text{ J/m}, \quad K = 10^2 - 10^5 \text{ J/m}^3$$

## Magnetic vortex

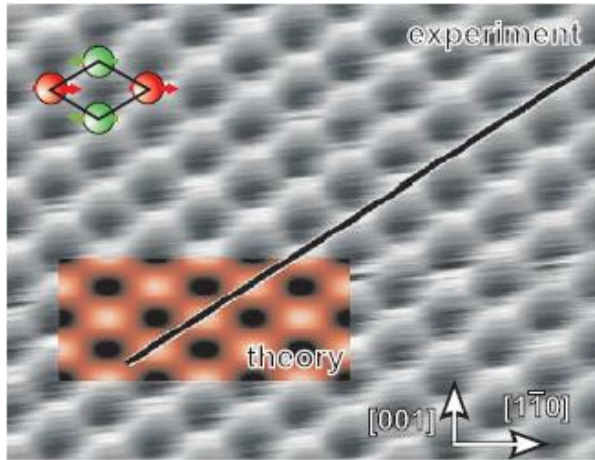


$$\Lambda = \sqrt{\frac{2A}{\mu_0 M_s^2}} \quad \Lambda = \text{few nm}$$

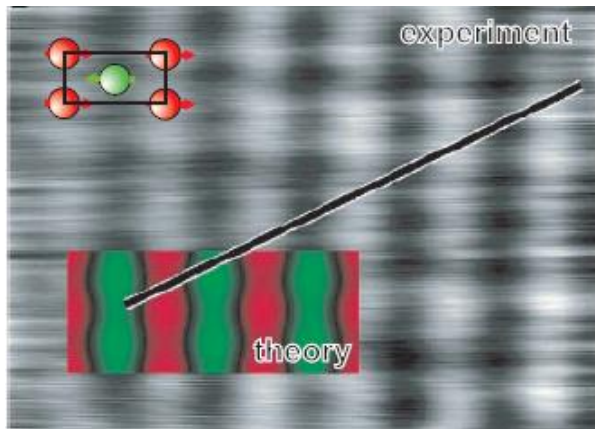
$$M_s = 10^6 \text{ A/m}$$

# The SP-STM resolution

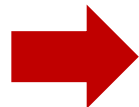
Mn monolayer on W(110)



Spin averaged image of the atomic lattice (W tip)



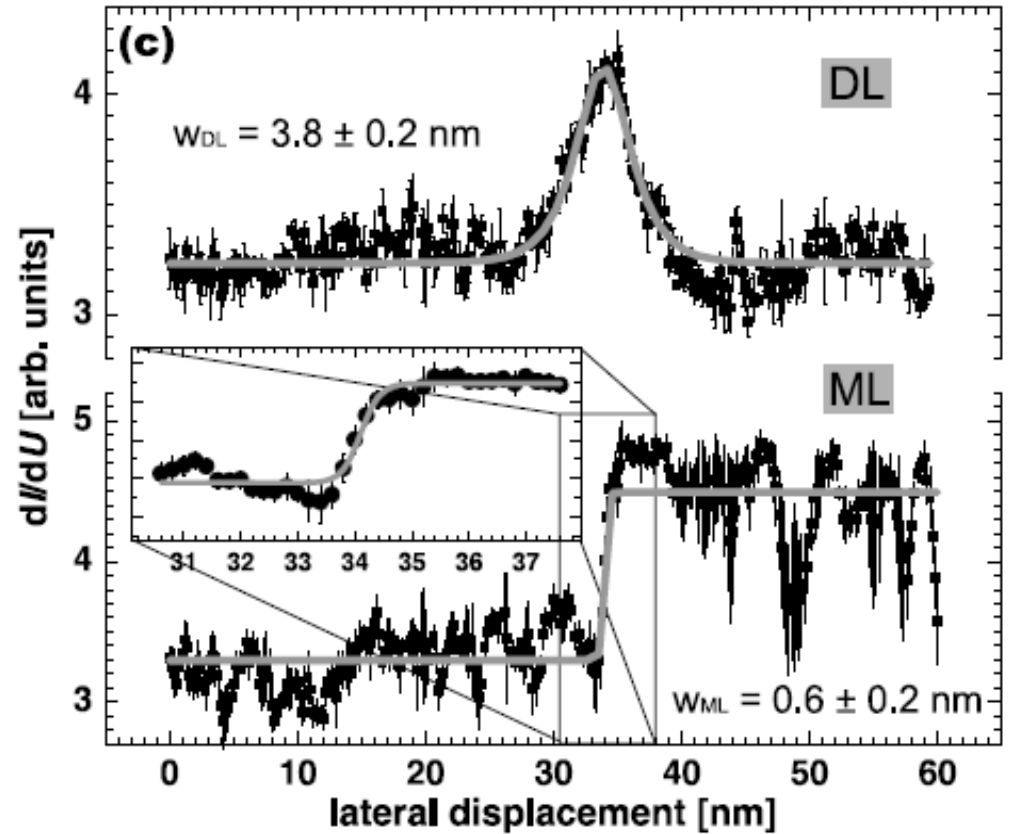
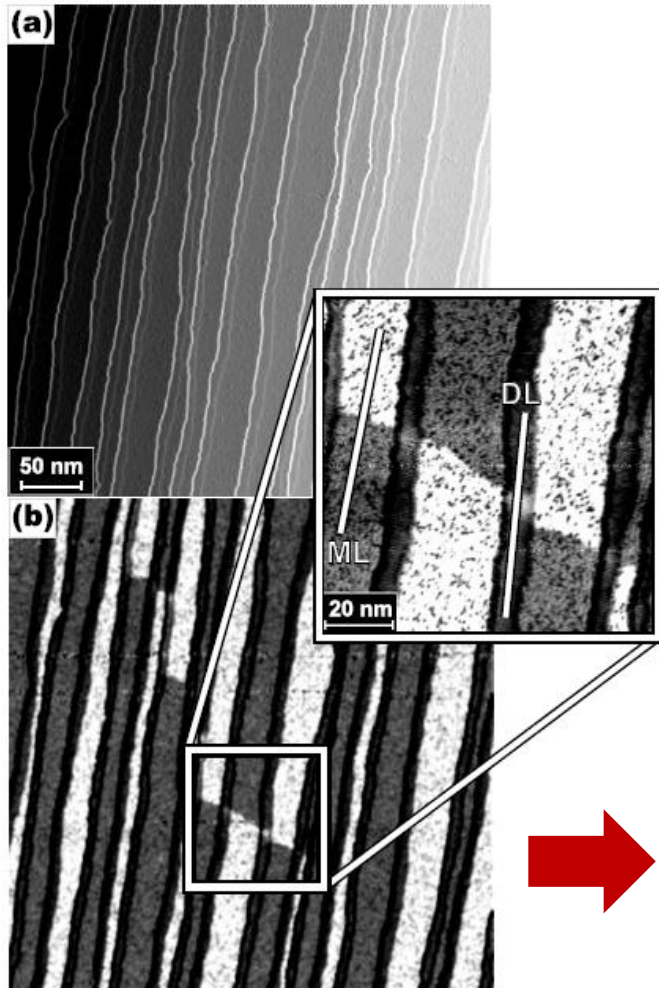
Spin polarized image of the spin lattice (Fe/W tip)



Spin sensitivity down to the atomic scale !

# Magnetic domain wall

Fe layer on W(110) :

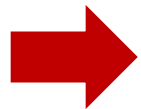
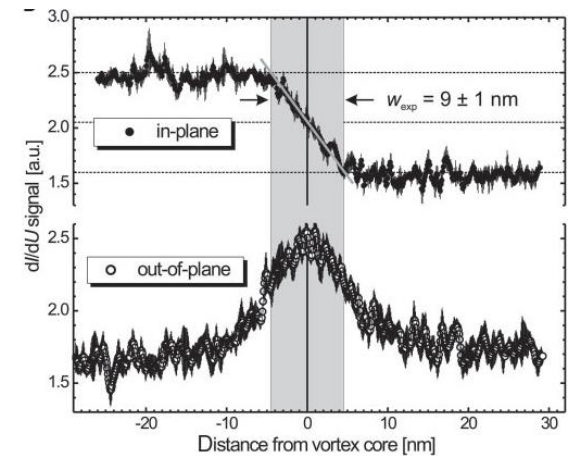
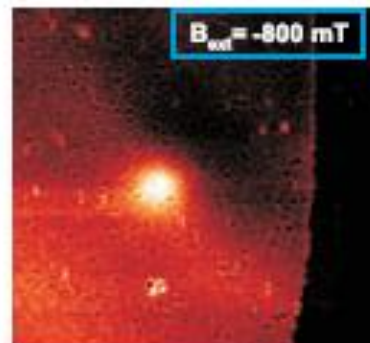
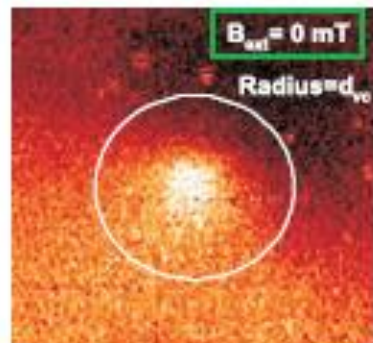
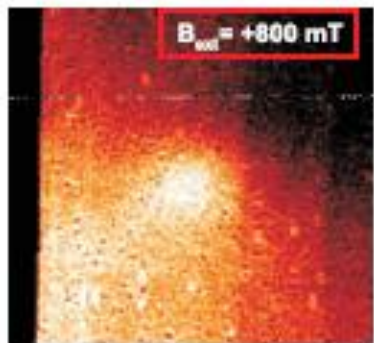
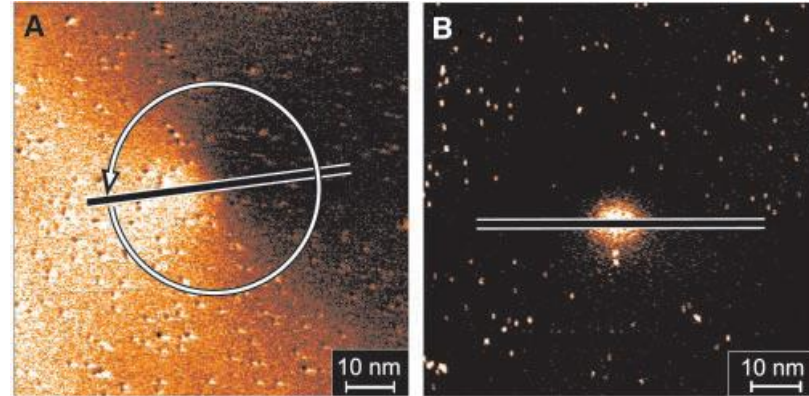
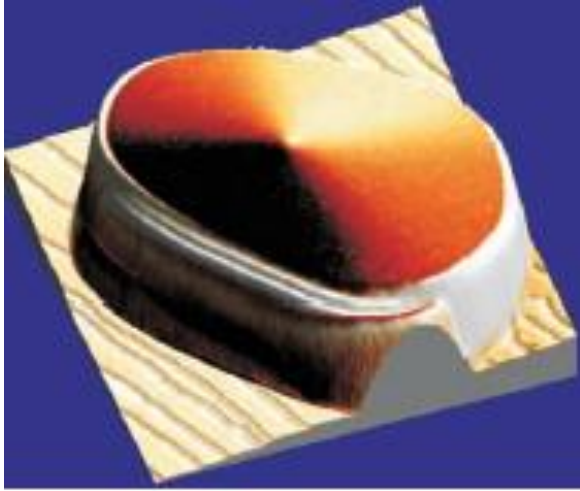


Atomic domain wall, fits well micromagnetic theory

$$K = 20 \times 10^6 \text{ J/m}^3 !$$

# Magnetic vortex

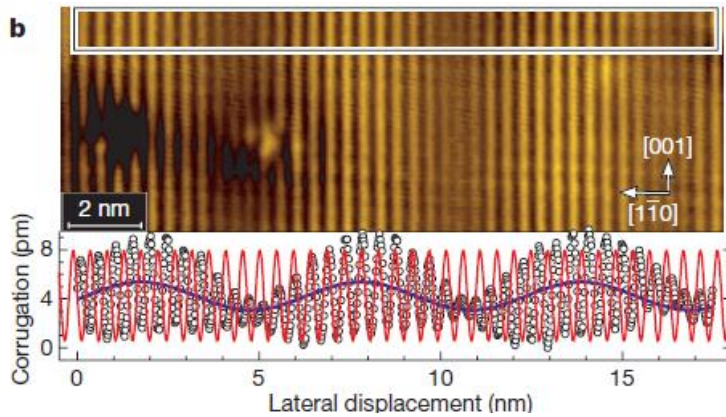
Magnetic vortex in Fe islands on W(110) :



First measure of a vortex core and its size dependence with magnetic field

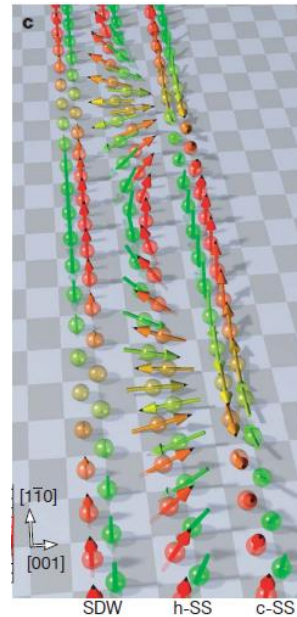
# Towards non collinear magnetism

Mn monolayer on W(110) : spin spiral



➔ Dzialoszynski-Moriya interaction

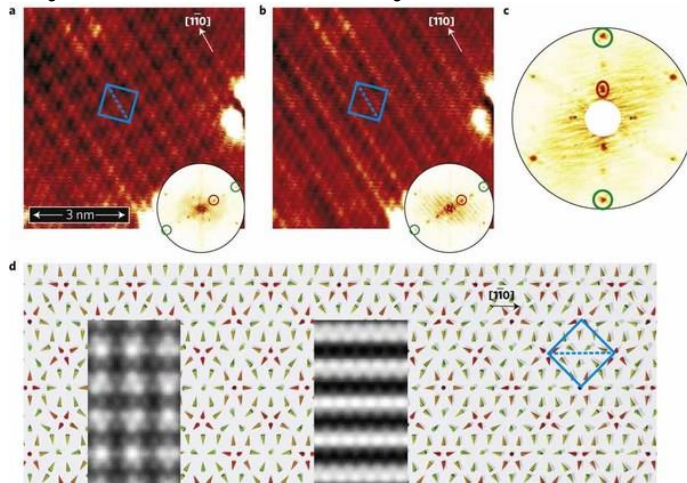
M. Bode et al. Nature 447 (2007) 190



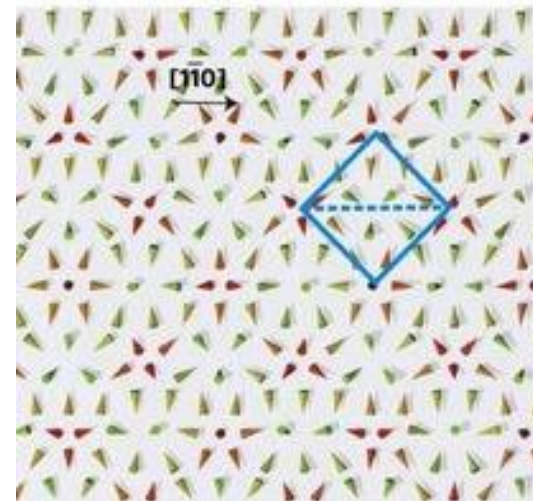
$$E_{\text{DM}} = \sum_{\langle i,j \rangle} d(\vec{u}_{ij} \times \hat{z}) \cdot (\vec{S}_i \times \vec{S}_j)$$

Due to spin-orbit coupling  
and low symmetry

Fe monolayer on Ir(111) : skyrmion lattice

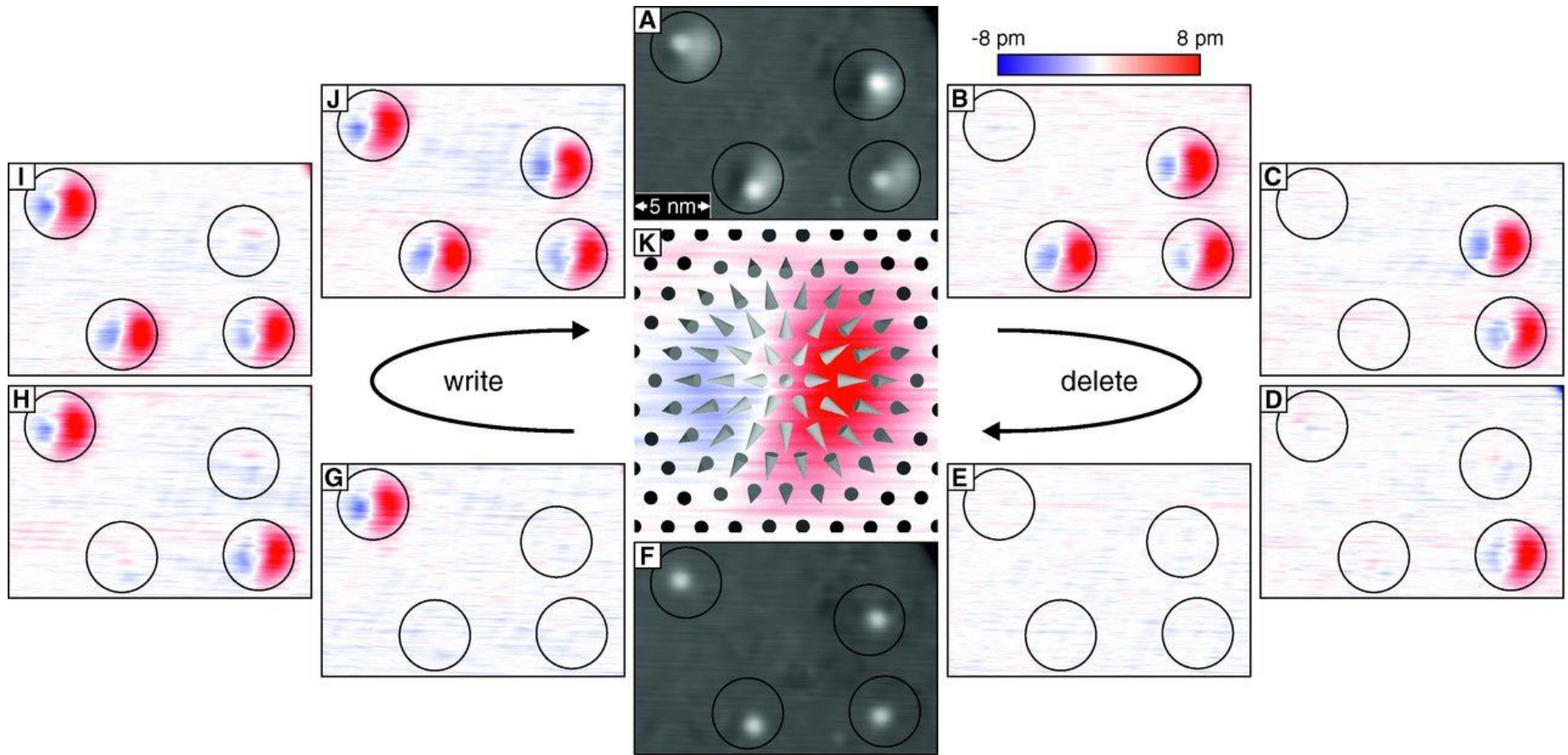


S. Heinze et al. Nature Phys. 7 (2011) 713



# Writing and deleting nanobubbles

Pd/Fe/Ir(111) : skyrmion lattice under magnetic field



The creation and annihilation of these magnetic nanobubbles is induced by the spin torque of the tunneling current (Spin Torque Transfer)

# Nanobubbles magnetic memory ?

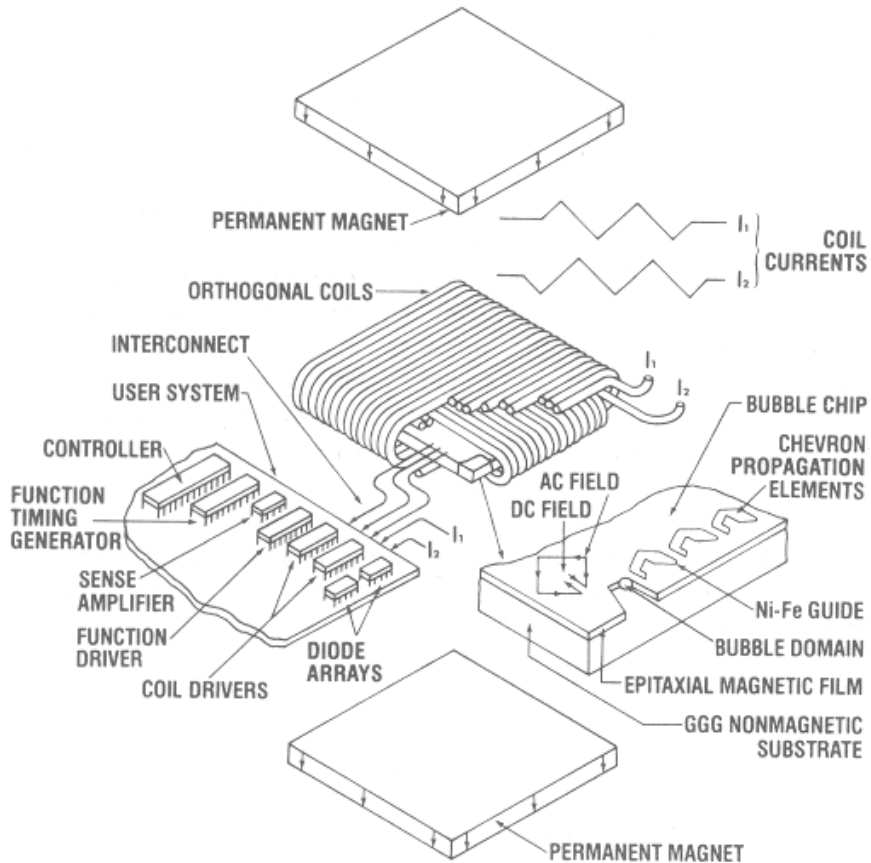


FIGURE 1—MAGNETIC-BUBBLE MEMORY (EXPLODED VIEW)

# Outline

## Theoretical and technical background

Tunnel magneto-resistance

Scanning Tunneling Spectroscopy

Magnetic tips and surfaces

## SP-STM : a tool to study nanomagnetism

Background of magnetism

Domain wall, vortex

Skyrmions

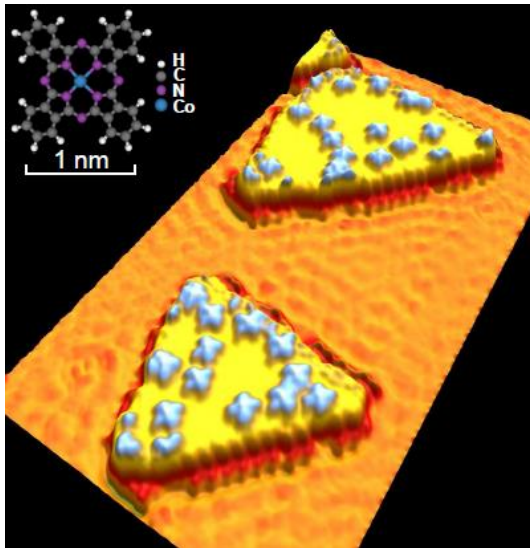
## Towards nanospintronics

Molecular spintronics

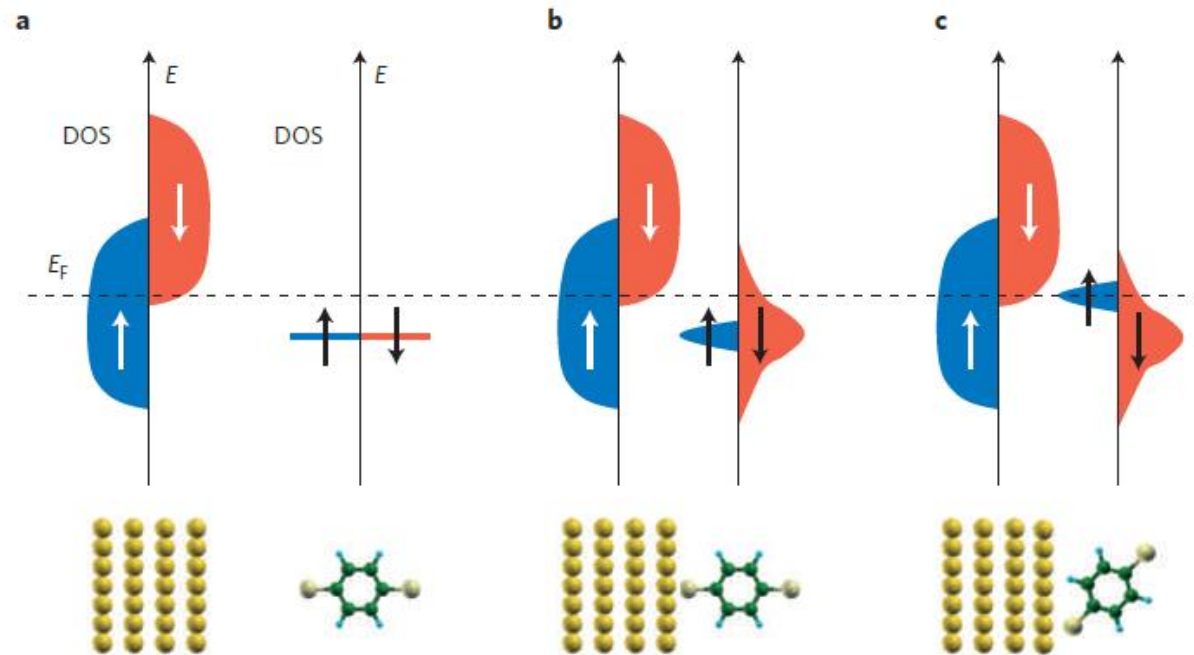
Atomic spin logic

# Coupling a single molecule to magnetic electrodes

## Magnetic molecule

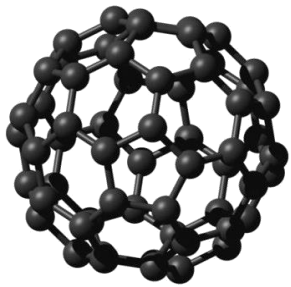


## Non magnetic molecule



# Molecular spin polarization

C<sub>60</sub>

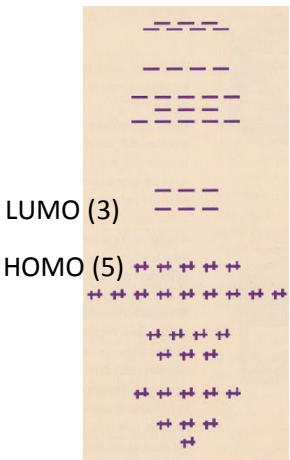


12 pentagons  
20 hexagons

$$H = \begin{bmatrix} H_{mol} & \tau \\ \tau^+ & H_{sub} \end{bmatrix}$$

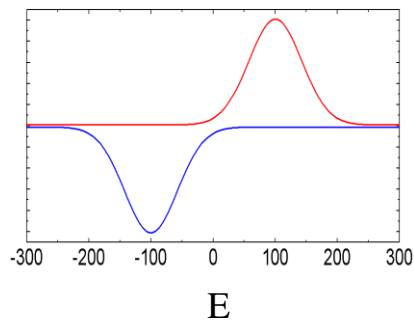
$$\rho(\vec{r}, E) = \sum_{n,m} G^{mol}_{n,m}(E) \cdot p_z(\vec{r} - \vec{r}_n) \cdot p_z(\vec{r} - \vec{r}_m) \propto \frac{dI}{dV}$$

$$G^{mol}(E) = [EI - H_{mol} - \Sigma(E)]^{-1}$$

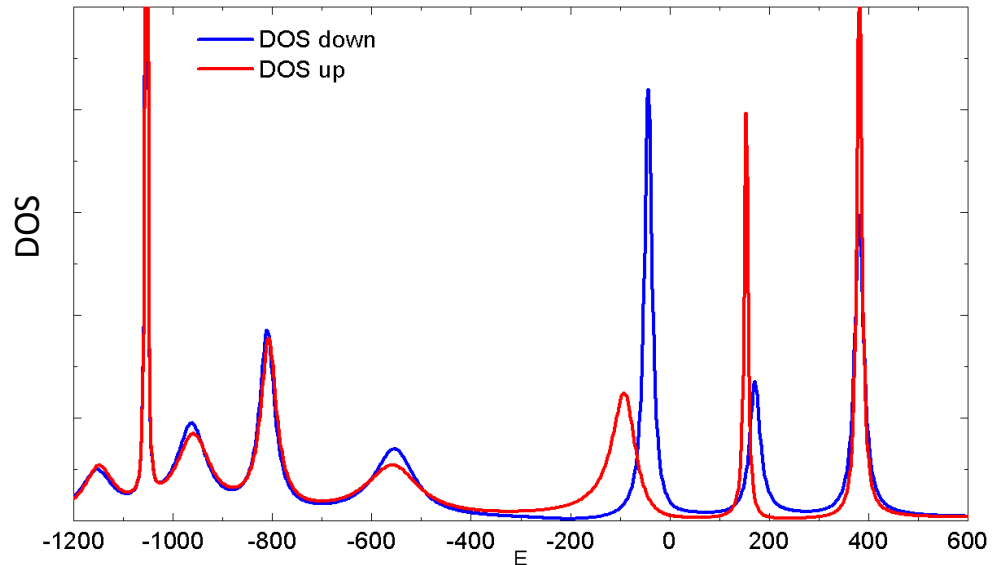


Tight-binding scheme of the C<sub>60</sub> molecule

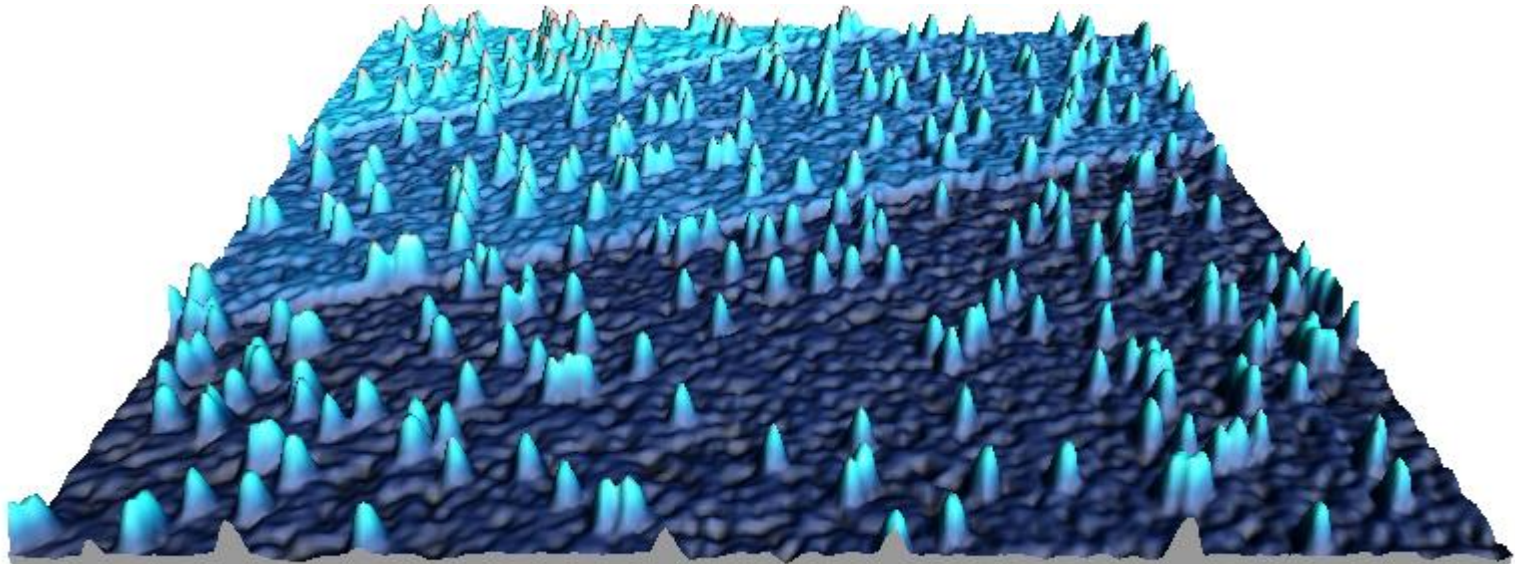
DOS of the magnetic substrate



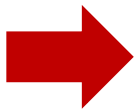
Spin dependant molecular orbitals



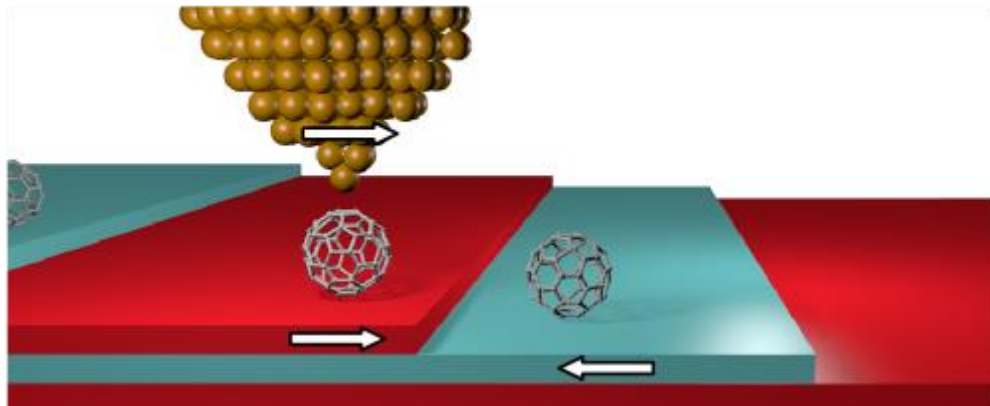
# $C_{60}$ molecules on Cr(001)



100\*100 nm<sup>2</sup>



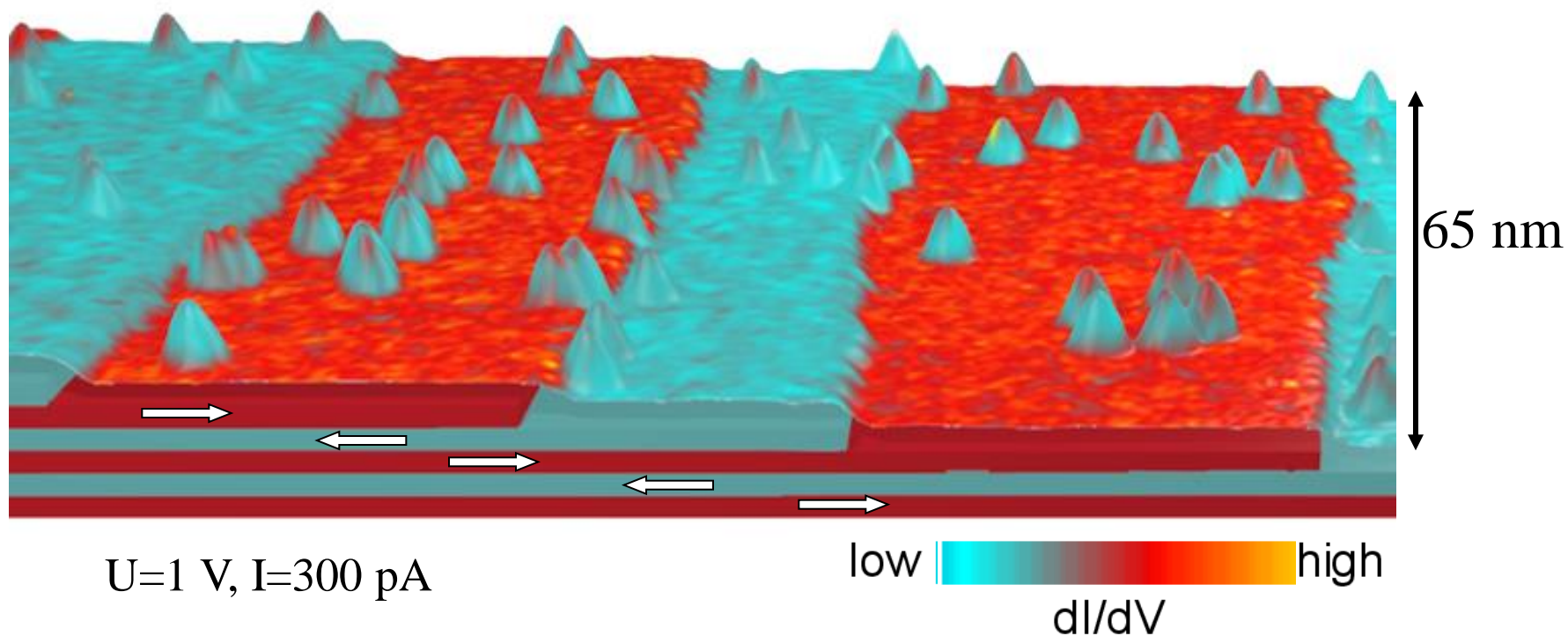
Compare  $C_{60}$  on spin up and spin down terraces to measure the  $C_{60}$  spin polarization



# SP-STM on $C_{60}/Cr(001)$

3d scale: topography

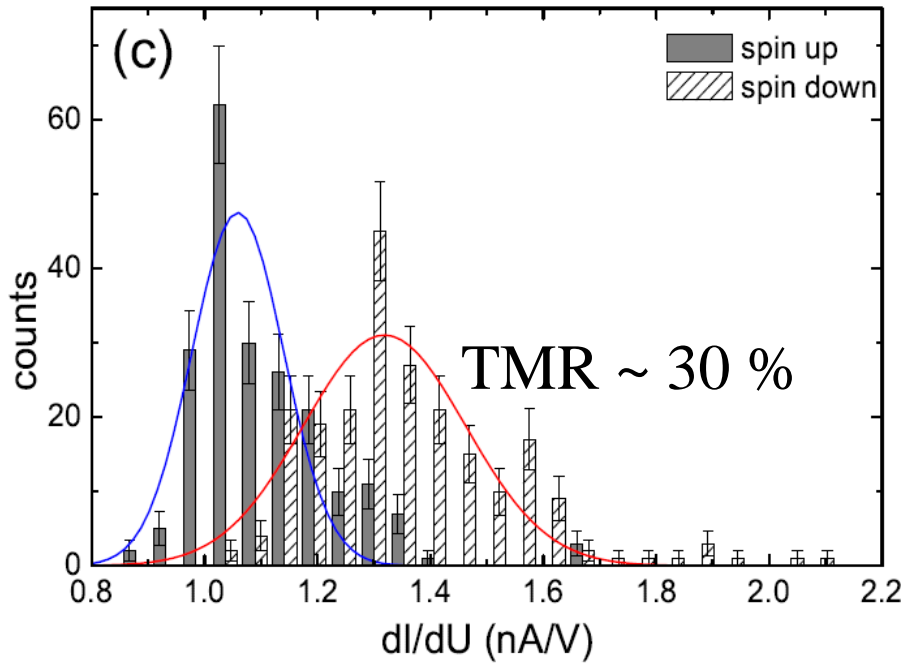
colorscale: conductance map at  $-0.025$  V



**Magnetic contrast and intramolecular resolution**

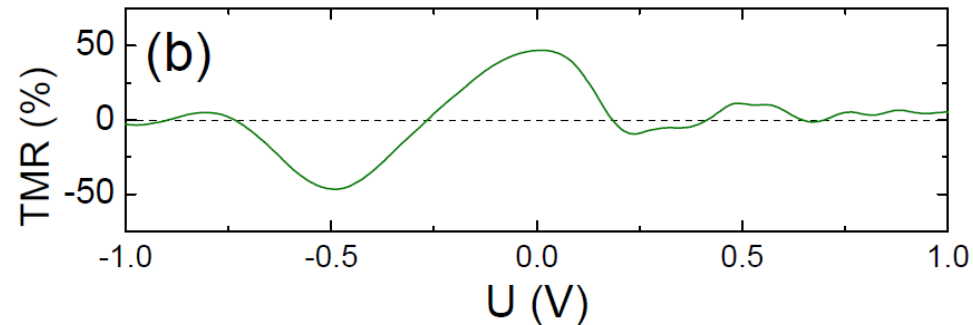
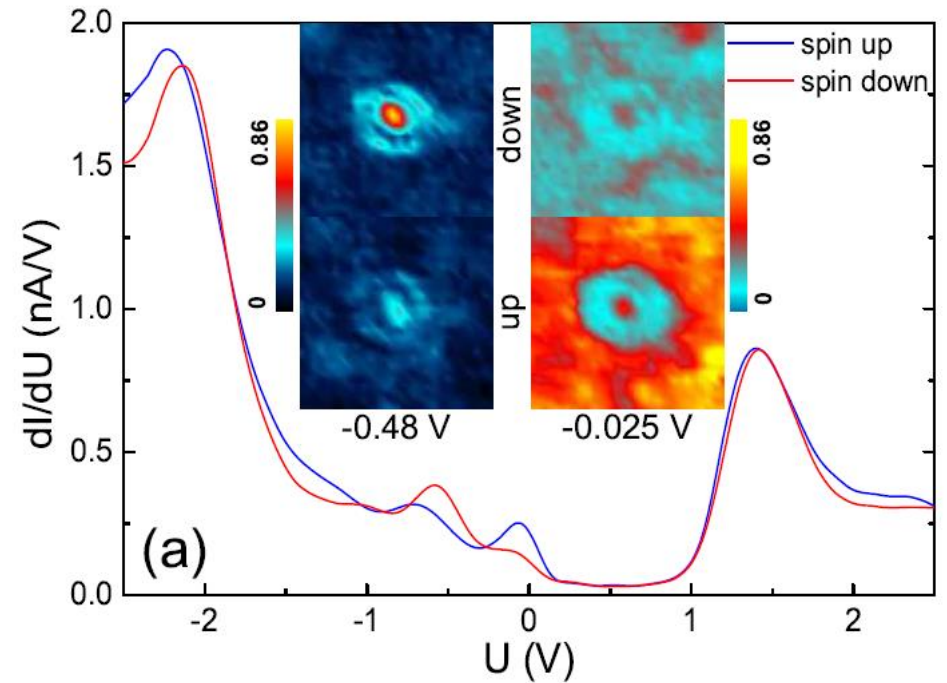
# A statistical analysis

Local conductance at -0.5 V  
of 450 molecules



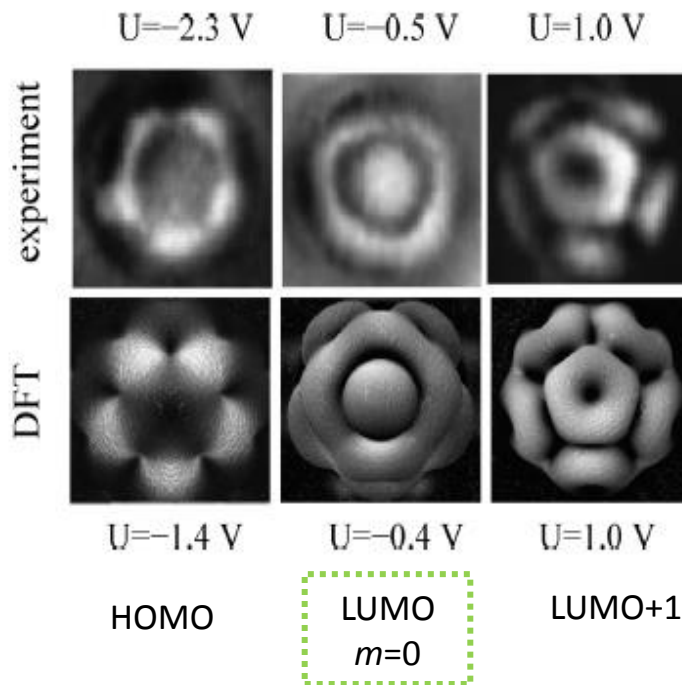
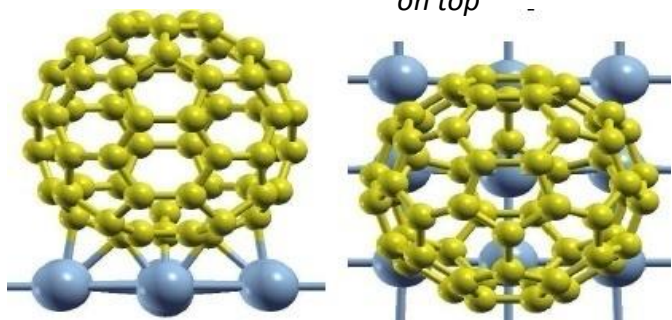
$$TMR = \frac{G_{\uparrow\uparrow} - G_{\uparrow\downarrow}}{G_{\uparrow\downarrow}}$$

Spin polarized molecular density of states



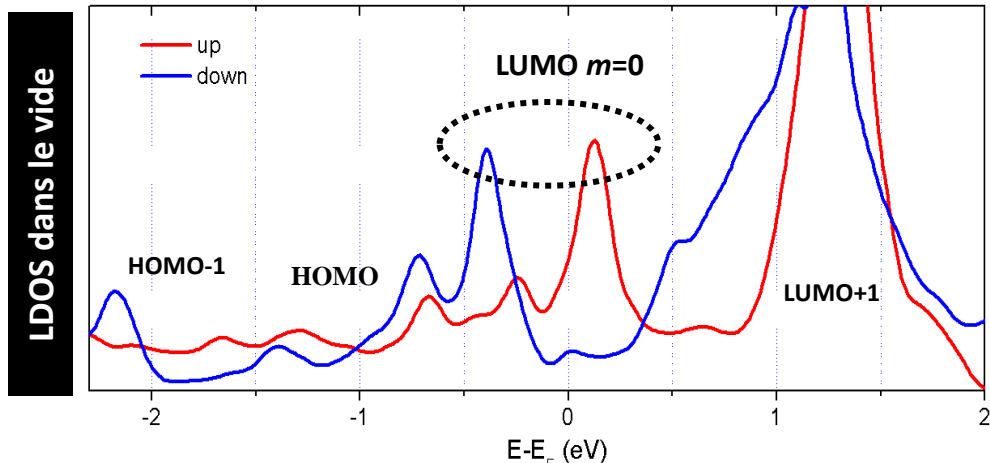
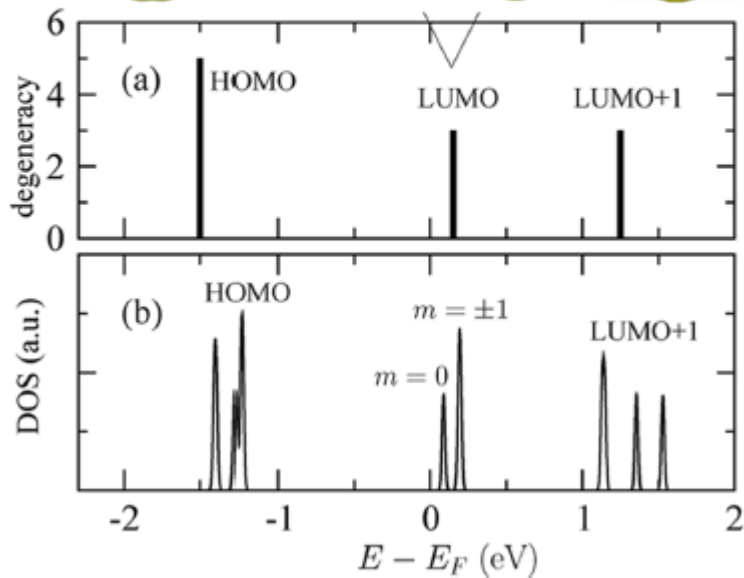
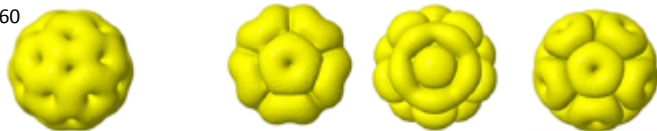
# Ab initio calculations

Relaxed structure on the most favored adsorption site :  
*on top*

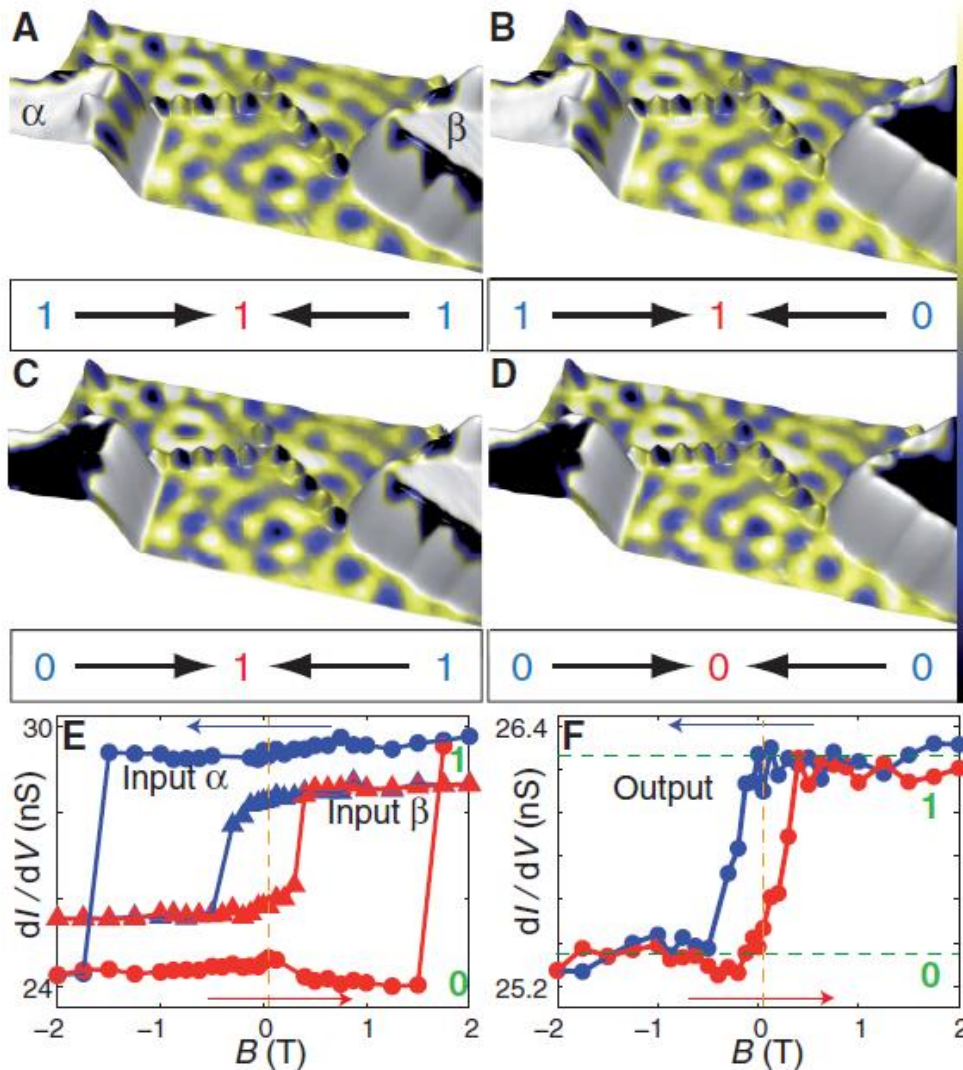


Iso-surfaces  
of a free C<sub>60</sub>

$m = \pm 1$     $m = 0$



# Controlling the spin at the atomic scale



- Manipulation and SP-STM of single atoms
- RKKY interactions between Co adatoms
- Hysteresis cycle on a single Co adatom
- Realisation of a OR gate

# SP-STM : a unique tool to study magnetism at the atomic scale

The poor control of the spin direction and polarization of the tip makes this technique difficult

It allows the observation of new spin structures at the nanoscale : opens new routes for magnetism

Towards quantum spintronics  
at the atomic and molecular scale