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:**

\[ K \]

\[ H_{s.o.} = \xi \mathbf{L} \cdot \mathbf{S} \]

\[ = \sum \xi \mathbf{s}_i \cdot \mathbf{l}_i \]

Dipolar Interaction:

**SHAPE ANISOTROPY**

\[ H_{dip} = \frac{\mathbf{m}_1 \cdot \mathbf{m}_2}{r^3} - 3 \left( \frac{(\mathbf{m}_1 \cdot \mathbf{r})(\mathbf{m}_2 \cdot \mathbf{r})}{r^5} \right) \]
Dipolar interaction

Long range interaction between magnetic moments

\[ H_{dip} = \frac{\mathbf{m}_1 \cdot \mathbf{m}_2}{r^3} - 3 \frac{(\mathbf{m}_1 \cdot \mathbf{r})(\mathbf{m}_2 \cdot \mathbf{r})}{r^5} \]

\( m_1 \) and \( m_2 \) can be the magnetic moments of two atoms in a particle or the moments of two particles.

In out-of-plane configuration the dipolar interaction is reduced.
The magnetic configurations are determined by the competition, at a local scale, of four different energies: 

Zeeman, exchange, magnetocrystalline anisotropy, and dipolar coupling.

\[ E = -\mu_0\mu H \sum_i m_i - J \sum_{\langle i,j \rangle} m_i \cdot m_j - \sum_i k_i (m_i \cdot e_i)^2 - \frac{\mu_0\mu^2}{8\pi} \sum_{i,j \neq i} \left[ \frac{3(m_i \cdot r_{ij})(m_j \cdot r_{ij})}{r_{ij}^5} - \frac{m_i m_j}{r_{ij}^3} \right], \]

exchange, magnetocrystalline energy -> short range
dipolar energy -> long range

Structure of a domain wall between two ferromagnetic domains with opposite orientation of the local magnetization (180° wall)

SP-STM of 1.3 monolayers Fe / stepped W(110)

Magnetic phase diagram for ultrathin films with perpendicular anisotropy ($l_{ex} = 2nm$)


Magnetic domain pattern of perpendicularly magnetized ultra-thin Fe particles grown on Cu(0 0 1)

Magnetic phase diagram for ultrathin particles with in-plane anisotropy (Fe/W(001))


Magnetic domain pattern of in-plane magnetized ultra-thin Fe particles grown on W(0 0 1)

Demagnetizing field: shape anisotropy

\[ E_{dip} = -\frac{\mu_0}{2} \int M \cdot H_{dem} dV \]

\[ H_{dem} = -D M \]

Pushes the magnetization M along the longer side of the nanostructure:
- Cylinder: \( M \parallel \) axis
- Disk: \( M \parallel \) disk surface

For a sphere:

\[
D = \begin{bmatrix}
\frac{1}{3} & 0 & 0 \\
0 & \frac{1}{3} & 0 \\
0 & 0 & \frac{1}{3}
\end{bmatrix}
\]

For an infinite cylinder:

\[
D = \begin{bmatrix}
\frac{1}{2} & 0 & 0 \\
0 & \frac{1}{2} & 0 \\
0 & 0 & 0
\end{bmatrix}
\]

For an infinite plane (thin film):

\[
D = \begin{bmatrix}
0 & 0 & 0 \\
0 & 0 & 0 \\
0 & 0 & 1
\end{bmatrix}
\]

Co/Pt(111)

Orientation and shape of Co magnetic domains

X-ray photoemission electron microscopy, SIM beamline @ Swiss Light Source
A bit is a binary system where 1 and 0 correspond to the magnetization being up or down.

Magnetization along a defined axis: easy magnetization axis

\[ E(\theta, \theta_0, \varphi) = -\mathbf{\mu} \cdot \mathbf{B} - K \cos^2(\text{easy} \cdot \mathbf{\mu}) \]

Assuming a coherent magnetization reversal (i.e. all spins turning at the same time) K is the MAE.
Magnetic anisotropy energy and superparamagnetic limit

The magnetic anisotropy energy determines the lifetime of the magnetic state

\[ E(\theta, \theta_0, \varphi) = -\mu \cdot B - K \cos^2 (\text{easy} \cdot \mu) \]

Avg. time (relaxation time) taking to jump from one minimum to the other:

\[ \tau = \tau_0 \exp(\frac{K}{kT}) \quad \tau_0 \approx 10^{-10} \text{s} \]

\[ \begin{align*} 
\tau = 1 \text{ year} & \quad K = 40 \text{ kT} \\
\tau = 1 \text{ second} & \quad K = 23 \text{ kT}
\end{align*} \]

Blocking temperature \( T_b \)

Blocking: \( K/kT > 30 \)

Superparamagnetic: \( K/kT << 30 \)
Single-domain particles: the Stoner-Wohlfart model

Magnetization of a single-domain particle in an external field.

\[ E = E_{\text{Zeeman}} + E_{mc} + E_{dm} \]

Suppose \( \mu = MV = \text{const.} \) for any \( H \) value (coherent rotation) and, for simplicity, \( E_{dm} = 0 \). \( E_{mc} = K_1 V \)

\[ E = -\mu H \cos \theta - K_1 V \cos^2(\theta - \phi) \]  \( \tag{1} \)

The magnetic moment \( \mu = MV \) will point along a direction that makes \( E \) a minimum:

\[ \frac{\partial E}{\partial \theta} = \mu H \sin \theta + K_1 V \sin(2(\theta - \phi)) = 0 \]  \( \tag{2} \)

Eq. 2 can be solved for \( \theta \) and we can plot \( M_z = M \cos \theta \) (this is what one usually measures) as a function of \( H \).

The reversal field is the field at which the energy minimum in eq. (1) vanishes ( \( \frac{\partial^2 E}{\partial \theta^2} = 0 \) )

During the magnetization reversal all the atom spins in the particle stay aligned
The hysteresis loop for an ensemble of noninteracting monodomain particles (containing $s$ atoms each of them having magnetic moment $m$) and with uniaxial anisotropy represents the asymmetry in the number of particles pointing up $n^\uparrow$ and down $n^\downarrow$ changing over time with the applied field.

\[
\frac{dn^\uparrow}{dt} = -\kappa^\uparrow\downarrow n^\uparrow + \kappa^\uparrow n^\downarrow
\]

\[
\kappa^\uparrow\downarrow = \nu_0 e^{-E^\uparrow\downarrow/k_B T}
\]

\[
E^\uparrow\downarrow = K \sin^2 \vartheta - s m H \cos(\vartheta - \varphi)
\]

1.1 ML Co/Au(11,12,12)
Two atomic layer high particles $s = 600$ atoms
What is the smallest size of a ferromagnetic particle at room temperature?

\[ nK > 1 \text{ eV} \]

\[ K = \text{magneto-crystalline anisotropy} + \text{shape anisotropy (usually small)} \]

Co atoms on Pt(111) with 2-fold coordination: \( K = 3 \text{ meV/atom}, \ n = 350 \text{ atoms} \)
Compared to pure Co islands:  
1) same total MAE (0.9 meV/edge-atom)  
2) reduced magnetic moment


About 250 atoms sitting on the island edges

MOKE susceptibility
(same blocking temperature $T_b$)
Nano-engineering: interline effect

In the mean the rim has a width of two atoms
But….  

Real island shape at $\theta_s = 0.04$ ML

Interline decreases $T_b$ (similar to Pt case)

Interface increases $T_b$

Islands containing about 1300 atoms with $T_b$ close to room $T$
Au(788) vicinal surfaces

(111)-oriented terraces with reconstruction lines perpendicular to step edges

Surface reconstructions on two consecutive terraces are coherent

Co nucleates in bi-layer dots where the reconstruction lines cross the step edges

MAE distribution narrower than size distribution

0.75 ML Co

Uniaxial out-of-plane easy axis => one particle per bit

For circular particle $\Delta N/N = 2 \Delta p/p$

Unprecedented narrow MAE distribution

Negligible dipolar interaction at 26 Tdots/in$^2$

Switching field $H_{sw} = 2K/M = 4$ T
Dipolar field < 0.04 T

0.75 ML Co

1.1 ML Co

Bimodal size distribution

Bimodal $\chi$ vs. T
Self-assembly of colloid particles

Particles with organic capping

Self-assembly via solvent evaporation

Assembly onto functionalized substrate via ligand exchange

Tunable size in the range 1-10 nm

Control of the particle volume: HWHM = 15-20 %

Organic capping used as a spacer to define the array density
4 nm Fe$_{56}$Pt$_{44}$ annealed particles (L1$_0$ phase)

MAE $\approx$ 48 kT

Stability criterion at room temperature: MAE = 40 kT


Annealing to about 600°C
Magnetism of colloid particles: drawbacks

1) Randomly oriented easy axis

SNR requires more than one particle per bit

Density limit: 1 Tbit/in²

2) Relatively large MAE distribution

Co particles

10 year stable

1 hour stable

3) Order lost after annealing

T= 20°C

T= 530°C

T= 600°C

S. I. Woods et al., PRL 87, 137205 (2001)

N. Blanc, PhD thesis (Lyon dec 2009)
Scheme of a writing procedure: the bias field depends on the versus of the external field during cooling.

Co in a CoO matrix

CoO $T_N = 290$K

The Au(111) herringbone reconstruction: 23 surface atoms on top of 22 second layer atoms result in partial dislocations that separate fcc and hcp regions.

Nucleation triggered by exchange

[co-tourtesy S. Rousset, CNRS, Univ. Paris 7 and 6]
Co pillars on Au(111)

(a) 300×300 STM image after deposition of 0.2 ML of Co at 300 K on Au(111)

(b) after deposition of Au up to the fourth ML, performed while raising the temperature from 425 to 475 K

(c) after another deposition of 0.2 ML of Co at 500 K.

Final result: 300×300 STM image after 0.2 ML of Co have been piled one on top of the other.

O. Fruchart et al., PRL 83, 2769 (1999)
Pillar height adjusted to select the blocking temperature

**Limitations**

Domain deformation approaching a (100) step:
- Coherence lost at step edges
- Rotated domains coexist on the same terrace

Possible dipolar coupling: $H_c$ does not change
Thermally Activated Magnetization Reversal in Elongated Ferromagnetic Particles

Hans-Benjamin Braun

\[ \mathcal{E} = \int_{-L/2}^{L/2} dx \left\{ \frac{A}{M_0^2} \left[ (\partial_x M_x)^2 + (\partial_y M_y)^2 + (\partial_z M_z)^2 \right] + \frac{K_h}{M_0^2} M_z^2 - \frac{K_e}{M_0^2} M_x^2 - H_{\text{ext}} M_x \right\} \]

Magnetic anisotropy (including the dipolar)

This solution is true in the limit of \( H_{\text{ext}} \rightarrow 0 \)

Reversal by domain wall creation and displacement

H.-B. Braun Phys. Rev B 50, 16502 (1994);
H.-B. Braun Phys. Rev B 50, 16485 (1994);
H.-B. Braun Phys. Rev Lett. 71, 3557 (1993);
H.-B. Braun J. Appl. Phys. 85, 6172 (1999);
Thermal stability vs MAE

Domain wall motion costs less energy

Elongated islands switch faster than compact islands: different reversal mechanism

Spin Polarized-STM image of monolayer high Fe islands on Mo(110)

$L < L_{\text{crit}} \rightarrow$ Coherent rotation
$L > L_{\text{crit}} \rightarrow$ domain wall motion

$L_{\text{crit}} = 4 \sqrt{J/K}$ if $K \gg \mu_0 M^2$

$L_{\text{crit}} = 9 \text{ nm}$ for Fe/Mo(110)

Micromagnetic simulation of Co islands on Pt(111)

Vortex domain are potential candidates for magnetic storage devices.

The out-of-plane polarization of the magnetic vortex core can be regarded as '0' or '1' of a bit element.

The inter-grain exchange interaction is stopped by the oxide layer.

FIG. 2. (Color online) (a) Plan-view TEM image showing granular FePtAg-C media. The inset shows a histogram of the grain size distribution. The solid line in the inset shows a lognormal fit to the grain size distribution, which results in an average grain diameter $<D> = 7.2$ nm and a grain size distribution $\sigma_D/<D> = 16\%$. A cross-sectional TEM image is shown in (b). Note that the grains have a spherical shape.

Constraints on the magnetic grain:
1) Size below 8 nm
2) Uniform size distribution
3) Well defined boundary
4) Magnetically decoupled

The grain size distribution results in a rather wide switching field distribution.

FIG. 2. (Color online) (a) Plan-view TEM image showing granular FePtAg-C media. The inset shows a histogram of the grain size distribution. The solid line in the inset shows a lognormal fit to the grain size distribution, which results in an average grain diameter \( \langle D \rangle = 7.2 \) nm and a grain size distribution \( \sigma_D/\langle D \rangle = 16\% \). A cross-sectional TEM image is shown in (b). Note that the grains have a spherical shape.

FIG. 3. (Color online) Easy and hard axis VSM magnetization loops measured at room temperature are shown with black and grey (red online) lines, respectively. A high coercive field \( H_c = 4.85 \) T was obtained for this sample with remanent magnetization above 90\% of the saturation value. Note that the hard axis is not saturated at 9 T applied field and its amplitude was normalized to that of the easy axis loop for the highest applied field.

Each bit is made of a few hundreds of grains. The bit size and shape is defined during writing by the head.

The future: single particle per bit