Véronique Pierron-Bohnes
(IPCMS, Strasbourg)
"Electron holography on Magnetic nanoparticles"

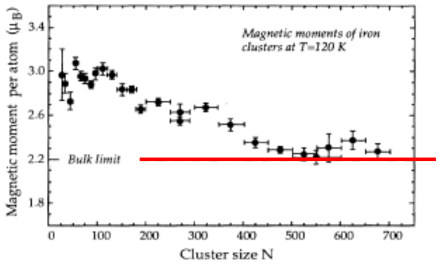
- Magnetic properties of bulk materials
  - Dia-para-ferromagnetism
  - Susceptibility
  - Applications
- Magnetic properties of nano-objects
  - Moments and Curie temperature
  - Energies in competition
  - Applications
- Electron holography
  - Principle
  - Examples

MAGNETISM OF NANO-OBJECTS magnetic moments

Moments at 0K often larger on surface

atomic moment in Fe clusters

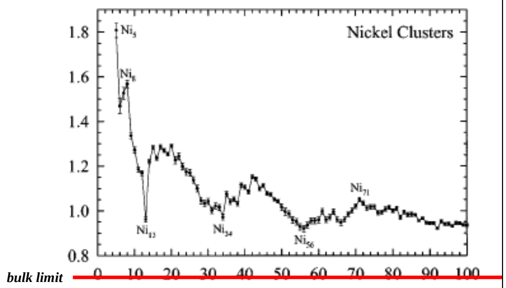
IML Billas, JA Becker, A Chatelain, WA de Beer, PRL 71 (1993) 4067
Magnetic moments of Iron clusters with 25 to 700 atoms and their dependence on temperature



atomic moment in Ni clusters

S. E. Apsel, J. W. Emmert, J. Deng, and L. A. Bloomfield, Phys. Rev. Lett. 76, 1441 (1996),
Surface-Enhanced Magnetism in Nickel Clusters

Extrapolated @ 0 K (to compensate thermal fluctuations)



Density Functional Theory (DFT) calculations

G. Guzman-Ramırez, J. Robles, A. Vega, F. Aguilera-Granja, J. Chem. Phys. 134, 054101 (2011)
Stability and magnetic phase diagram of ternary ferromagnetic 3d-transition-metal nanoalloys with five and six atoms: DFT study

$\mu_{at}(\mu B)$	N=5	N=6	*N=∞*
Ni_N	1.20	1.33	*0.7*
Co_N	2.60	2.33	*1.7*
Fe_N	3.60	3.33	*2.2*

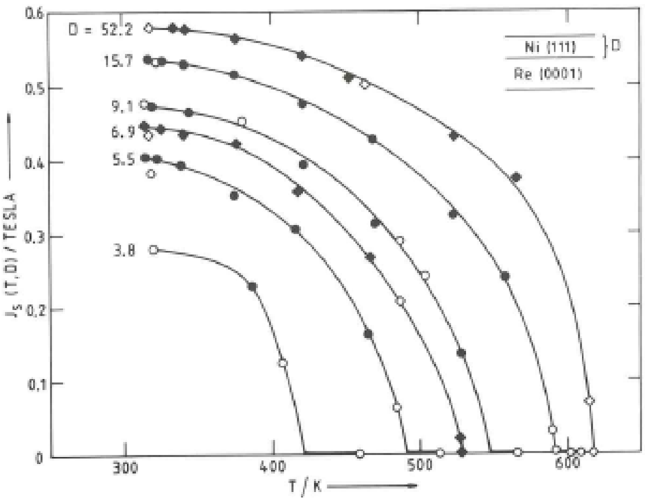
The magnetic moments are sensitive to the presence of a surface : broken bonds and relaxation for example have a strong effect. In nanoparticles, the surface is near to many atoms and the effect is very strong. Usually the moments are increased in small objects. It has been shown experimentally using a Stern and Gerlach experiment with iron and nickel clusters. The average atomic moment is larger than in bulk and varies with the configuration of the clusters. The calculation have been done only for very small numbers of atoms and show the same trend.

MAGNETISM OF NANO-OBJECTS Curie temperature

Curie temperature near a surface is often lower than in bulk (smaller coordination):

$T_C = \alpha zJ/k_B$ in Heisenberg model

⇒ M(T)/M(0K) smaller on surface
⇒ decrease of magnetization on surface
⇒ M(T) in nanoparticles cannot be predicted easily



Saturation magnetization of Ni(111) films on Re(0001) substrate versus T with different numbers of atomic layers

U. Gradmann, in *Handbook of Magnetic Materials*, edited by K.H. J. Buschow (North-Holland, Amsterdam, 1993), Vol. 7, Chap 1.

U. Gradmann, in *Handbook of Magnetic Materials*, edited by K.H. J. Buschow (North-Holland, Amsterdam, 1993), Vol. 7, Chap 1.

The coupling between atomic moments is also changed, giving rise to a change of the Curie temperature, that generally decreases due to the presence of a surface.The effect has been shown for example in thin film of nickel on a renium substrate. The combination of the two effects : increase of the moment, but decrease of Curie temeprature imly that at room temperature either an increase or a decrease of the magnetization can be observed.

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MAGNETISM OF NANO-OBJECTS Energies in competition

$$F = F_{exch} + F_{ani} + F_{dip} + F_{zee} \quad \text{and} \quad k_B T \ !$$

$$E_{exch} = -J \sum_{i,j} \boldsymbol{\mu}_j \boldsymbol{\mu}_i$$

at atomic scale

$$F_{exch} = -J\cos(\theta_{MM}) = -\mu_0 \lambda M^2$$ Mean Field approximation

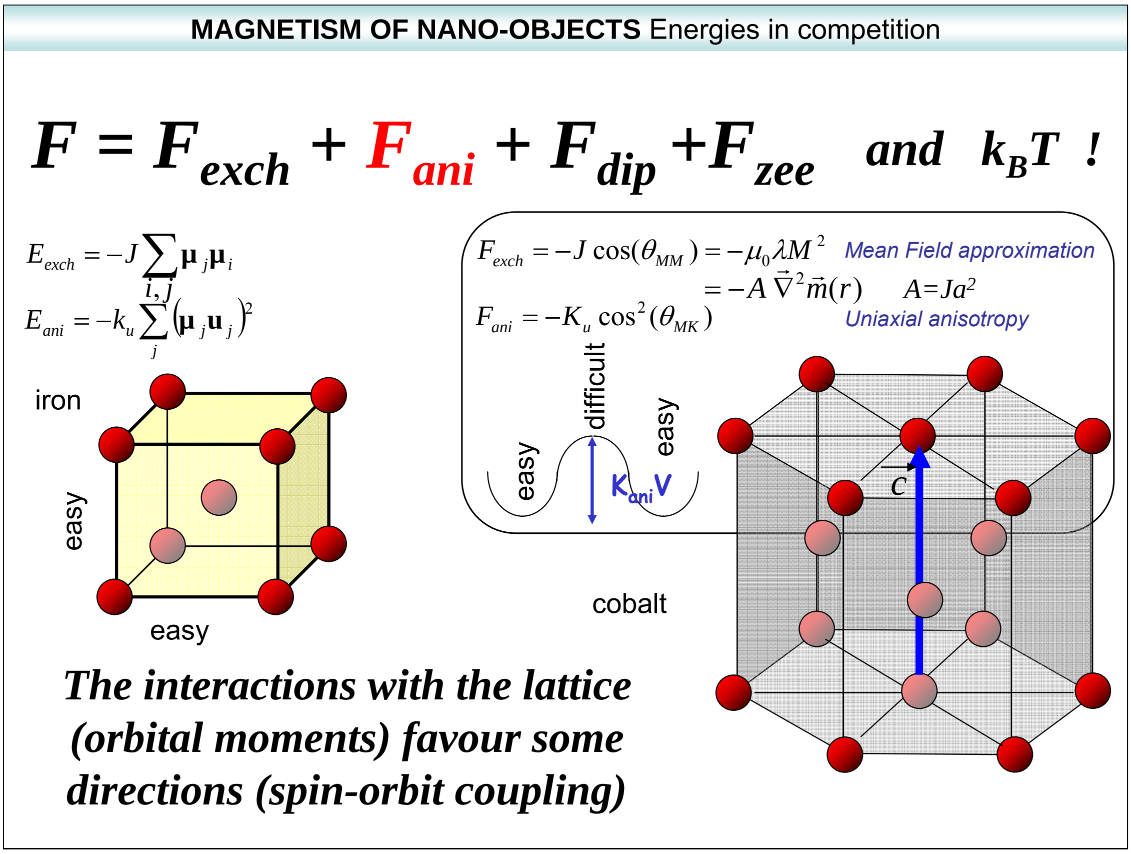
$$= -A\,\vec{\nabla}^2 \vec{m}(r) \qquad A = Ja^2$$ Weiss

macroscopic expression

Simplest approximate expressions (continuous approximation)

Neighbour moments prefer to be aligned

The molecular field described by Weiss is the responsable of the magnetisation existence locally. I will give the atomic scale and the macroscopic scale expressions for each energy. Weiss expression is at macroscopic scale. Magnetic moments of neighbours prefer to be aligned.



When there is a coupling between the orbital moments and the spin moments, the total energy is sensitive to the orientation of the magnetisation compared to the cristal structure. There is a favored direction that is called the easy axis. In bcc Iron it is the [100] direction. In hcp Cobalt it is the direction of the c axis. An energy has to be given to the sample to deviate the magnetisation from the easy direction.

MAGNETISM OF NANO-OBJECTS Energies in competition

$$F = F_{exch} + F_{ani} + F_{dip} + F_{zee} \quad \text{and} \quad k_B T \; !$$

$$E_{exch} = -J \sum_{i,j} \boldsymbol{\mu}_j \boldsymbol{\mu}_i$$

$$E_{ani} = -k_u \sum_j \left(\boldsymbol{\mu}_j \mathbf{u}_j\right)^2$$

$$E_{dip} = -\frac{\mu_0}{4\pi} \sum_{i,j} \frac{\lfloor 3(\boldsymbol{\mu}_i \mathbf{u}_{ij})\, \mathbf{u}_{ij} - \boldsymbol{\mu}_i \rfloor}{r_{ij}^3} \boldsymbol{\mu}_j$$

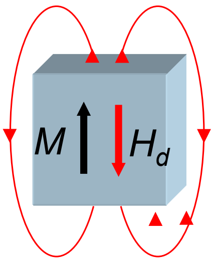
$F_{exch} = -J\cos(\theta_{MM}) = -\mu_0 \lambda M^2$ *Mean Field approximation*

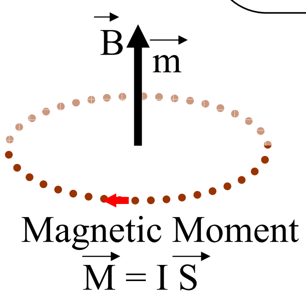
$= -A\,\vec{\nabla}^2 \vec{m}(r) \qquad A = Ja^2$

$F_{ani} = -K_u \cos^2(\theta_{MK})$ *Uniaxial anisotropy*

$F_{dip} = -\frac{\mu_0}{2} M H_d = N_d \frac{\mu_0}{2} M^2 \approx K_d$ *for uniform magnetisation*

Simplest approximate expressions (continuous approximation)





Farer neighbour moments create a magnetic field

$$H_{dip}(R_j) = -\frac{\mu_0}{4\pi} \sum_i \frac{\lfloor 3(\boldsymbol{\mu}_i \cdot \mathbf{u}_{ij})\, \mathbf{u}_{ij} - \boldsymbol{\mu}_i \rfloor}{r_{ij}^3}$$

(magnetic dipole field)

A third energy is due to the field created by the moments far from the farer moments. Depending on the symmetry of the sample: of the limits: sphere, cube, platelet… the average value is proportional to the squared magnetisation with a geometrical factor Nd called demagnetizing factor.

MAGNETISM OF NANO-OBJECTS Energies in competition

$$F = F_{exch} + F_{ani} + F_{dip} + F_{zee} \quad \text{and} \quad k_B T \ !$$

$$E_{exch} = -J \sum_{i,j} \boldsymbol{\mu}_j \boldsymbol{\mu}_i$$

$$E_{ani} = -k_u \sum_j \left(\boldsymbol{\mu}_j \mathbf{u}_j\right)^2$$

$$E_{dip} = -\frac{\mu_0}{4\pi} \sum_{i,j} \frac{\left[3\left(\boldsymbol{\mu}_i \mathbf{u}_{ij}\right) \mathbf{u}_{ij} - \boldsymbol{\mu}_i\right]}{r_{ij}^3} \boldsymbol{\mu}_j$$

$$E_{zee} = -\mu_0 \sum_j \boldsymbol{\mu}_j \mathbf{H}$$

$$F_{exch} = -J \cos(\theta_{MM}) = -\mu_0 \lambda M^2$$ Mean Field approximation

$$= -A \vec{\nabla}^2 \vec{m}(r) \qquad A = Ja^2$$

$$F_{ani} = -K_u \cos^2(\theta_{MK})$$ Uniaxial anisotropy

$$F_{dip} = -\frac{\mu_0}{2} M H_d = N_d \frac{\mu_0}{2} M^2 \approx K_d$$ for uniform magnetisation

$$F_{zee} = -\mu_0 M H \cos(\theta_{MH})$$

Simplest approximate expressions (continuous approximation)

interactions with external magnetic field

There is also the classical interaction with an external fiel if any

MAGNETISM OF NANO-OBJECTS Energies in competition

$$F = F_{exch} + F_{ani} + F_{dip} + F_{zee} \quad \text{and} \quad k_B T \; !$$

$$E_{exch} = -J\sum_{i,j} \boldsymbol{\mu}_j \boldsymbol{\mu}_i$$

$$E_{ani} = -k_u \sum_j \left(\boldsymbol{\mu}_j \mathbf{u}_j\right)^2$$

$$E_{dip} = -\frac{\mu_0}{4\pi}\sum_{i,j} \frac{\left[3\left(\boldsymbol{\mu}_i \mathbf{u}_{ij}\right)\mathbf{u}_{ij} - \boldsymbol{\mu}_i\right]}{r_{ij}^3}\boldsymbol{\mu}_j$$

$$E_{zee} = -\mu_0 \sum_j \boldsymbol{\mu}_j \mathbf{H}$$

$$F_{exch} = -J\cos(\theta_{MM}) = -\mu_0 \lambda M^2$$ Mean Field approximation

$$= -A\,\vec{\nabla}^2 \vec{m}(r) \qquad A = Ja^2$$

$$F_{ani} = -K_u \cos^2(\theta_{MK})$$ Uniaxial anisotropy

$$F_{dip} = -\frac{\mu_0}{2} M H_d = N_d \frac{\mu_0}{2} M^2 \approx K_d$$ for uniform magnetisation

$$F_{zee} = -\mu_0 M H \cos(\theta_{MH})$$

Simplest approximate expressions (continuous approximation)

Magnitude		(Energy density)	typical temperature
J	~	10^{+9} J/m^3	1000K (T_{Curie})
K_u	~	$10^{+5\pm 2}$ J/m^3	1mK-10K
$K_d = \frac{1}{2}\mu_0 M^2$	~	10^{+6} J/m^3	1K
$k_B T$	~	10^{+8} J/m^3	300K

Lecture of P.Panissod - French-Korean school NMS Strasbourg 2008

And the thermal energy that has to be compared to all other energies.

The orders of magnetitude of these energies are quite different: the exchange energy is the largest, the Curie temperature gives its value.

Magnetocrystalline and dipolar energies are quite simular and will be crucial to know the magnetic configuration.

We will now see the different anisotropy origins in nano-objects

MAGNETISM OF NANO-OBJECTS Magnetic anisotropy

Anisotropy = F depends on magnetization direction for several reasons

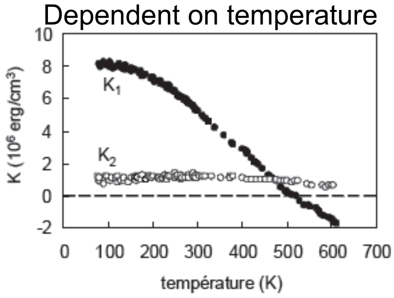
(a) magneto-crystalline anisotropy in bulk (related to structure symmetry)

$$E_{MC} = K_1 \sin^2 \theta + K_2 \sin^4 \theta$$

		fcc Co		hcp Co	
Easy axis		[111]		[0001]	
		K_1 (μeV/at)	K_2 (μeV/at)	K_1 (μeV/at)	K_2 (μeV/at)
300 K	Paige 84			37	9.0
	Weller 94	-3.9	0.90	30	9.0
	Suzuki 94	-4.5	0.07		
	Fassbender 98	-5.9			
77K	Suzuki 94	-5.0	1.4		
	Paige 84			57	6.9

HdR – R. Morel Grenoble 2009
http://tel.archives-ouvertes.fr/docs/00/39/25/96/PDF/HDR_Morel.pdf

Dependent on temperature



T_{Curie}=1115°C=1388K

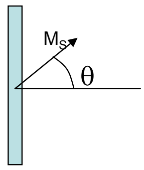
MAGNETISM OF NANO-OBJECTS Magnetic anisotropy

(b) Contribution of strains :

$F / V = K_\varepsilon \cos^2\theta$

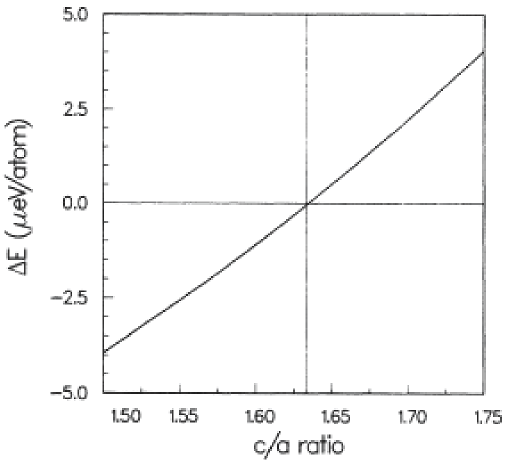
for biaxial strains

Effect of magnetostriction



same order of magnitude as magneto-crystalline anisotropy
in epitaxied films or nanoparticles

Co hcp



U. Gradmann, in *Handbook of Magnetic Materials*, edited by K.H. J. Buschow ~North-Holland, Amsterdam, 1993!, Vol. 7, Chap 1. p26

Le signe de l'anisotropie totale peut changer avec l'épaisseur selon le signe des différentes composantes

(c) Surface anisotropy (broken symmetry + cut bonds) Néel 1954

F / V = F / Sd = σ/d with : $\Sigma_m L \cos^2(\theta_m)$ où θ_m angle entre la liaison m et M

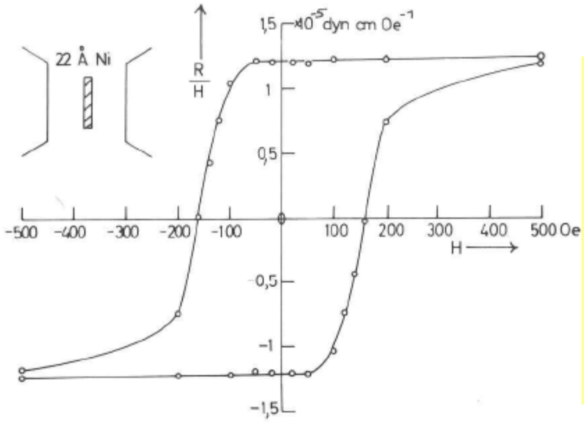
$$\sigma = K_s \cos^2 \vartheta + K_{s,p} \sin^2 \vartheta \cos^2 \varphi.$$

Bruno PRB 1989

In surface anisotropy (110 for example)

In any surface, M tends to be perpendicular to surfaces d'après Gradmann

Fe, Co, Ni : very thin films have easy magnetization axis perpendicular to surface (without strong strains)



Ni(111)2.2nm/Cu(111)
U. Gradmann, in *Handbook of Magnetic Materials*, edited by K.H. J. Buschow ~North-Holland, Amsterdam, (1993), Vol. 7, Chap 1. p26

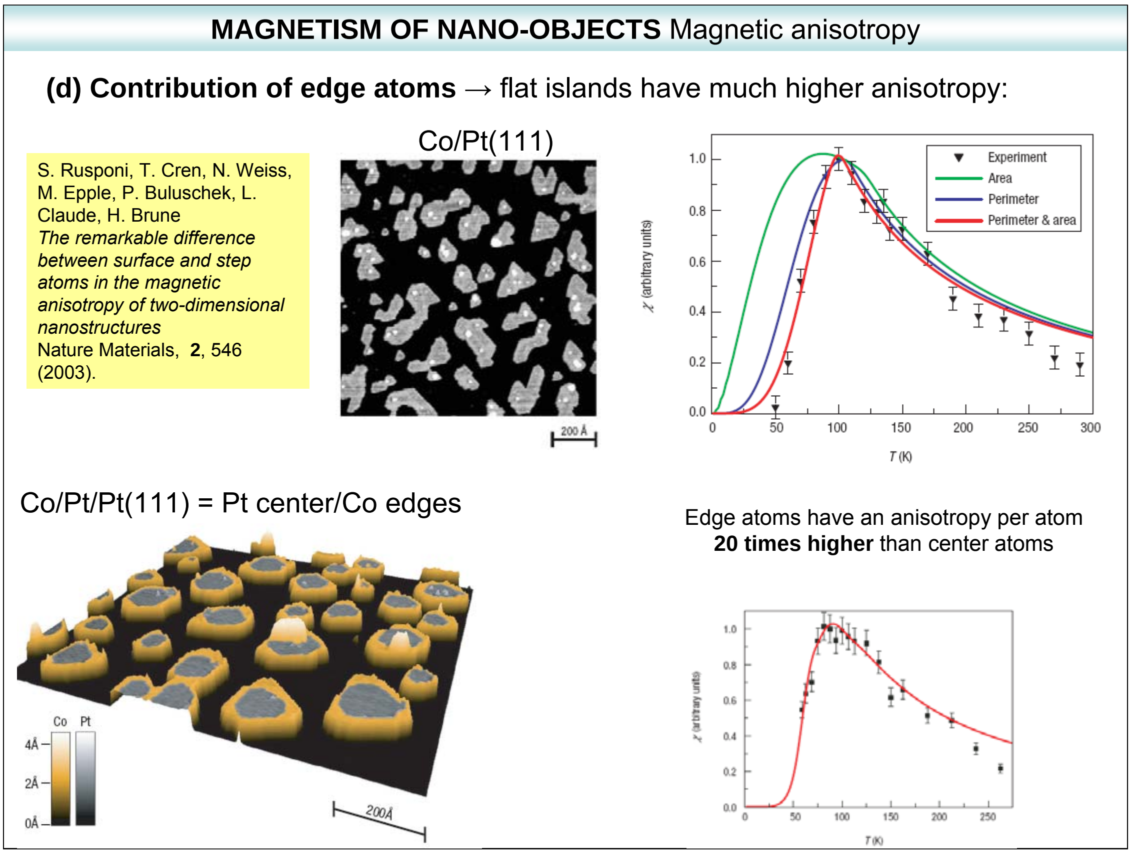
L. Néel
L'anisotropie superficielle des substances ferromagnétiques
CR Acad.Sci. Paris 237 (1953) 1468
J. Phys. Radium 15 (1954) 225

P. Bruno, PRB 39 (1989) 865
Tight-binding approach to the orbital magnetic moment and magnetocrystalline anisotropy in transition metal alloys

U. Gradmann, in *Handbook of Magnetic Materials*, edited by K.H. J. Buschow ~North-Holland, Amsterdam, 1993!, Vol. 7, Chap 1. p26

Le signe de l'anisotropie totale peut changer avec l'épaisseur selon le signe des différentes composantes

Néel a développé un modèle basé sur les liaisons coupées, modèle qui donne qualitativement les bons ordres de grandeur et le fait que les surfaces ouvertes ont un plus grande anisotropie de surface. La contribution de chaque liaison dépend du cos de l'angle de la liaison avec l'aimantation. Bruno a repris le modèle en liaisons forte en traitant le couplage spin-orbite en perturbations et retrouve plus quantitativement les même phénomènes.



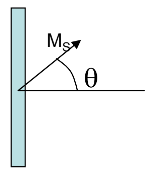
S. Rusponi, T. Cren, N. Weiss, M. Epple, P. Buluschek, L. Claude and H. Brune, Nature Materials, 2, 546 (2003). The remarkable difference between surface and step atoms in the magnetic anisotropy of two-dimensional nanostructures

A basse T le modèle d'Ising (seulement une direction et deux sens) est plus proche de la simulation numérique qui rend tout en compte. Plus T augmente plus on va vers un modèle de Langevin (toutes les directions possibles)

Formules valables seulement pour les articules épitaxiées étudiées selon leur axe de facile aimantation

(e) Shape anisotropy (magnetostatic – dipolar origin: F_{dip})

$$\vec{H}_d = -\mathbf{N}\,\vec{M} \Rightarrow F / V = (\mu_0 N M_S^2/2) \cos^2\theta$$



Tendancies:

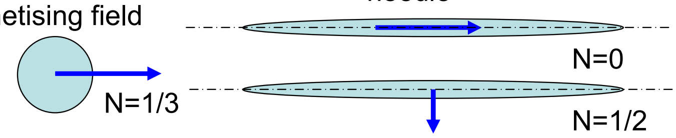
Formation of several domains with magnetization parallel to surface

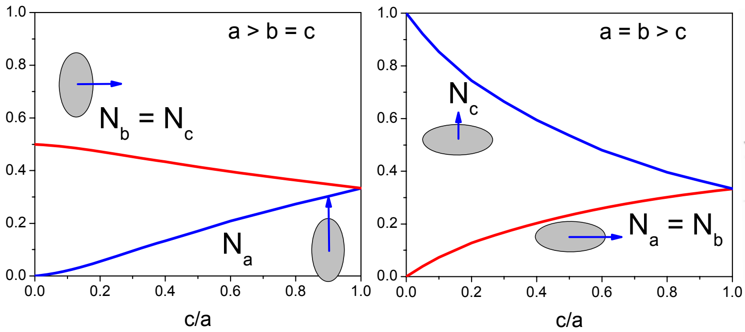
magnetization along the largest dimension if monodomain

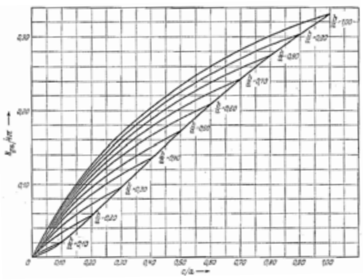
N tensor: coefficients of demagnetising field

ellipsoïds

diagonal with: $N_{xx}+N_{yy}+N_{zz}=1$







JA Osborn, phys. Rev.67 (1945) 35
ou E. Kneller, « Feromagnetismus » Springer Verlag, 1962

JA Osborn, phys. Rev.67 (1945) 35

Ou E. Kneller, « Feromagnetismus » Springer Verlag, 1962

$$F = F_{exch} + F_{ani} + F_{dip} + F_{zee} \quad \text{and} \quad k_BT\ !$$

E_{ani} = 0: Competition between dipolar and exchange energies

single domain?

or two domains ?

Scale #1: $l_{exch} = \sqrt{\dfrac{A}{K_d}}$

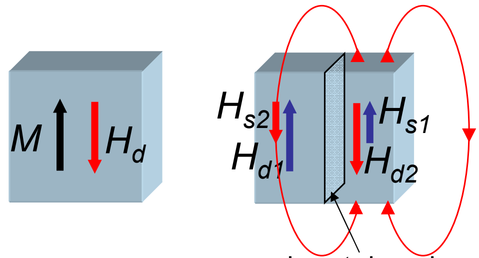
Typical value : 3 nm

($K_d=10^{+6}$ J/m³, $A=10^{-11}$ J/m)

(1000 atoms in the cube)

- *Sets the boundary between atomic and continuous*
- *Sets the mesh size in micromagnetic calculations*

1 domain or 2 domains ?



abrupt domain wall

1 domain	2 domains
$E=F_{dip}V$	$E=F'_{dip}V+F_{wall}S$
$E_{dip}= N_dK_da^3$	$E_{dip}=\left(\frac{1}{2}+\frac{1}{2}\right)\frac{1}{2}N_dK_da^3$
$E_{exch} = 0$	$E_{exch} =2Aa$

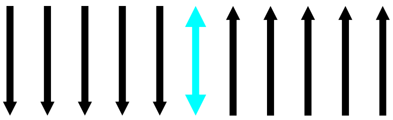
Single domain if $N_dK_da^3<4Aa$

i.e. $a < \sqrt{\dfrac{4A}{N_dK_d}} \approx \sqrt{\dfrac{A}{K_d}}$

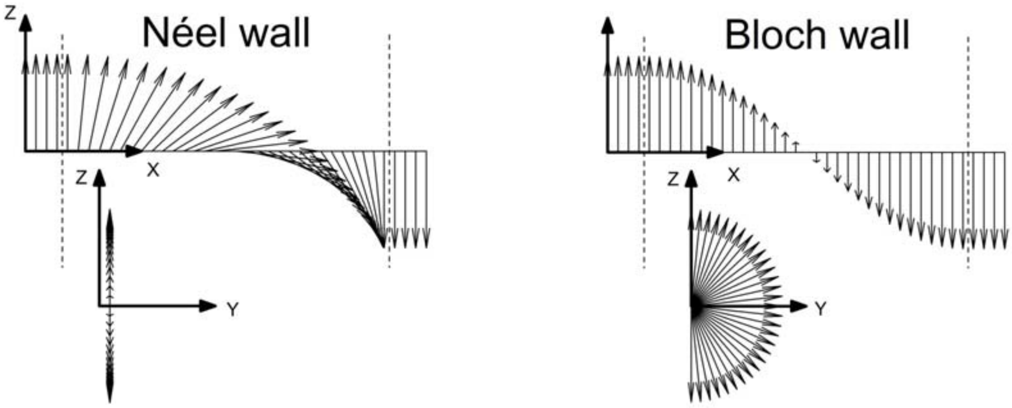
$$F = F_{exch} + F_{ani} + F_{dip} + F_{zee} \quad \text{and} \quad k_B T \ !$$

Competition between dipolar, exchange and anisotropy energies

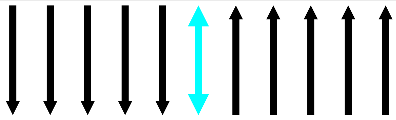
Abrupt domain wall ?
or extented domain wall ?



$E_{ani}=0$ but $E_{exch}=A$



$n \to \infty \Rightarrow E_{exch}=A\pi^2/n \to 0$ but $E_{ani}=nK_u/2 \to \infty$



E_{ani}=0 but E_{exch}=A

$E_{exch}=A\pi^2/n \rightarrow 0$ but $E_{ani}=nK_u/2 \rightarrow \infty$

Energy and domain wall width

Approximation : $d\theta/dx=\pi/na$, $\delta_{wall}= na$

$E_{exch}=Jna(\Delta\theta^2/2)=Ja^2\pi^2/2na=A\pi^2/2\delta_{wall}$

$E_{ani}= K_u na(1/2) = K_u\delta_{wall}/2$

E_{wall} minimum for $\delta_{wall} = \pi\sqrt{A/K_u}$

$E_{exch} = E_{ani} \rightarrow \sigma_{wall} = \pi\sqrt{AK_u}$

σ per wall area unit

Scale # 2 : $\delta_{wall} = \pi\sqrt{A/K_u}$

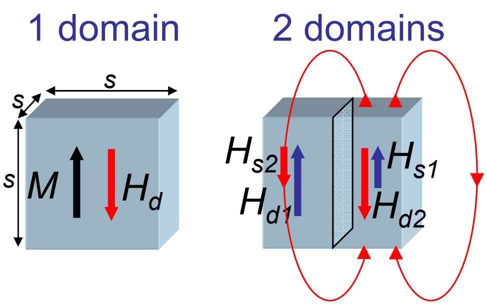
Typical values ($K_d=10^{+6}$ J/m³, $A=10^{-11}$ J/m)

Soft material ($K_u=10^{+3}$ J/m³) **:** δ_{wall} **~ 300 nm**

Medium ($K_u=10^{+5}$ J/m³) **:** δ_{wall} **~ 30 nm**

Hard material ($K_u=10^{+7}$ J/m³) **:** δ_{wall} **~ 3 nm**

MAGNETISM OF NANO-OBJECTS Magnetic configurations of nano-objects



$E=F_{dip}V$

$E_{dip}= N_dK_ds^3$

$E_{exch}+E_{ani}= 0$

$E=F'_{dip}V+F_{wall}S$

$E_{dip}= (1/2)\, N_dK_ds^3$

$E_{exch}+E_{ani}= \pi\sqrt{AK_u}\,s^2$

Single domain if $N_dK_ds^3<2$

$$\text{i.e.}\quad s < \frac{2\pi}{N_d}\frac{\sqrt{AK_u}}{K_d}$$

Scale # 3 : $d_{sing} = 6\pi\sqrt{AK_u}/K_d$

Typical values

($K_d=10^{+6}$ J/m^3, $A=10^{-11}$ J/m)

Soft material : d_{sing} **~ 2 nm**

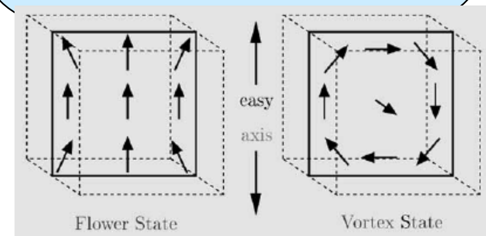
($K_u=10^{+3}$ J/m^3)

Medium : d_{sing} **~ 20 nm**

($K_u=10^{+5}$ J/m^3)

Hard material : d_{sing} **~ 200 nm**

($K_u=10^{+7}$ J/m^3)



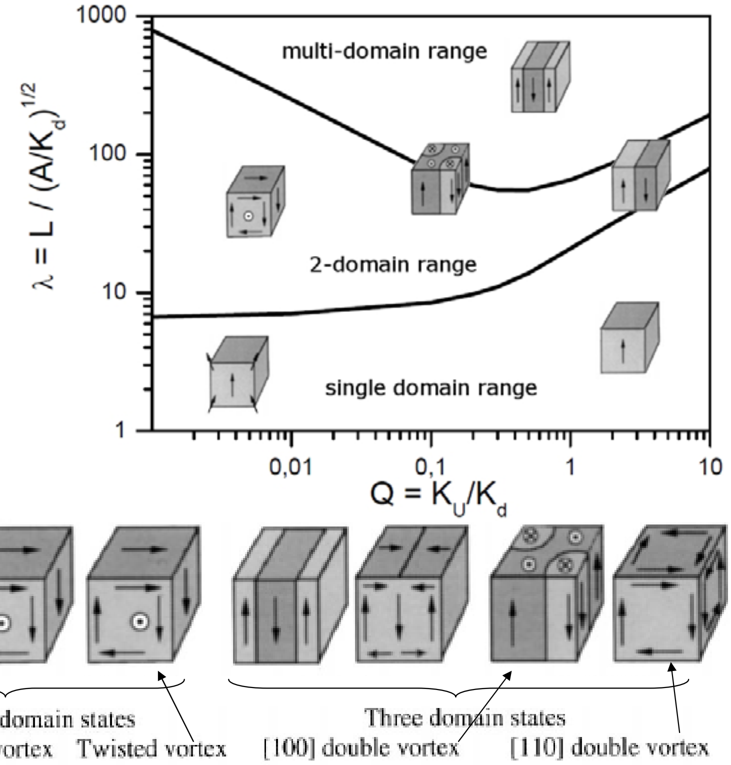
Inconsistency of the description/evaluation for soft materials

d_{wall} ~ 300 nm >> d_{sing} ~ 2 nm ! -> more complicated configurations in soft materials: flower, vortex…

MAGNETISM OF NANO-OBJECTS Magnetic configurations of nano-objects

for cubes:

Magnetic states of small cubic particles with uniaxial anisotropy
W. Rave, K. Fabian, A. Hubert
Journal of Magnetism and Magnetic Materials, ***190*** *(1998) 332*



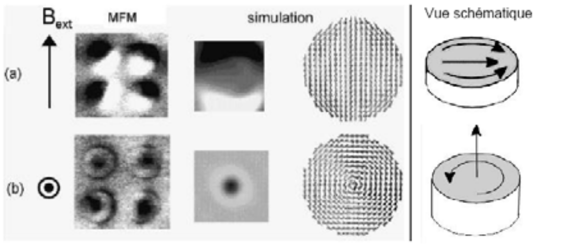
Magnetic states of small cubic particles with uniaxial anisotropy

W. Rave, K. Fabian, A. Hubert

Journal of Magnetism and Magnetic Materials, ***190*** *(1998) 332*

MAGNETISM OF NANO-OBJECTS Magnetic configurations of nano-objects

for discs:



MFM : Images enregistrées sur des plots de Co après application d'un champ (a) planaire ou (b) perpendiculaire (direction indiquée par la flèche noire à gauche). Simulation : contraste MFM simulé et distribution d'aimantation correspondante. Vue schématique de la distribution d'aimantation : état monodomaine planaire (a) et état vortex (b).

sans anisotropie K_U

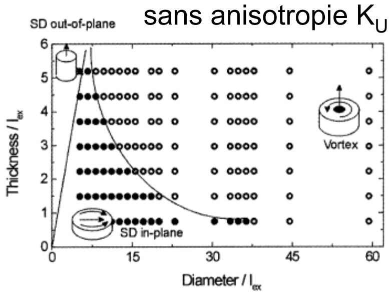


Fig. 2. The ground state phase diagram for polycrystalline ($K_u = 0$ J/m³) circular Co dots.

avec anisotropie K_U

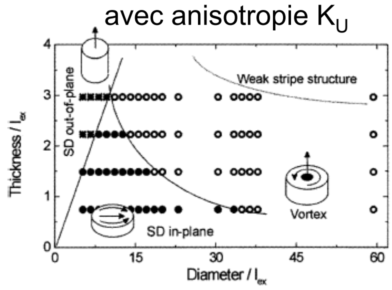


Fig. 3. The ground state phase diagram computed for epitaxial Co(0001) dots with $K_u = 5.0 \times 10^5$ J/m³.

Micromagnetic simulations of magnetisation in circular cobalt dots
Comp. Mat. Sc. 24 (2002) 181
L. D. Buda, I. L. Prejbeanu, U. Ebels, K. Ounadjela

PhD Thesis Liliana Buda – Strasbourg

Correlated Magnetic Vortex Chains in Mesoscopic Cobalt Dot Arrays

M. Natali, I. L. Prejbeanu, A. Lebib, L. D. Buda, K. Ounadjela, and Y. Chen1,

PRL 88 (2002) 157203

Investigation of 3D micromagnetic configurations in circular nanoelements

Journal of Magnetism and Magnetic Materials, ***Volumes 242**-245, Part 2, April 2002, Pages **996**-998*

L. D. Buda, I. L. Prejbeanu, U. Ebels, K. Ounadjela

Micromagnetic simulations of magnetisation in circular cobalt dots

COMPUTATIONAL MATERIALS SCIENCE 24 (2002) 181

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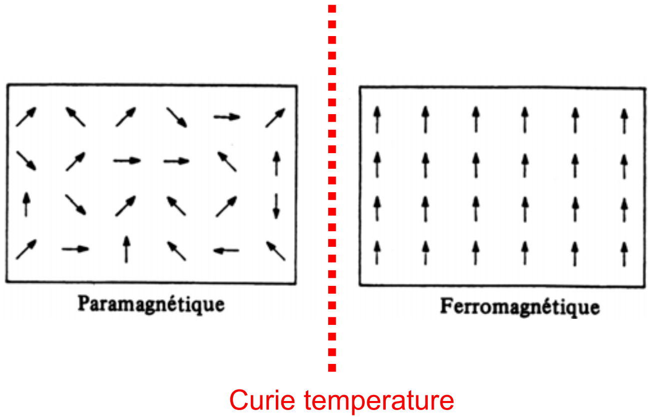
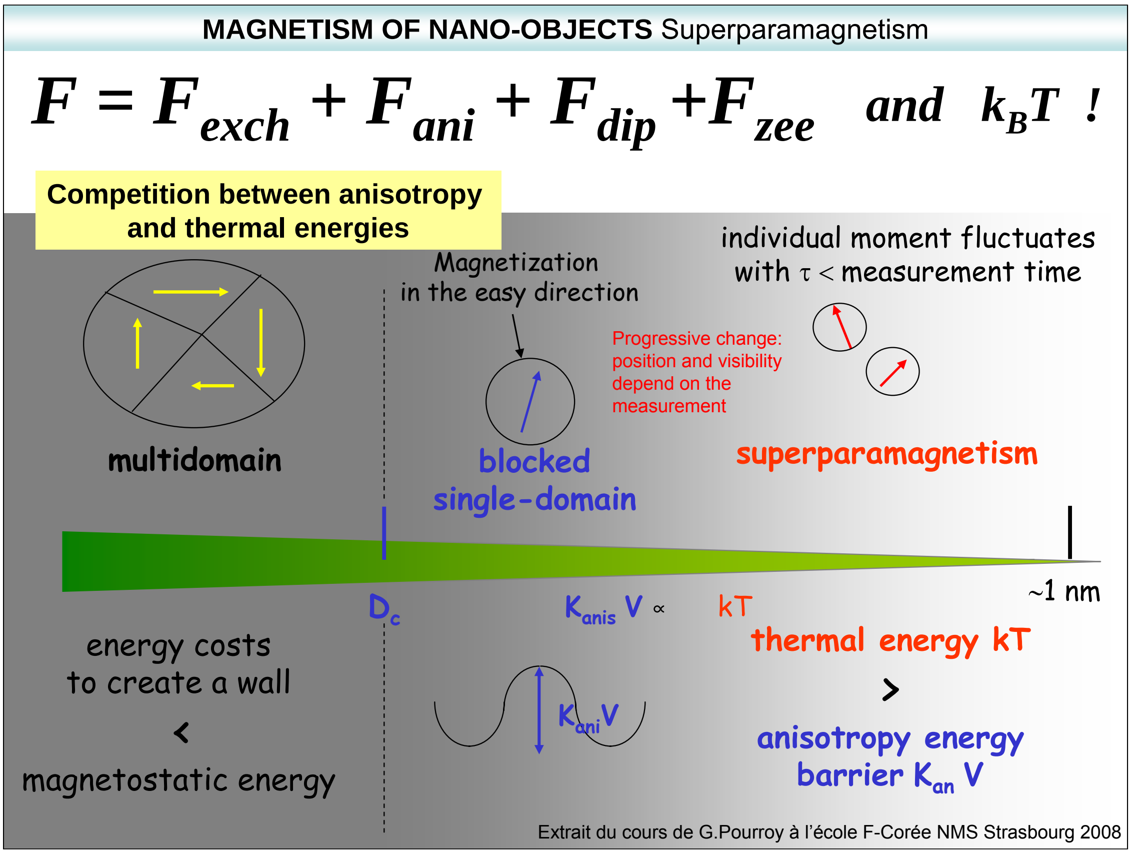
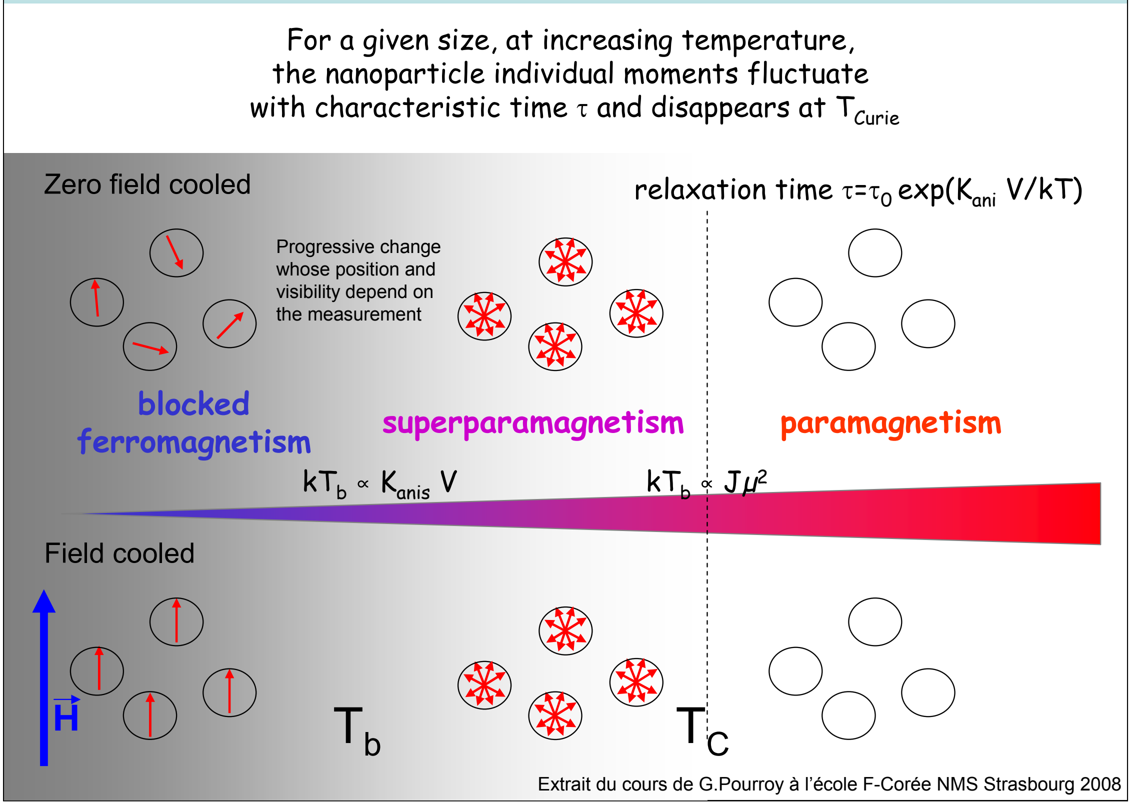
$$F = F_{exch} + F_{ani} + F_{dip} + F_{zee} \quad \text{and} \quad k_B T \ !$$

Competition between exchange and thermal energies




MAGNETISM OF NANO-OBJECTS Superparamagnetism
F = F exch + F ani + F dip +F zee and kBT !
Competition between anisotropy and thermal energies
multidomain
Magnetization in the easy direction
blocked single-domain
individual moment fluctuates with τ < measurement time
Progressive change: position and visibility depend on the measurement
superparamagnetism
Dc
~1 nm
Kanis V ∝ kT
energy costs to create a wall
<
magnetostatic energy
KaniV
thermal energy kT
>
anisotropy energy barrier Kan V
Extrait du cours de G.Pourroy à l'école F-Corée NMS Strasbourg 2008

MAGNETISM OF NANO-OBJECTS Superparamagnetism



How to image the magnetic domains ?

What direction? Single or multidomains? Coupling between particles?

Bulk samples: optical microscopy + colloidal suspension of ferro µP: resolution: 0.1mm

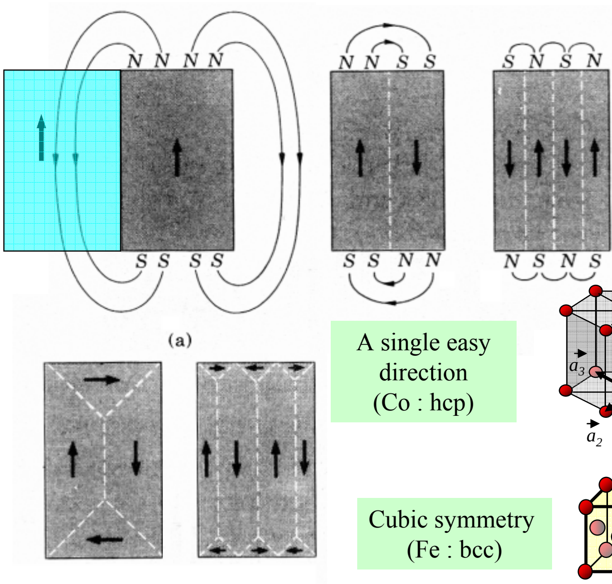
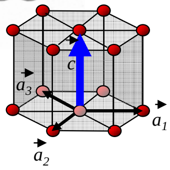


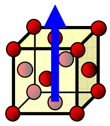
Fig. 4. The narrow lines are the deposit obtained on a crystal of nickel. Magnification ×16.

F. Bitter, Phys. Rev. 38, 1903 (1931)
On Inhomogeneities in the Magnetization of Ferromagnetic Materials

A single easy direction (Co : hcp)



Cubic symmetry (Fe : bcc)



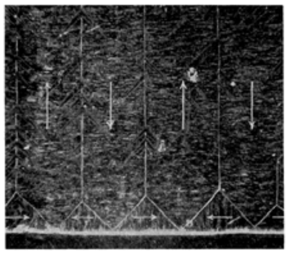


Fig. 32(a). Retouched photograph of domains of closure in Si-Fe crystal (Williams).

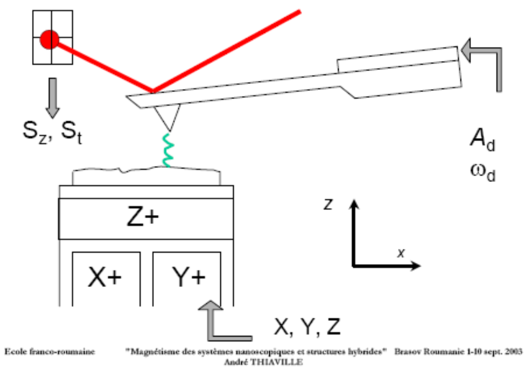
Williams, Bozorth, and Shockley, Magnetic domain patterns on single crystals of silicon iron, Phys. Rev. **75**, 155–178 (1949).

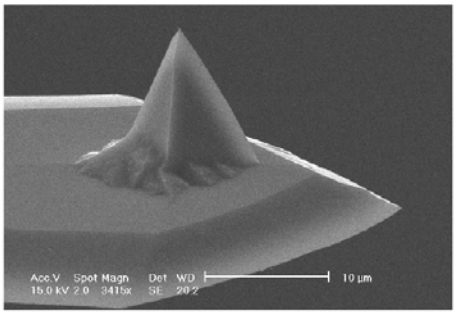
Kittel, C.: Physique de l'état solide. Ed. Dunod (1995)

How to image the magnetic domains ?

micrometric samples:

magnetic force microscopy : – sensitive to vertical magnetic field near the surface (stray field)
– resolution: 50 nm





*magnetism.eu/esm/2003-brasov/slides/**thiaville**-slides-2.pdf*

Image avec champs de fuite

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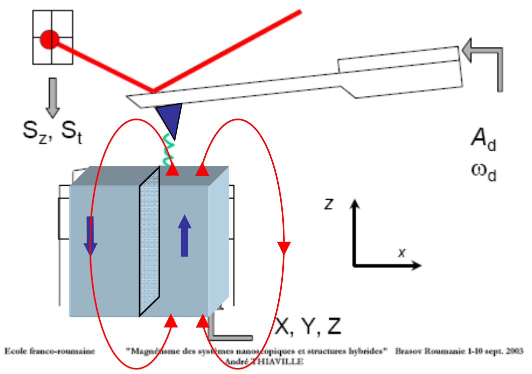
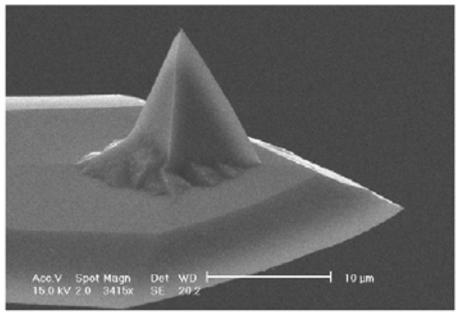


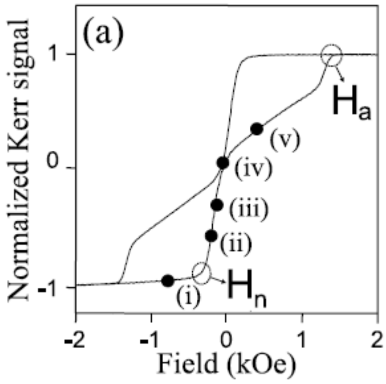


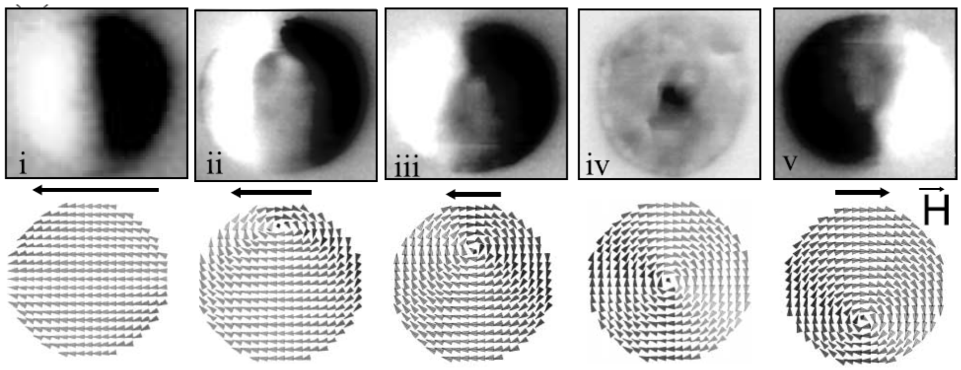
*magnetism.eu/esm/2003-brasov/slides/**thiaville**-slides-2.pdf*

MAGNETISM OF NANO-OBJECTS Interactions and distributions

Interaction between dots:
mainly dipolar interactions
Explain strange hysteresis loops

M. Natali, I. L. Prejbeanu, A. Lebib, L. D. Buda, K. Ounadjela, and Y. Chen
Phys. Rev. Lett. **88**, 157203 (2002)
Correlated Magnetic Vortex Chains in Mesoscopic Cobalt Dot Arrays





The influence of the dipolar interactions is reflected in both the nucleation and annihilation field's behavior. Their variation with the interdot separation, for an array of dots with f 550 nm, is illustrated in Fig. 1(c) and is compatible with a significant increase of the interaction fields for spacing below 1000 nm. The experimental data are well fitted by the expression *Hn(a) = Hn(a)infini+/-* 4.2*Ms (V/S***3) that describes the interaction field in a twodimensional square lattice of dipoles. Here *V* denotes the volume of the dot and *Ms* is the saturation magnetization of Co (1400 emu/cm**3). The fitting parameter used, *Hn(a)infini*, represents the nucleation/annihilation field for isolated dots. The right-hand side term gives the dipolar interaction field which acts at nucleation (1) and annihilation (2).

M. Natali, I. L. Prejbeanu, A. Lebib, L. D. Buda, K. Ounadjela, and Y. Chen

Phys. Rev. Lett. **88**, 157203 (2002)

Correlated Magnetic Vortex Chains in Mesoscopic Cobalt Dot Arrays

How to image the magnetic domains ?

nanometric samples:

Electron holography : sensitive to the phase changes of the electronic wave – resolution: 5 nm

Other methods:

Spin polarised STM (lecture of W. Wulfhekel)

Ballistic Electron Magnetic Microscopy

…

- Magnetic properties of bulk materials
  - Dia-para-ferromagnetism
  - Susceptibility
  - Applications
- Magnetic properties of nano-objects
  - Moments and Curie temperature
  - Energies in competition
  - Applications
- Electron holography
  - Principle
  - Examples

Applications of nano-magnetism

A magnet can be oriented in a field

Nanomotors, drug delivery, bacteria, pigeons…

A magnet produces a field

Reading heads

A magnet has a remanence

High density information storage

Electric resistivity of a magnetic system depends on the magnetisation orientation

GMR reading heads, sensors

A magnet can be heated using hysteresis cycling

Hyperthermia (cancer healing)

Applications of nano-magnetism

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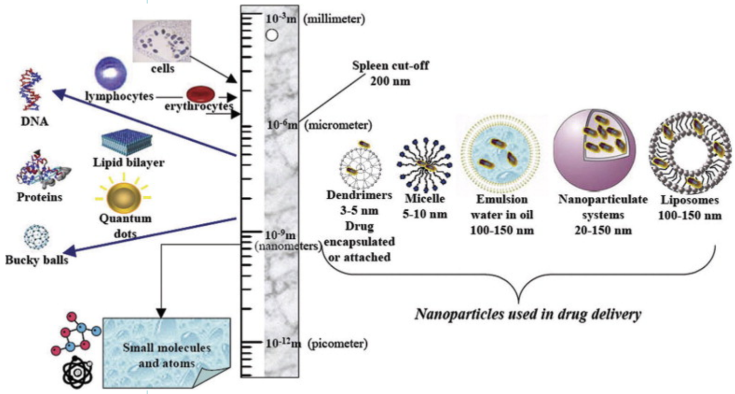
http://www.sciencedirect.com/science/article/pii/S1748013207700841



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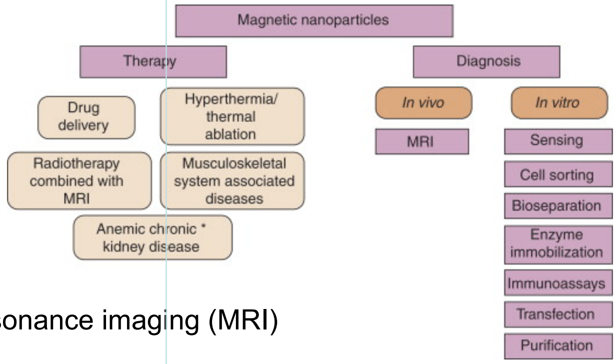


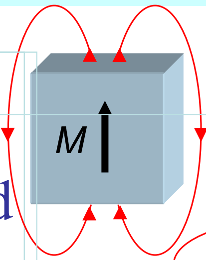
magnetic resonance imaging (MRI)

A magnet can be heated using hysteresis cycling

Hyperthermia (cancer healing)

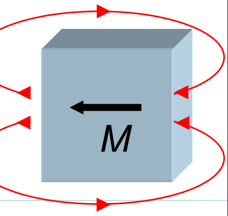
Applications of nano-magnetism

A magnet produces a field

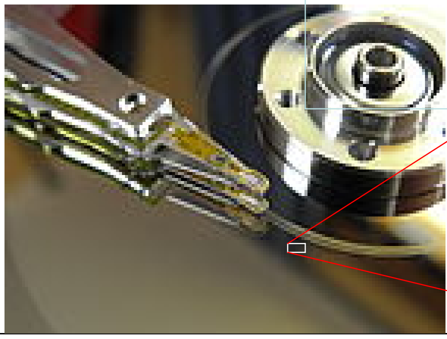


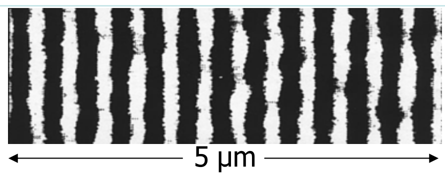
Reading heads

A magnet has a remanence



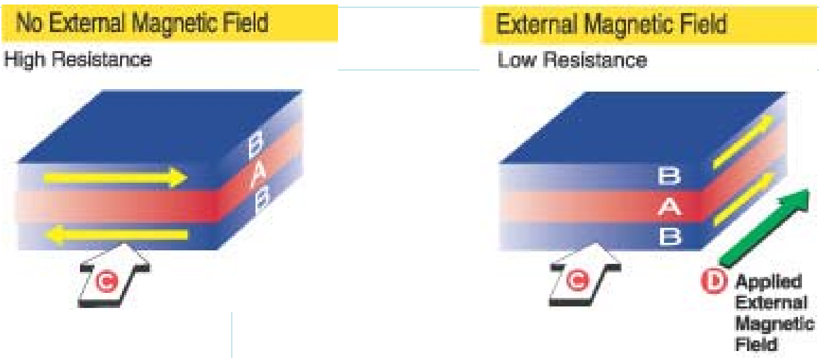
High density information storage





MFM image of bits magnetized in the hard drive

Applications of nano-magnetism



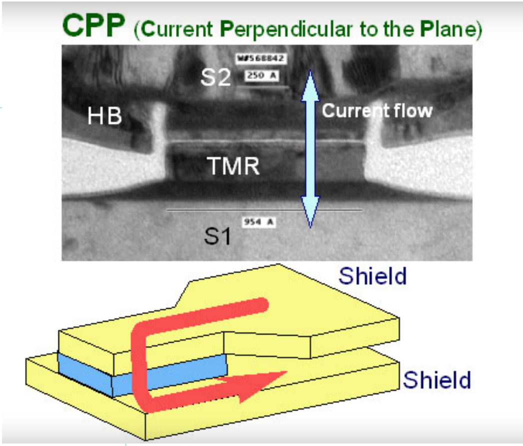
Electric resistivity of a magnetic system depends on the magnetisation orientation

GMR reading heads, sensors

Applications of nano-magnetism

http://news.cnet.com/2300-1041_3-6213399-2.html

Hitachi new GMR head – 50 nm tracks



Electric resistivity of a magnetic system depends on the magnetisation orientation

GMR reading heads, sensors