Biomagnetism-I

Fernando Palacio
Instituto de Ciencia de Materiales de Aragón.
CSIC – Universidad de Zaragoza
palacio@unizar.es

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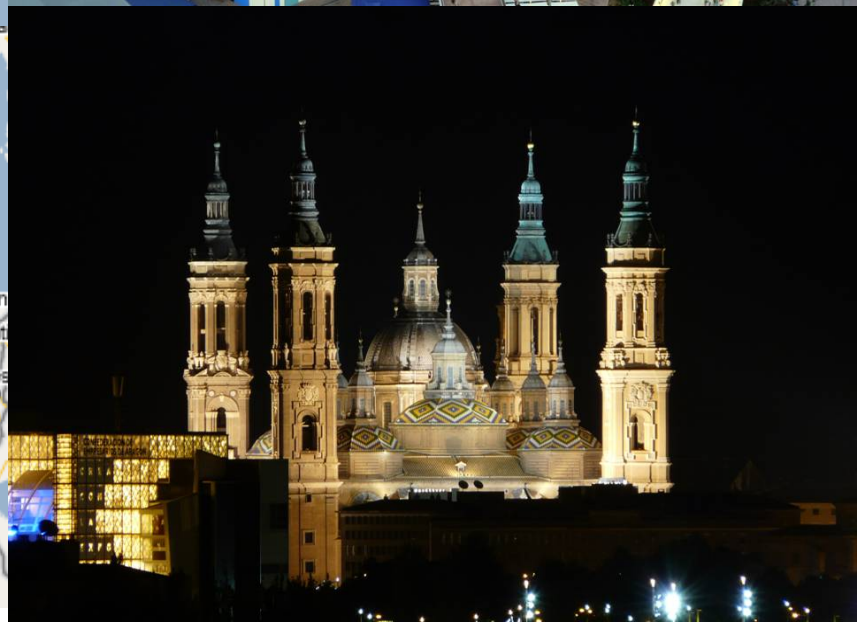
Zaragoza City

Founded by romans 2000 years ago
700.000 habitants
Logistic center in the North of Spain



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Zaragoza University

Founded in 1542

4 campus

33.000 students

2.300 postgraduate

9 research Institutes

ICMA Institute

Founded 27 years ago

180 researchers

47% permanent

53% students+post-dos

ICMA Institute

Instituto de Ciencia de Materiales de Aragón

Campus Río Ebro

Campus San Francisco

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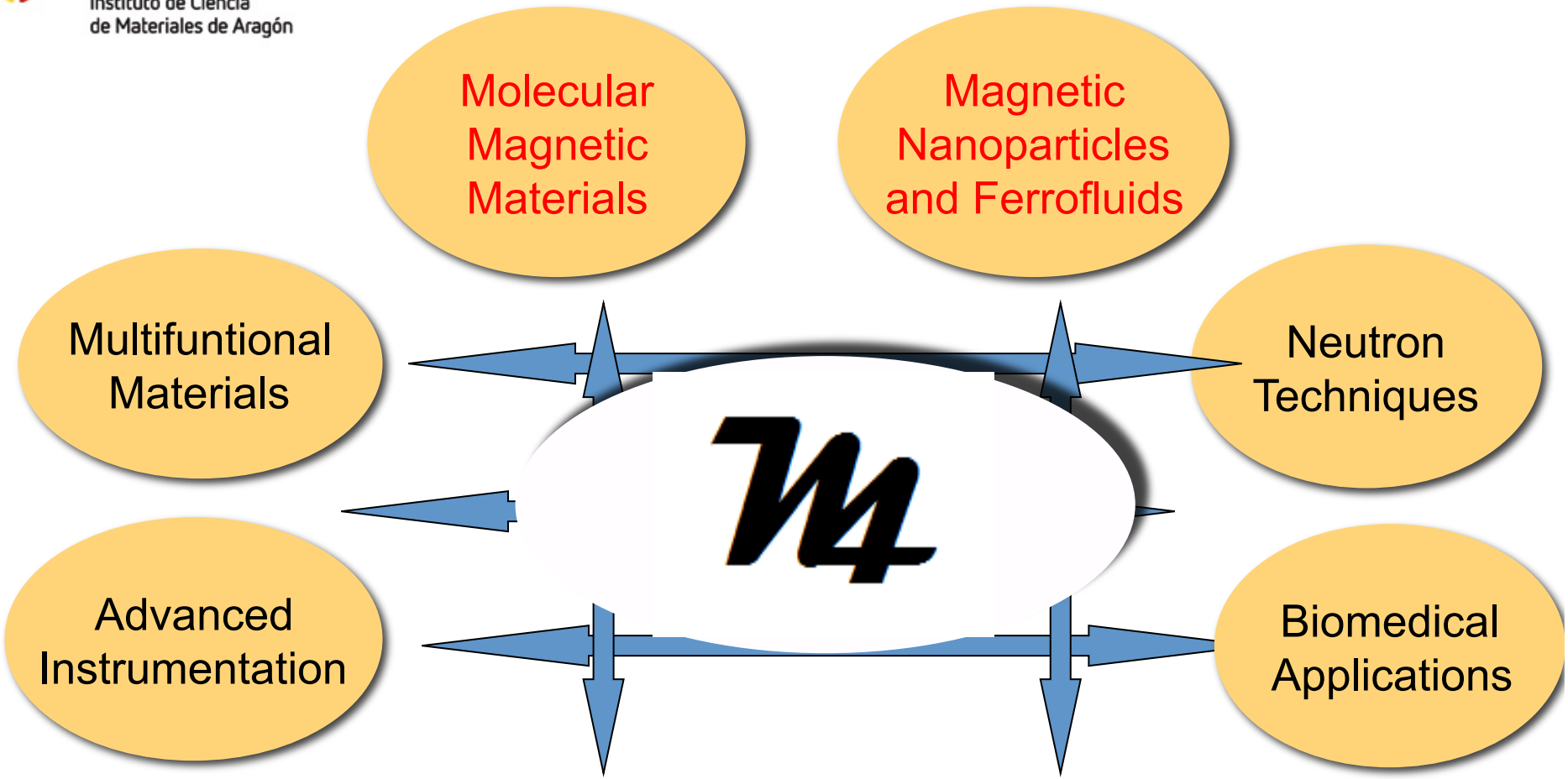


M4 = Multifunctional Molecular Magnetic Materials
30 group members. High multidisciplinarity:
chemists, physicists, biologists, clinical doctors

Outline P.1

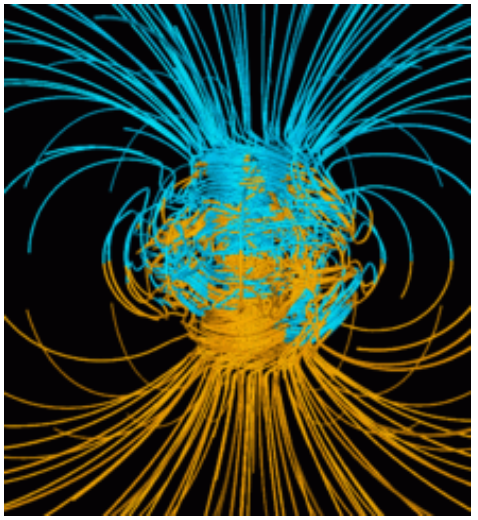
In this 1st part we will cover:

- Introduction
- Magnetic fields and health: any risks?
- Do animals sense magnetic fields?
- The use of magnetism in medicine
- Fundamentals of the magnetism of nanoparticles
- Preparative techniques of magnetic nanoparticles

Introduction

Life in Earth is immersed in the geomagnetic field

- Its magnitude at the Earth surface is very week, between 0,25G to 0,65G
- It creates the magnetosphere, at several thousands of Km. into space, which protects the Earth from cosmic rays



http://en.wikipedia.org/wiki/Earth's_magnetic_field

In addition, in our everyday life we can be in contact with electric and magnetic fields of varied magnitude and frequency

- Extremely low frequency fields, ELF, ($n \leq 300$ Hz)
- Intermediate frequency fields, IF, ($300 \text{ Hz} < n \leq 10$ MHz)
- Radiofrequency fields, RF, ($10 \text{ MHz} < n \leq 300$ GHz)

The effects of electromagnetic fields on the human body depend not only on their **field magnitud** but on their **frequency and energy**.

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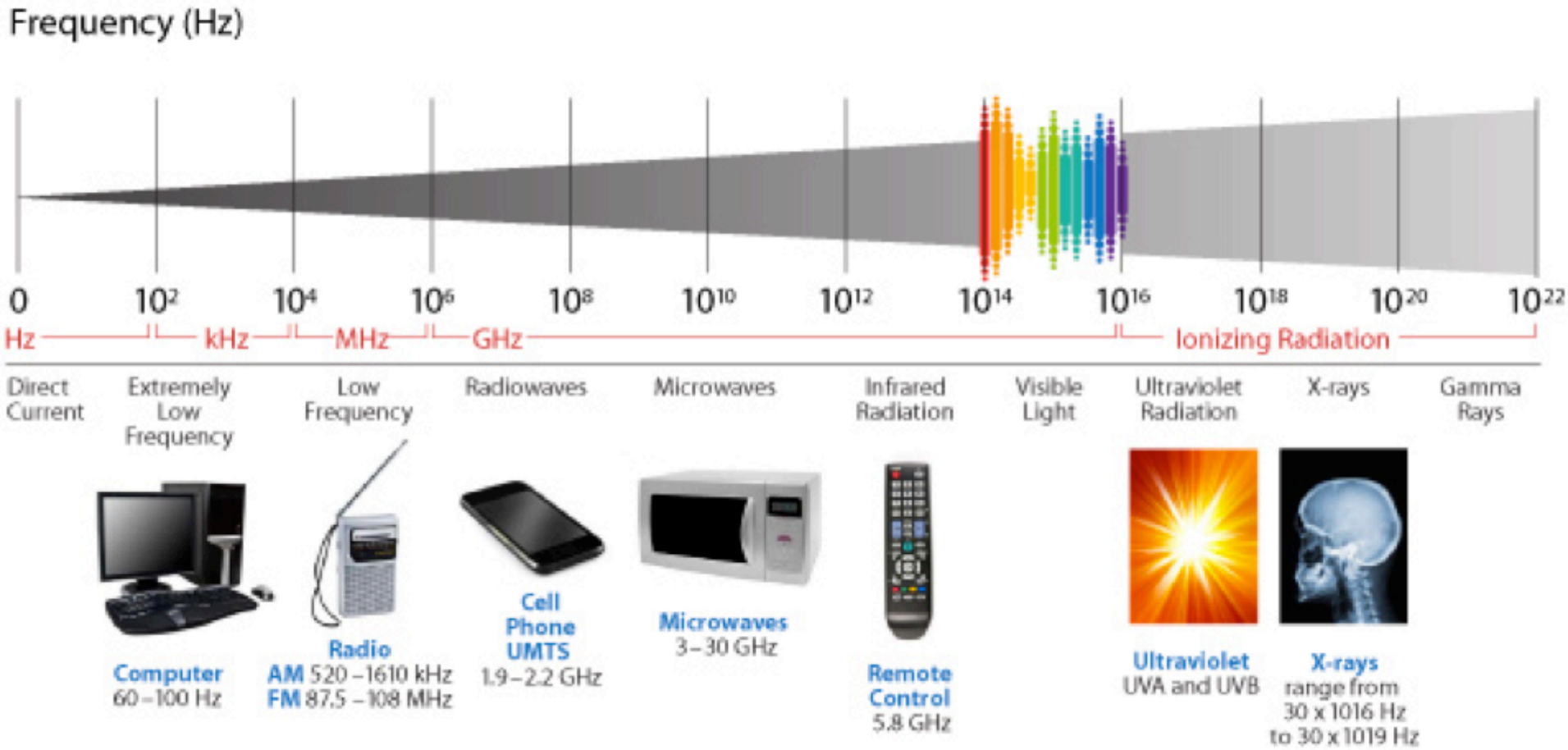
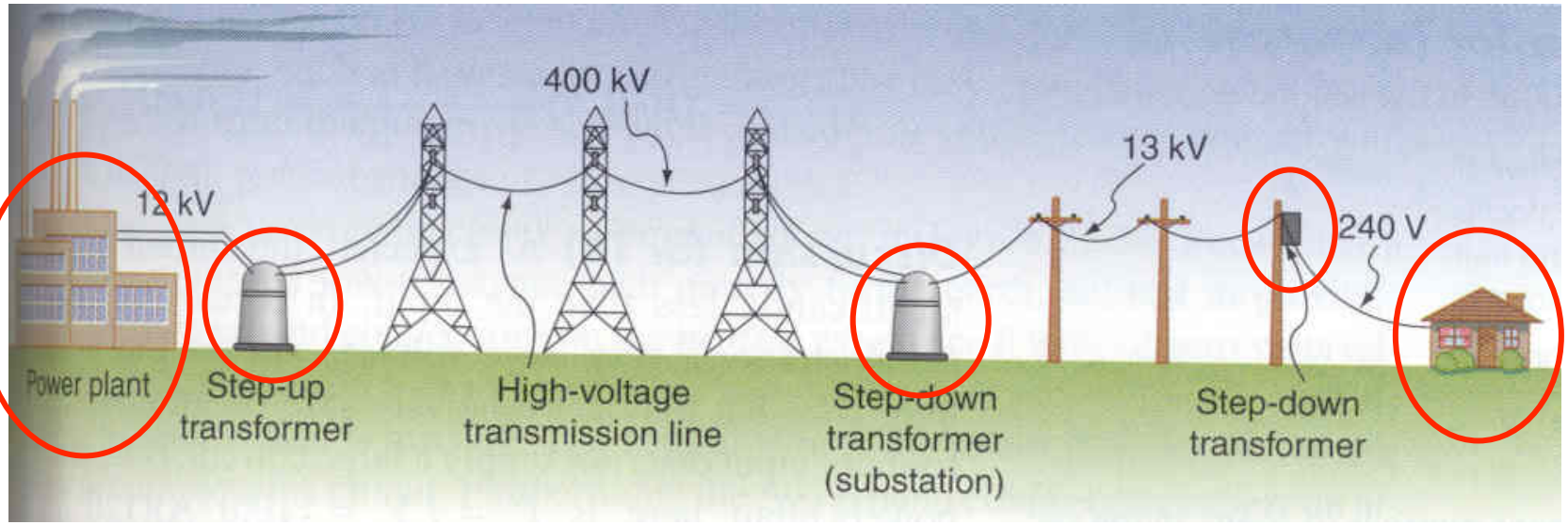
Introduction

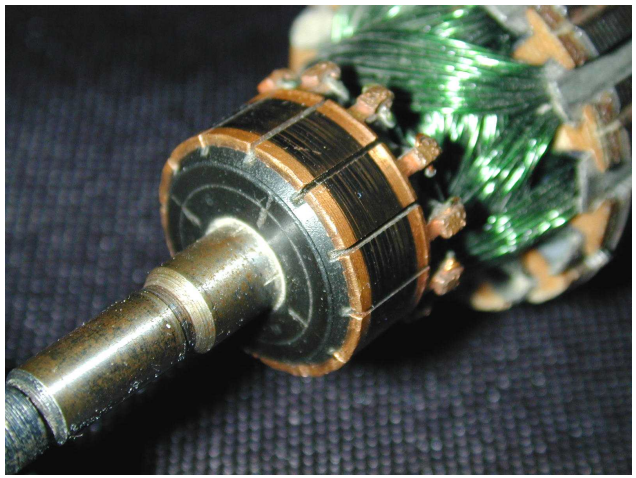
Electromagnetic Spectrum

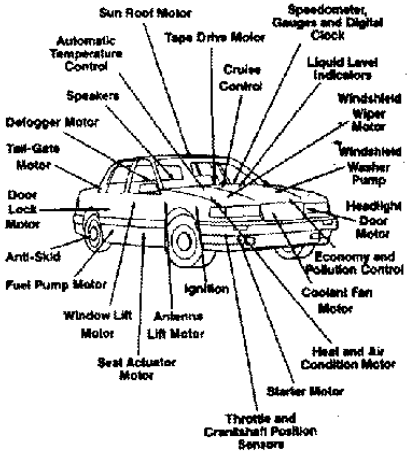


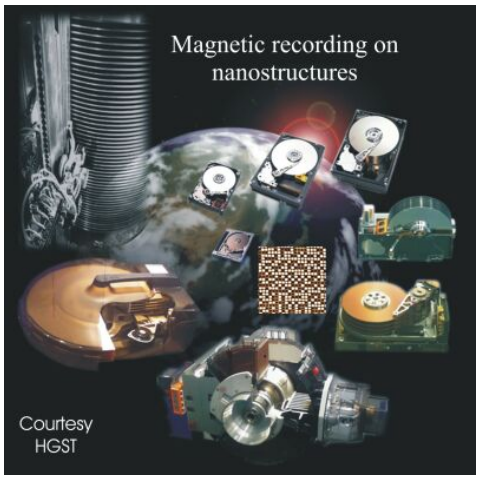
Introduction



Magnets are everywhere



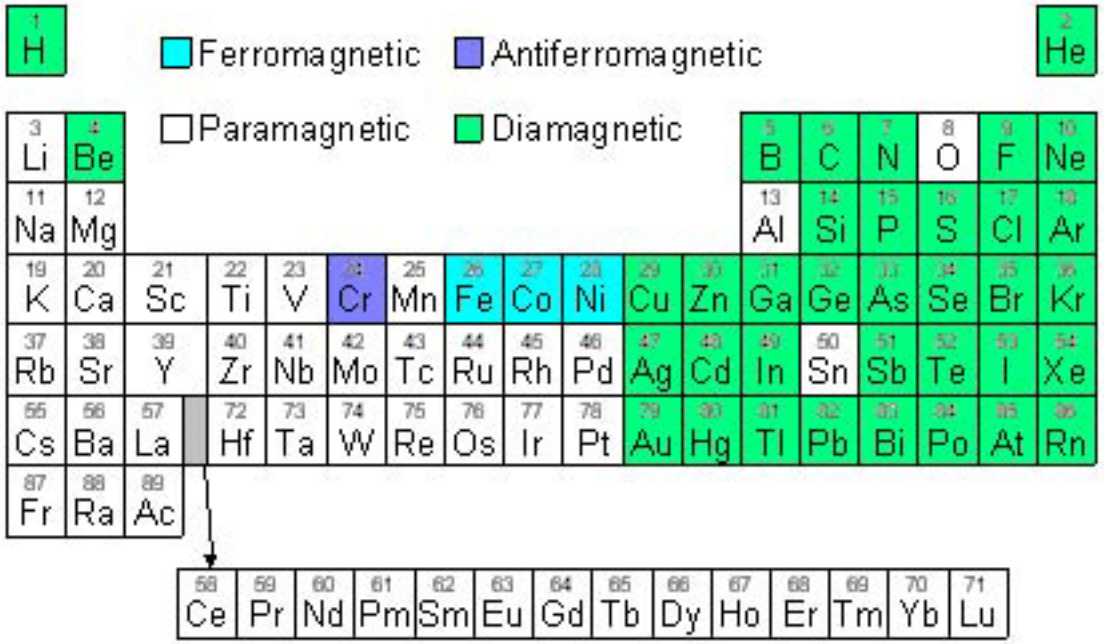




Introduction

Some minerals and metals are called magnetic because they orient in a magnetic field

This is the case of lodestone (Fe3O4, Fe, Co, rare earth alloys, etc.)



http://www.splung.com/content/sid/3/page/magnetism

Introduction

Magnets (magnetic stone = *magnetite*) are known since the early times of human civilization. However, the first practical use of magnetite was developed by the Chinese.

By the third century AD, Chinese scientists had learned that magnetite tended to align itself in a North/South position. Scientists learned to "make magnets" by heating pieces of iron ore to red hot temperatures and then cooling the pieces in a North/South position. The magnet was then placed on a piece of reed and floated in a bowl of water marked with directional bearings. These first navigational compasses were widely used on Chinese ships.

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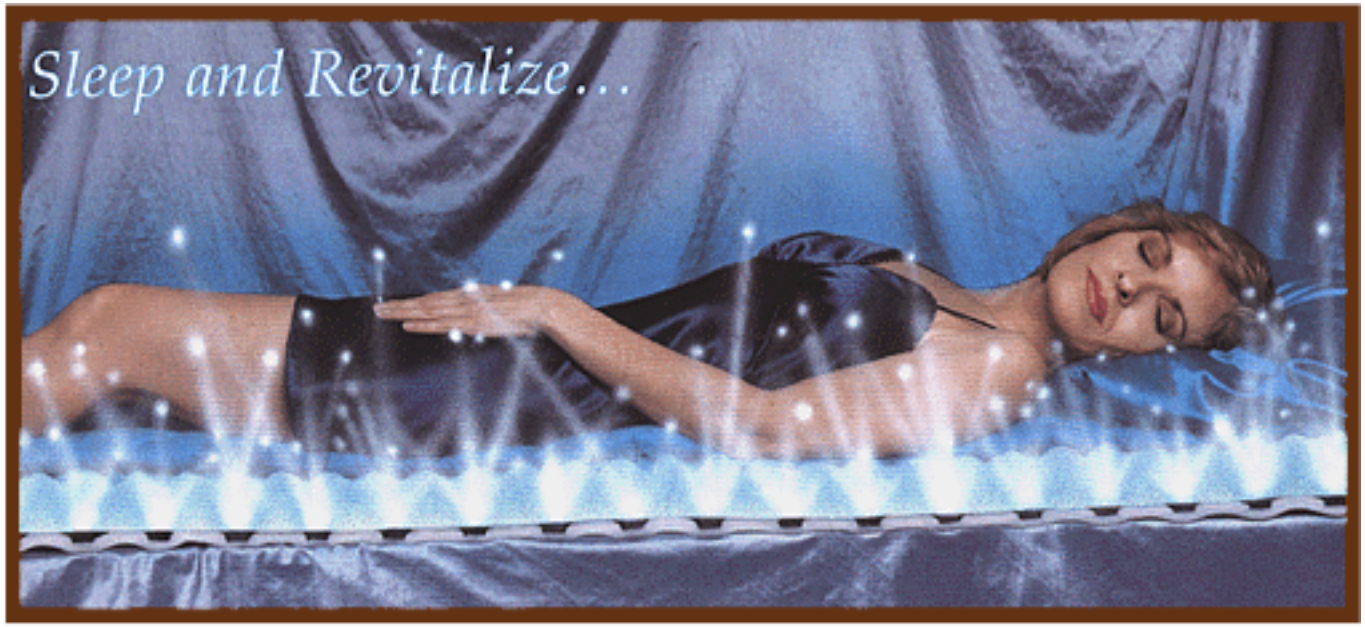
Magnetic fields and health

Magnetic fields are

- Not seen nor sensed
- Pass throughout walls and many other solids

In a sense they are a kind of *magic* for the plain people and a subject often used to sell products that are between the illusory and the fraud.

Magnetico
magnetic bed power sleep pads recreate ancient Earth's magnetic field.



The Magnetic Bed (http://www.shokos.com/)

Magnetic fields and health

A well known hoax is the famous Celestial Bed offered by James Graham in 1779 in his *Temple of Health*. This was a most hedonistic house where those who could afford the fee could wander through ornately furnished rooms, breath the perfumed air, listen music, or watch lightly dressed young woman posing around.

The centrepiece of the *Temple of Health* was the **Celestial Bed**, where for 50£ a night Graham advertised that anyone using it would be **blessed with progeny** and **sterility and impotence would be cured**.

Behind the lovers lying in the bed, electricity crackled across the headboard of the bed, filling the air with a **magnetic fluid** "calculated to give the necessary degree of strength and exertion to the nerves."

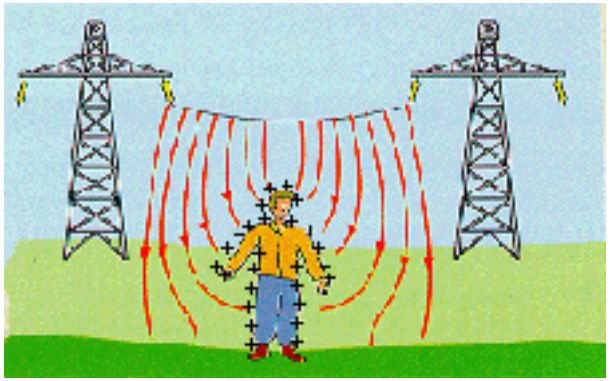
http://www.museumofhoaxes.com/hoax/archive/permalink/grahams_celestial_bed

Magnetic fields and health

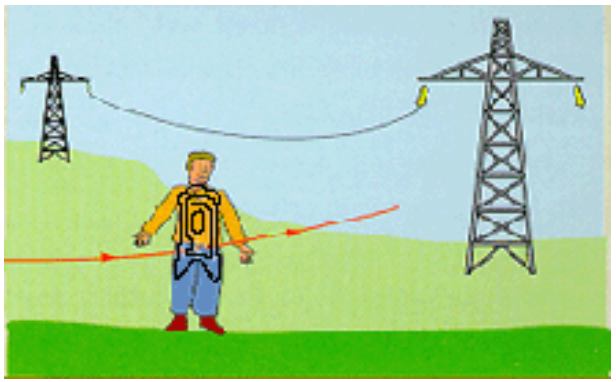
A most important question is:

Can electric and magnetic fields be a risk for health?

Low-frequency magnetic fields induce circulating currents within the human body. The strength of these currents depends on the intensity of the outside magnetic field. If sufficiently large, these currents could cause stimulation of nerves and muscles or affect other biological processes.



Both electric and magnetic fields induce voltages and currents in the body but even directly beneath a high voltage transmission line, the induced currents are very small compared to thresholds for producing shock and other electrical effects.



Magnetic fields and health

A most important question is:

Can electric and magnetic fields be a risk for health?

Heating is the main biological effect of the electromagnetic fields of radiofrequency fields. In microwave ovens this fact is employed to warm up food. The levels of radiofrequency fields to which people are normally exposed are very much lower than those needed to produce significant heating.

Over the course of the past decade, numerous electromagnetic field sources have become the focus of health concerns, including power lines, **microwave ovens**, computer and TV screens, security devices, radars and most recently **mobile phones** and **their base stations**.

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Magnetic fields and health

Typical magnetic field strength of household appliances at various distances

Electric appliance	3 cm distance (μT)	30 cm distance (μT)	1 m distance (μT)
Hair dryer	**6 – 2000**	0.01 – 7	0.01 – 0.03
Electric shaver	**15 – 1500**	0.08 – 9	0.01 – 0.03
Vacuum cleaner	200 – 800	**2 – 20**	0.13 – 2
Fluorescent light	40 – 400	**0.5 – 2**	0.02 – 0.25
Microwave oven	73 – 200	**4 – 8**	0.25 – 0.6
Portable radio	16 – 56	**1**	< 0.01
Electric oven	1 – 50	**0.15 – 0.5**	0.01 – 0.04
Washing machine	0.8 – 50	**0.15 – 3**	0.01 – 0.15
Iron	8 – 30	**0.12 – 0.3**	0.01 – 0.03
Dishwasher	3.5 – 20	**0.6 – 3**	0.07 – 0.3
Computer	0.5 – 30	**< 0.01**	
Refrigerator	0.5 – 1.7	**0.01 – 0.25**	<0.01
Colour TV	2.5 - 50	0.04 – 2	**0.01 – 0.15**

With most household appliances the magnetic field strength at a distance of 30 cm is well below the guideline limit for the general public of 100 μT.

Magnetic fields and health

A most important question is:

Can electric and magnetic fields be a risk for health?

Despite about 25,000 articles published over the past 30 years, in a recent in-depth review of the scientific literature, **the World Health Organization** concluded in its **International EMF Project,** revising most of the scientific literature and current knowledge, that current evidence does not confirm the existence of any health consequences from exposure to low level electromagnetic fields.

However, some gaps in knowledge about biological effects exist and need further research. The focus of international research is the investigation of **possible links between cancer and electromagnetic fields at power lines and radiofrequencies**.

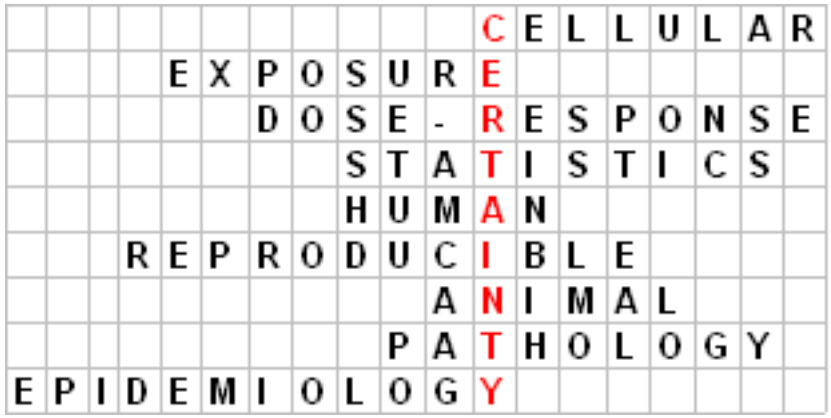
Human health studies are very good at identifying large effects, such as a connection between smoking and cancer. Unfortunately, **they are less able to distinguish a small effect from no effect at all**.

Magnetic fields and health

A most important question is:

Can electric and magnetic fields be a risk for health?

Research in WHO's International EMF Project integrate results from cellular, animal and human health studies to allow as comprehensive a health risk assessment as possible. A **holistic assessment** of a variety of relevant and reliable studies will provide the most reliable answer possible about the adverse health effects, if any exist, of long term exposure to weak electromagnetic fields.



Magnetic fields and health

To learn more …

- **Public Health England.**
  http://www.hpa.org.uk/webw/HPAweb&Page&HPAwebAutoListName/Page/1317133146649
- **World Health Organization**
  http://www.who.int/peh-emf/about/WhatisEMF/en/index.html
  http://www.who.int/peh-emf/about/WhatisEMF/en/index1.html
  http://www.who.int/peh-emf/about/WhatisEMF/en/index2.html
  http://www.who.int/peh-emf/about/WhatisEMF/en/index3.html
- **National Institute of Environmental Health Sciences**
  http://www.niehs.nih.gov/health/topics/agents/emf/
- **National Cancer Institute**
  http://www.cancer.gov/cancertopics/factsheet/Risk/magnetic-fields

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Do animals sense magnetic fields?

Magnetoception is a sense used by some animals to detect magnetic fields.

It has been proposed to explain animal **navigation**, allowing vertebrates and insects to develop regional maps with the detection of Earth's magnetic field.

Magnetoception has been observed in

- Bacteria
- Insects (honeybees, fruit flies)
- Birds, turtles, lobsters, sharks, stingrays, etc.

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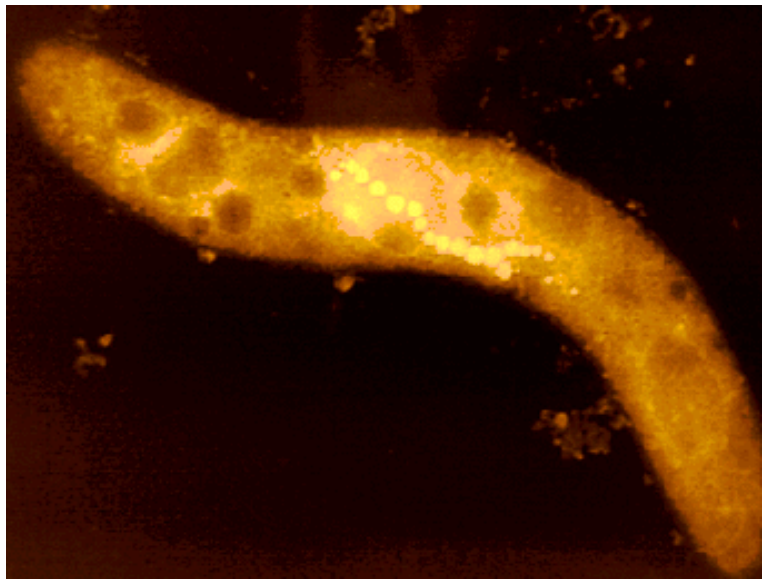
Magnetoception

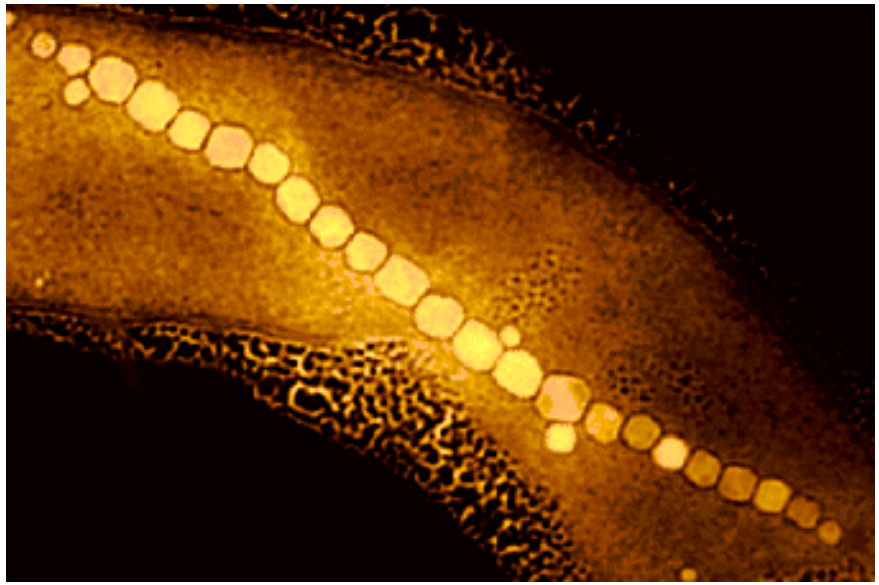
Four mechanisms have been proposed to explain **Magnetoception**.

- Magnetotaxis
- Cryptochrome-based mechanism
- Magnetite-based mechanism
- Electroreceptive organ

Magnetoception

Magnetotaxis. This mechanism is followed by magnetotactic bacteria. The bacteria contain *magnetosomes*, which are *particles of magnetite* or *iron sulfide* enclosed within the bacteria cells. They form in chains where the moments of each magnetosome align in parallel, giving the bacteria its permanent-magnet characteristics. The bacteria orients itself and migrates in the direction along the Earth's magnetic field lines.





http://www.energy.soton.ac.uk/pollution/bacteria.html

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Magnetoception

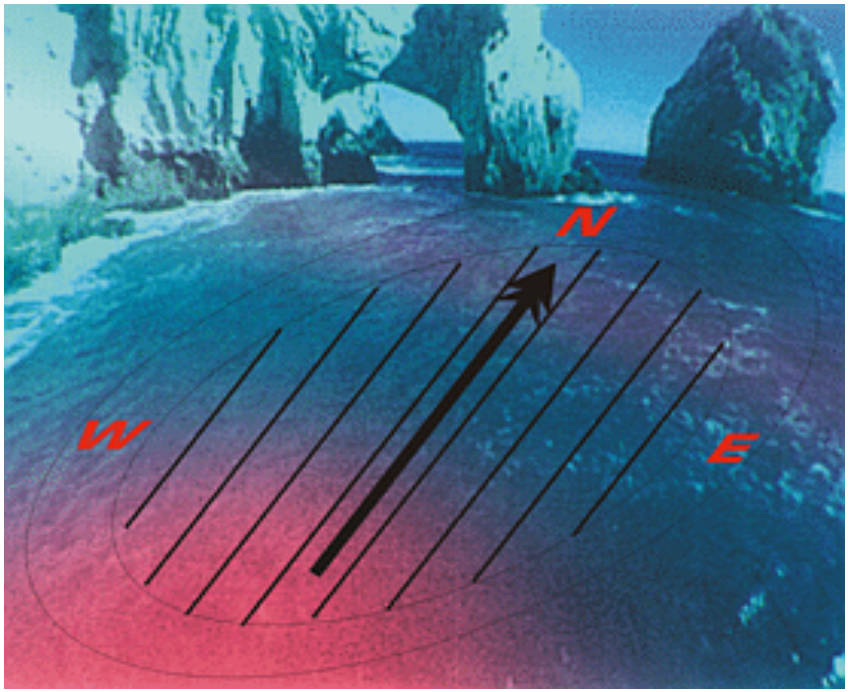
Cryptochrome-based mechanism. Cryptochromes are a class of blue light-sensitive flavoproteins found in plants and animals. In some of them they are also involved in the sensing of magnetic fields.

The mechanism proposes that the crysptochrome molecule forms a pair of two radicals with correlated spins when exposed to blue light. The surronding magnetic field would affect the correlation (parallel or anti-parallel) of these radicals, which affects the duration that cryptochrome remains activated.

Activation of cryptochrome may affect the light-sensitivity of retinal neurons with the overall result that **the animal can "see" the magnetic field**.

Magnetoception

Cryptochrome-based mechanism



Computer simulation from the NIH CENTER FOR MACROMOLECULAR MODELING & BIOINFORMATICS. UNIV. OF ILLINOIS AT URBANA-CHAMPAIGN http://www.ks.uiuc.edu/Research/magsense/ms.html

Magnetoception

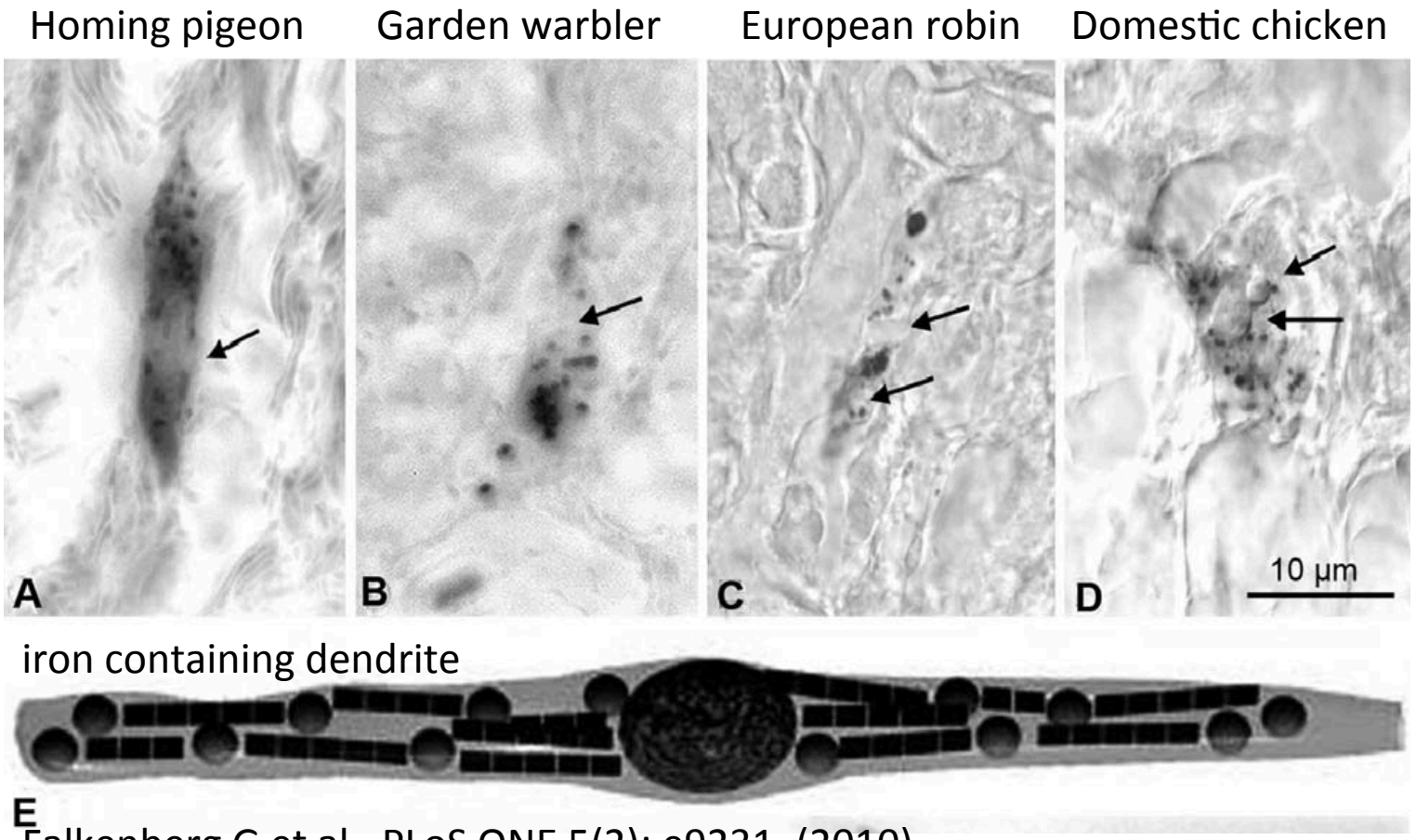
Maghemite-based mechanism. Maghemite particles have been found in a number of animals .

This iron (III) oxide remains permanently magnetized when particles length is larger than 50 nm . When the particles length is less than 50 nm the particles become magnetised in the presence of a magnetic field.

In either situation the Earth's magnetic field leads to a transducible signal via a physical effect on this magnetically sensitive oxide.

Magnetoception

Maghemite-based mechanism.



Falkenberg G et al., PLoS ONE 5(2): e9231, (2010).

Magnetoception

Electroreceptive organ. . Some species possess a unique electroreceptive organ known as *ampullae of Lorenzini* which can detect a slight variation in electric potential.

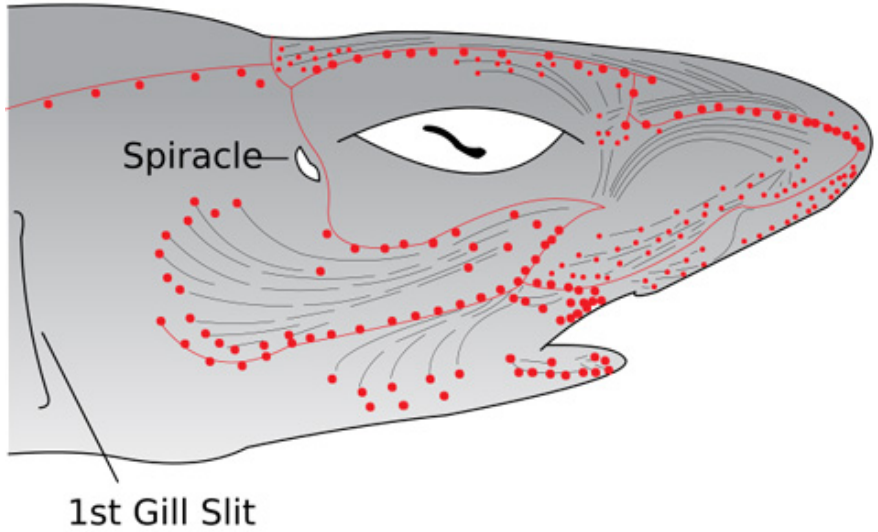
These organs are made up of mucus-filled canals that connect from the skin's pores to small sacs within the animal's flesh that are also filled with mucus. The ampullae of Lorenzini are capable of detecting DC currents and have been proposed to be used in the sensing of the weak electric fields of prey and predators.

The sensing method of these organs is based in Farady's law: as a conductor (the fish) moves through a magnetic field an electric potential is generated. An increase in potential results in a decrease in the rate of nerve activity, and a decrease in potential results in an increase in the rate of nerve activity.

These receptors are located along the mouth and nose of sharks and stingrays and can detect field of micro and even nanovolts.

Magnetoception

Electroreceptive organ.



Map of Life. University of Cambridge

http://www.mapoflife.org/browse/category_11_Brains-and-Intelligence/

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Magnetoception

To learn more …

Wikipedia
http://en.wikipedia.org/wiki/Magnetoception

NIH Center for Macromolecular Modeling & Bioinformatics. The University of Illinois at Urbana-Champign
http://www.ks.uiuc.edu/Research/magsense/

http://biology.duke.edu/johnsenlab/pdfs/pubs/magnetoreception.pdf

http://www.unc.edu/depts/geomag/PDFGeomag/MagneticMapsInAnimals.pdf

Magnetic orientation in migratory birds. PhD Thesis

http://www.angel.ekol.lu.se/~rachel/publications/AvhandlingIntro.pdf

Map of Life. University of Cambridge

http://www.mapoflife.org/browse/category_11_Brains-and-Intelligence/

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Magnetism in medicine

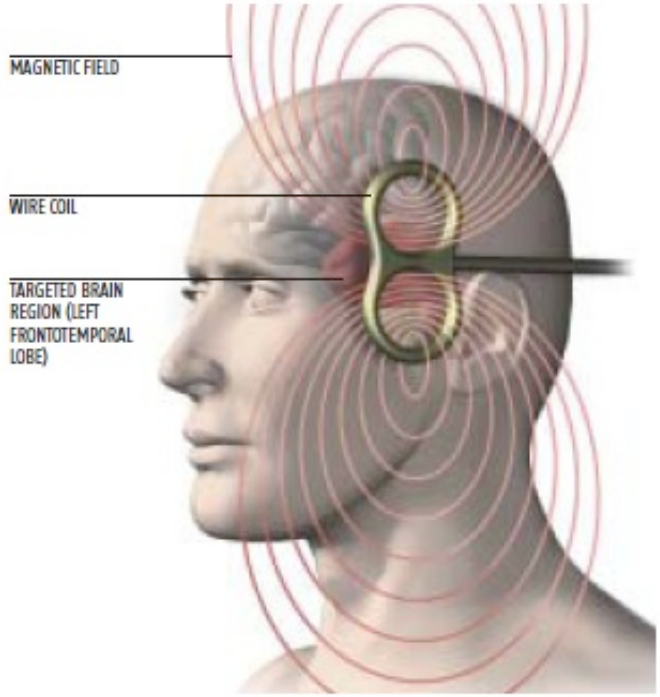
- ✓ Magnetic functionality => magnetic fields penetrate human tissues
- ✓ Strong magnetic moments => can affect relaxation times of nearby protons
- ✓ They obey Coulomb's law => can be controlled at distance
- ✓ They can convert energy into heat from an alternating magnetic field
- ✓ Controllable sizes (≥ 100 nm - ≤ 10 nm) and shapes (spheres, needles, beads)

Magnetic fields for diagnostic and therapy

Magnetic fields in medicine

Several techniques for either diagnostic or therapy in medicine use magnetic fields.

- **Transcraneal magnetic stimulation (TMS)**



Magnetic fields in medicine

Transcranial magnetic stimulation (TMS) is a procedure that uses magnetic fields of about 1 – 10mT to stimulate nerve cells in the brain to improve symptoms of depression. It causes *depolarisation* and *hyperpolarisation* in the neurones of the brain.

It can be used for **diagnosis**, to evaluate damage from stroke, multiple sclerosis, movement disorders, damages affecting cranial nerves and spinal cord, and

therapy, to treat certain types of major depression, Parkinson's disease and some kinds of schizophrenia.

Magnetic fields in medicine

Magnetic Resonance Imaging (MRI) allows to examine changes of protons in tissues. (We will talk about it in the 2nd part of these lectures).



Magnetic fields in medicine

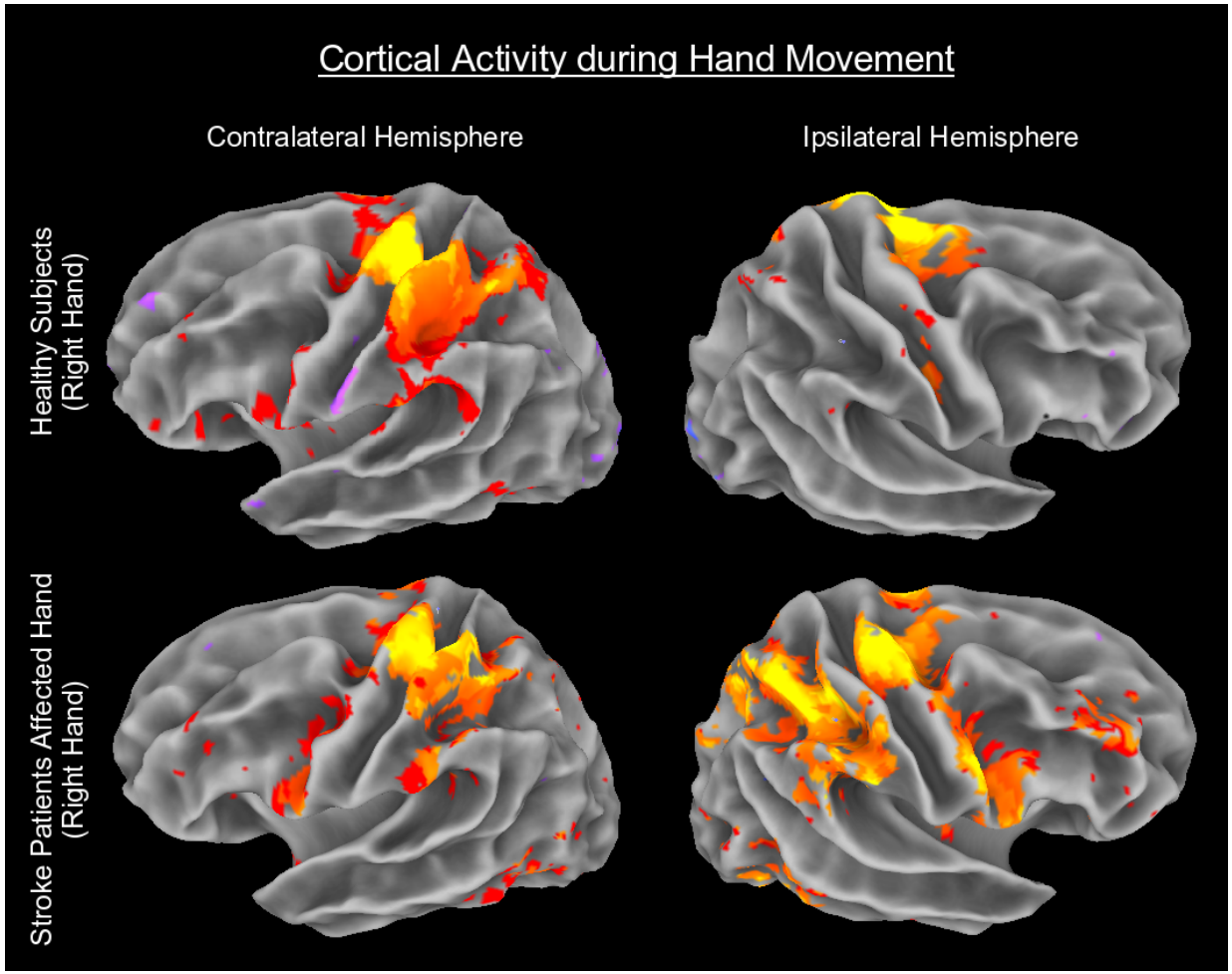
Functional Magnetic Resonance Imaging (fMRI) is a type of MRI that allows to examine changes in blood flow to local parts of brain, providing an indirect measure of brain activity. Changes in brain activity occur when a subject performs a movement or responds to stimulation.

The level and pattern of activity can be altered in a person with a brain injury such as stroke or in response to therapies that improve motor function.

An important goal is to better characterize the relationship between changes in brain activity and recovery of movement after stroke.

Magnetic fields in medicine

Functional Magnetic Resonance Imaging



http://www.martinos.org/neurorecovery/technology.htm

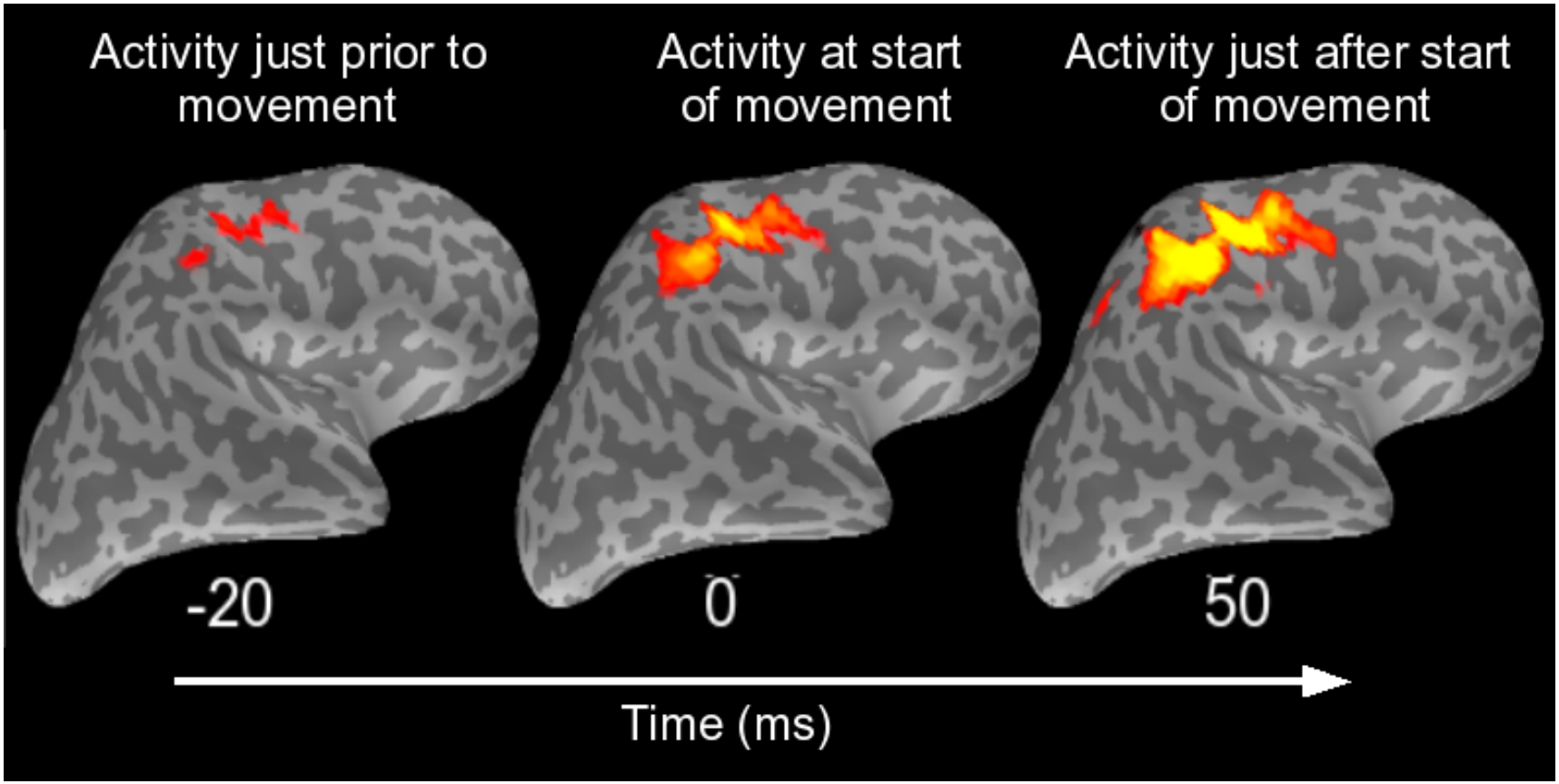
Magnetic fields in medicine

Magnetoencephalography (MEG). Is a technique for mapping brain activity by recording magnetic fields produced by electrical currents occurring naturally in the brain using very sensitive magnetometers.

The sensing mechanism is an array of more than 300 SQUIDS contained in a helmet shaped criostat.

Magnetic fields in medicine

- **Magnetoencephalography (MEG)**.



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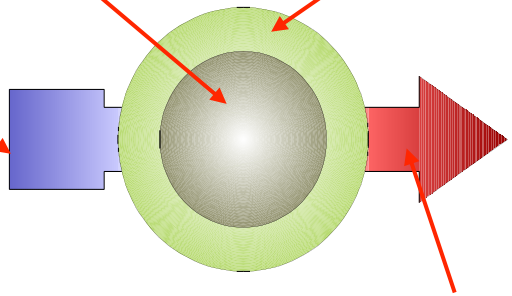
Magnetic nanoparticles for diagnostic and therapy

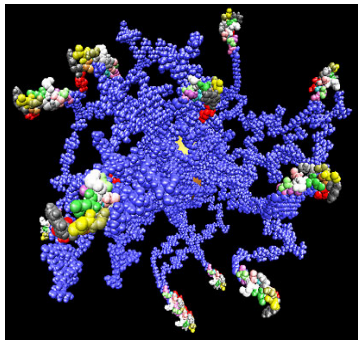
The magnetic functionality

Magnetic nucleus

Protecting coating, anchoring element

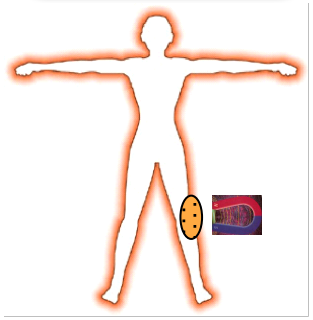
Functionalized tail for therapeutic uses: drugs, enzyms, etc.



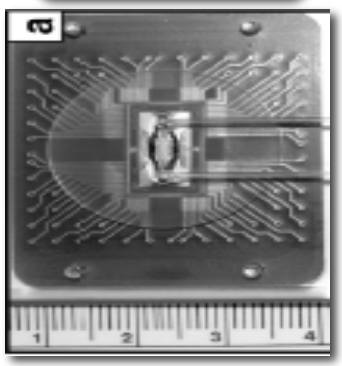


Biological vector

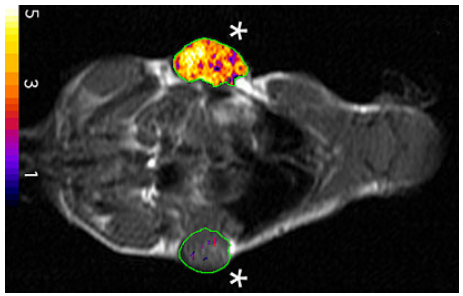
DRIVING



SENSING



IMAGING



HEATING

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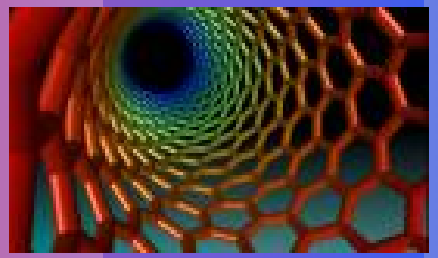
Is *nano* just a matter of size?

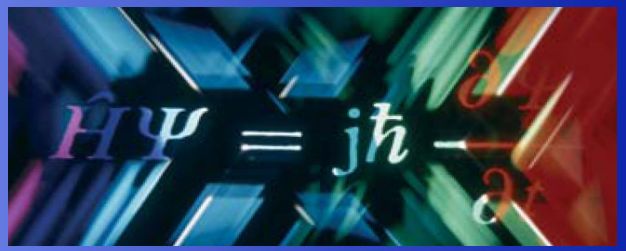
From the physics point of view Nano- is the interface separating the atomic from the macroscopic scales

Macroscopic World ruled by Classical Mechanics and Electromagnetism laws

NANO WORLD

Atomic World ruled by the laws of Quantum Mechanics





In the atomic world there are properties whose critical lengths are at the nano-scale

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Is *nano* just a matter of size?

At the scale below a critical length new properties arise that can give rise to new materials and new applications

Critical lengths such as

- one electron Fermi wavelength
- exciton Bohr radius
- single magnetic domain length

lead to Quantum Dots and Superparamagnetic particles

Iron oxides

Iron Oxo-hydroxo and Hydroxides	Iron Oxides
Goethite α-FeOOH	Hematite α-Fe_2O_3
Lepidocrocite γ-FeOOH	Magnetite Fe_3O_4
Akaganeite β-FeOOH	Maghemite γ-Fe_2O_3
Schwertmannite $Fe_{16}O_{16}(OH)_y(SO_4)_2 \cdot nH_2O$	β-Fe_2O_3
δ-FeOOH	ε-Fe_2O_3
Feroxyhyte δ'-FeOOH	Wüstite FeO
High pressure FeOOH	
Ferrihydrite $Fe_5HO_8 \cdot 4H_2O$	
Bernalite $Fe(OH)_3$	
$Fe(OH)_2$	
Green Rusts $Fe_x^{III}Fe_y^{II}(OH)_{3x+2y-z}(A^-)_z$; A^- = Cl^-; 1/2 $SO_4^=$	

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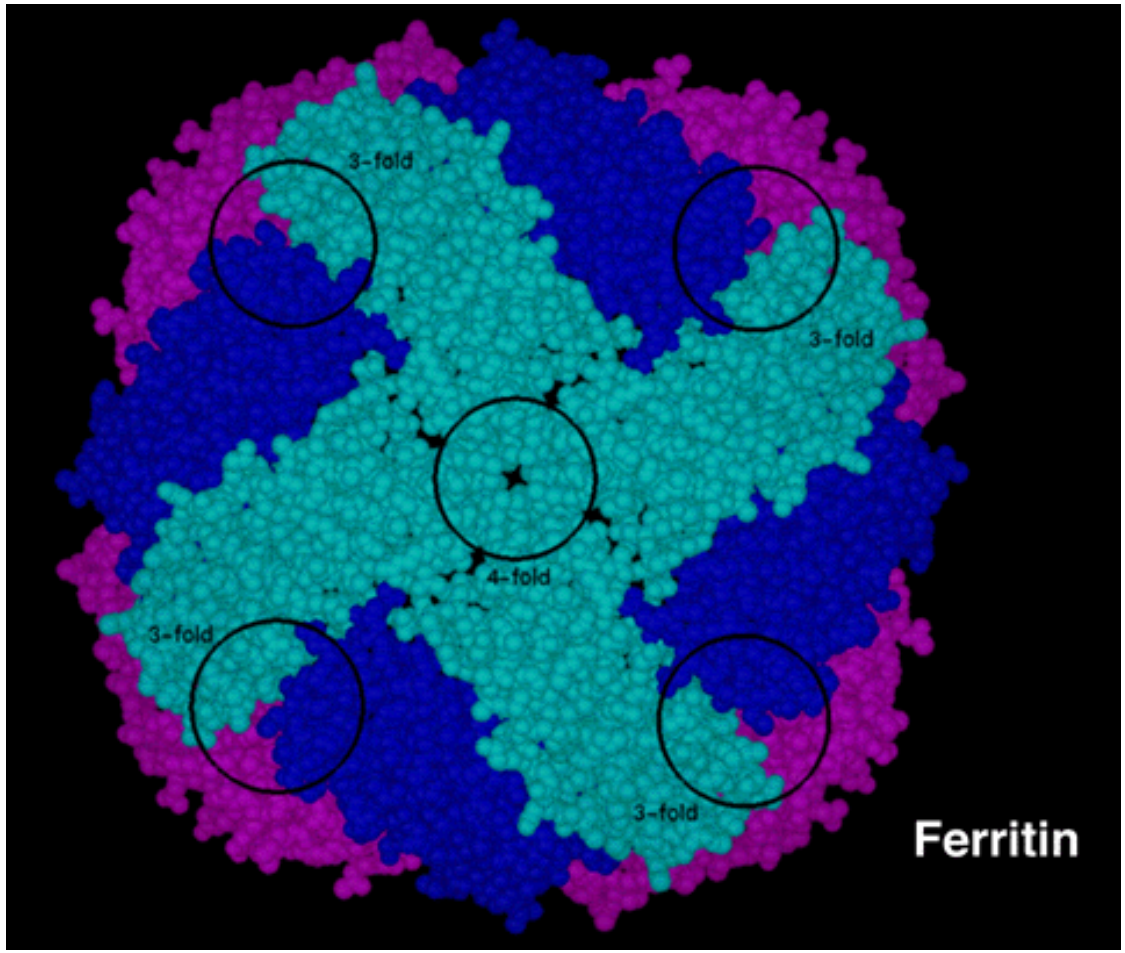
Iron oxides

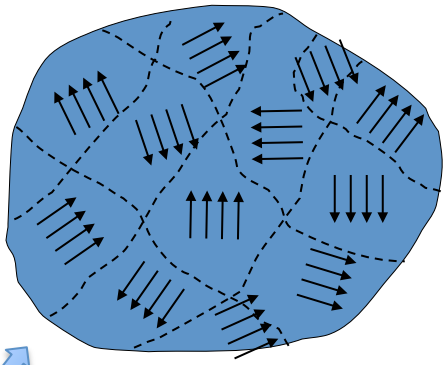
Iron Oxide	Ordering Temp. (K)	Magnetic structure	Ms
Goethite	400	Antiferromagnet	0.01 - 1
Lepidocrocite	77	Antiferromagnet	
Akaganeite	280	Antiferromagnet	
δ-FeOOH	440-460	Ferrimagnet	7 - 20
Feroxyhyte	455	Ferrimagnet	
HP FeOOH	470	Antiferromagnet	
Ferrihydrite	≈ 350	Speromagnet	
Bernalite	≈ 427	Weakly ferromagnetic	
Magnetite	**850**	**Ferrimagnet**	**92 - 100**
Maghemite	**820 - 986**	**Ferrimagnet**	**60 - 80**
Wüstite	203 - 211	Antiferromagnet	

Iron oxides

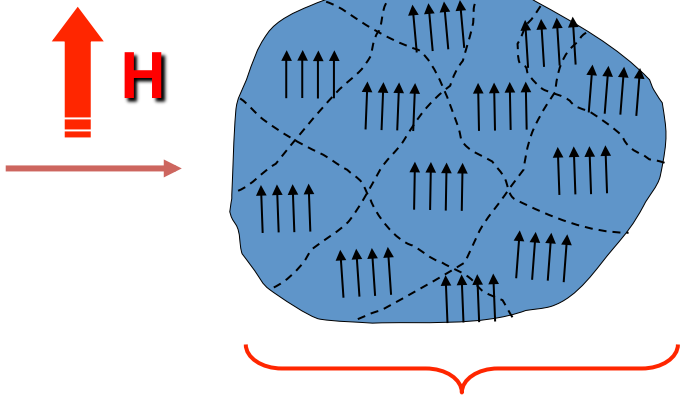
Iron control in living organisms is made with the help of ferritines, a family of iron-storage proteins holding iron oxide inside.



Magnetic Particles

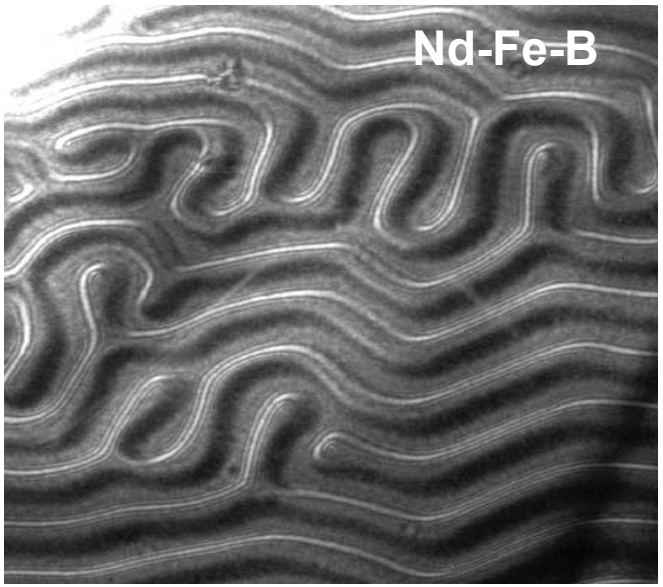


+ Magnetic field **H**

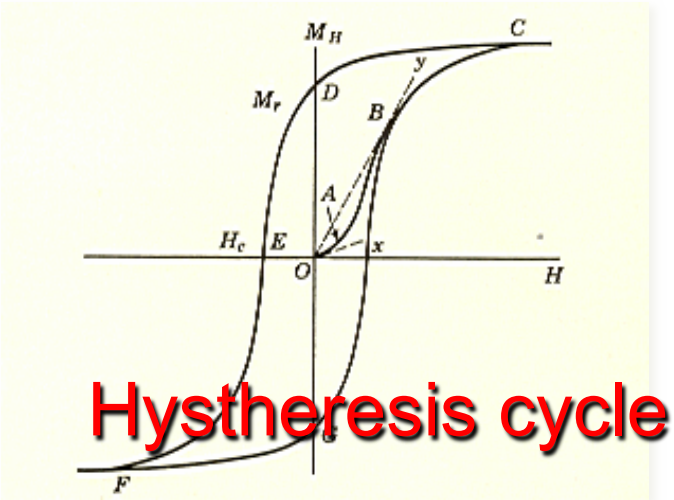


Magnetic domains

Magnetisation M = m/V_m



www-hrem.msm.cam.ac.uk/gallery/index.shtml

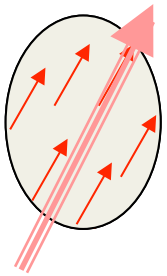


Hystheresis cycle

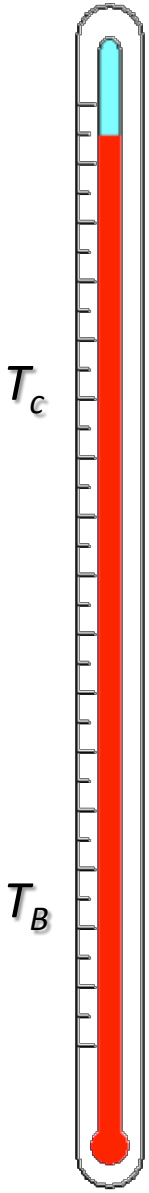
Single-domain particles

When the size of a particle is smaller than the minimum allowing the formation of domains (≈ 20 - 30 nm), it becomes single-domain and

superparamagnetic

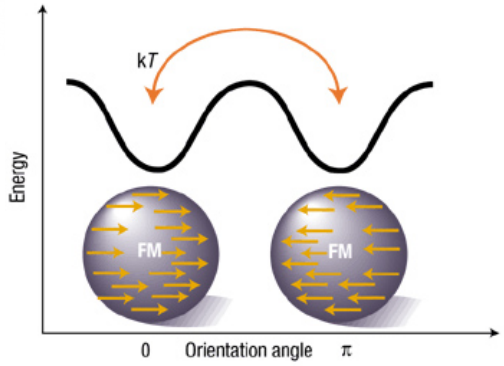


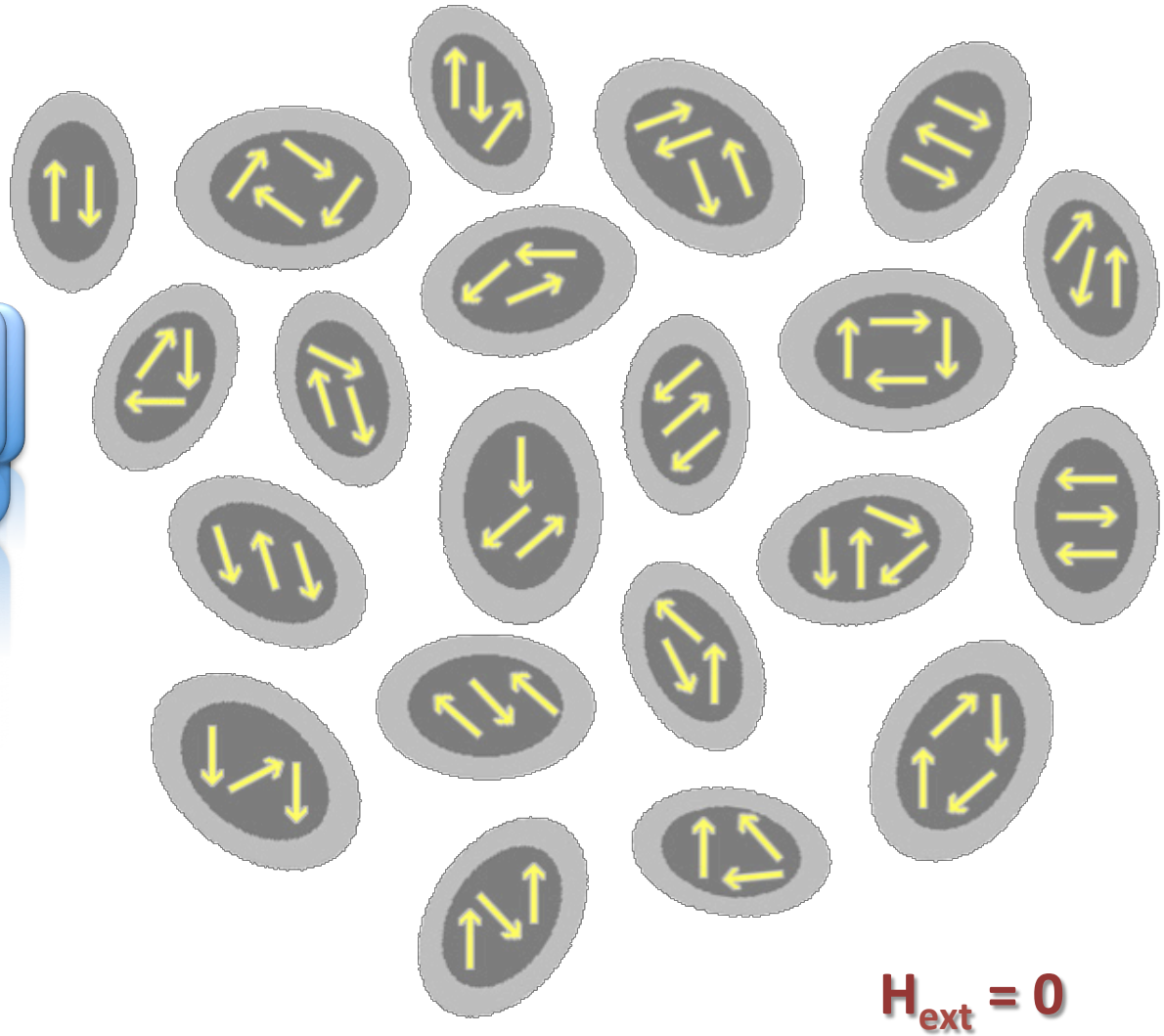
Superparamagnetism



$T > T_C$

Paramagnetic





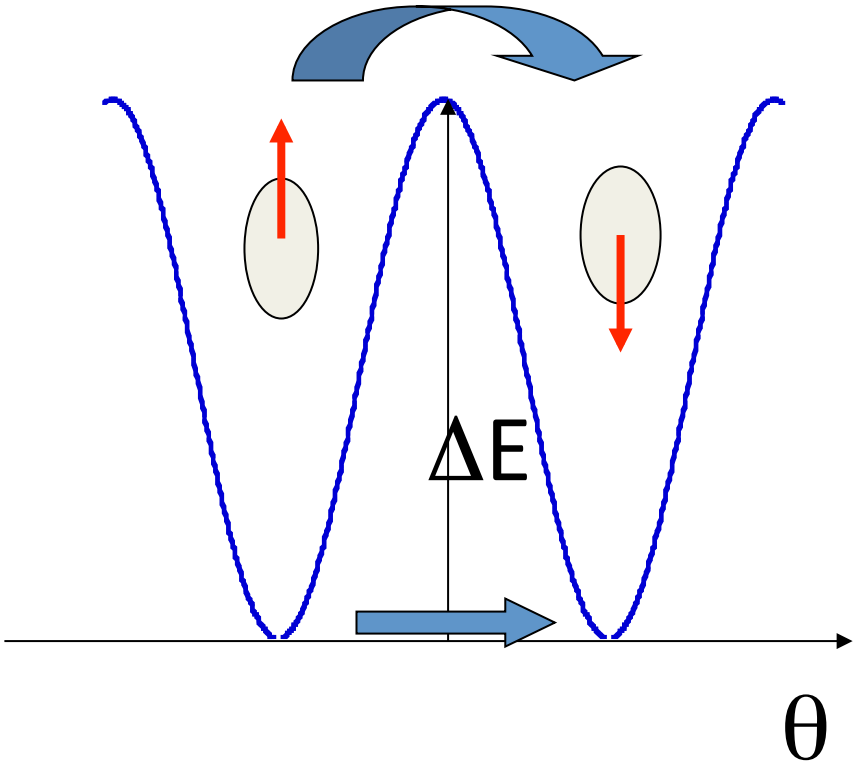
$H_{ext} = 0$

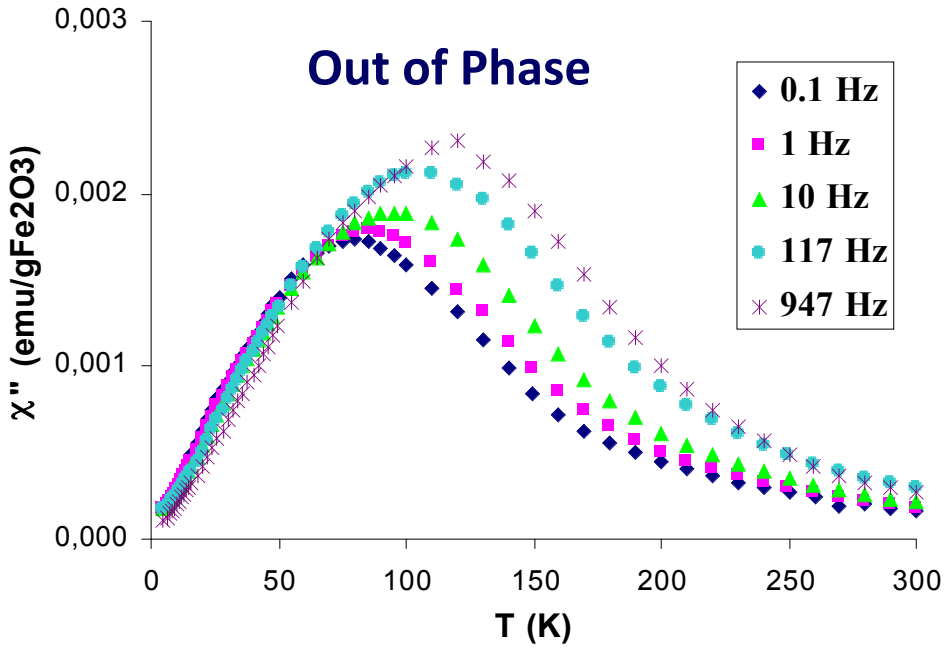
Magnetic nanoparticles

H_{ac} +single domain particle
+ magnetic anisotropy

$$E_v = K_{eff} \sin^2\theta$$

$$\Delta E = K_{eff} V$$

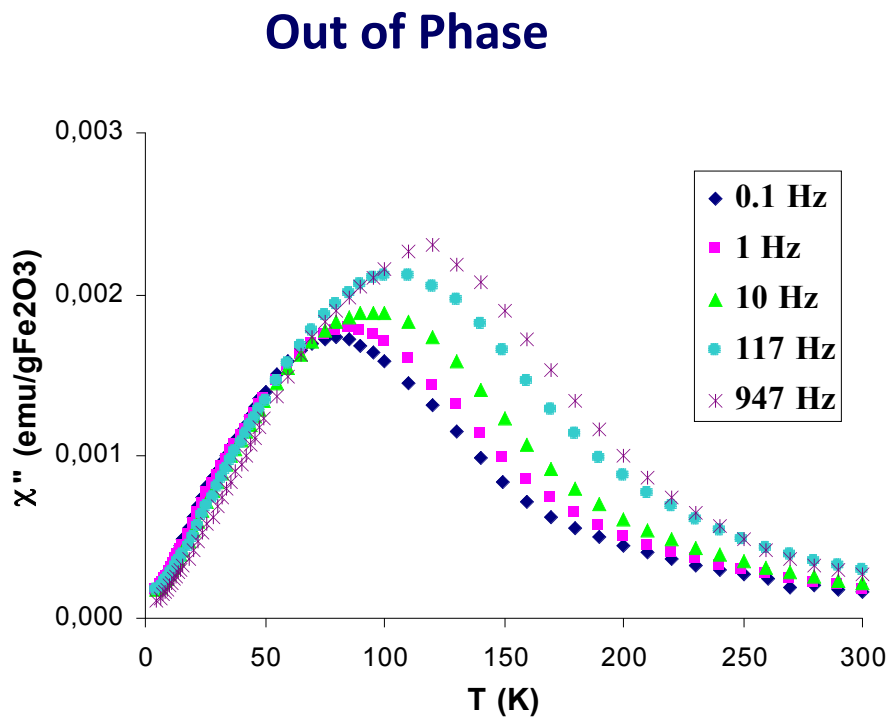




Magnetic nanoparticles

$\Delta E = K_{eff}V = K_V V + K_S S$

$\chi''(f, T) \propto \Delta E g(\Delta E)$



at the maxima, T_B,

$\tau_m = \tau_0 \exp(\Delta E/k_B T_B) =$

$= 1/(2\pi f_m)$

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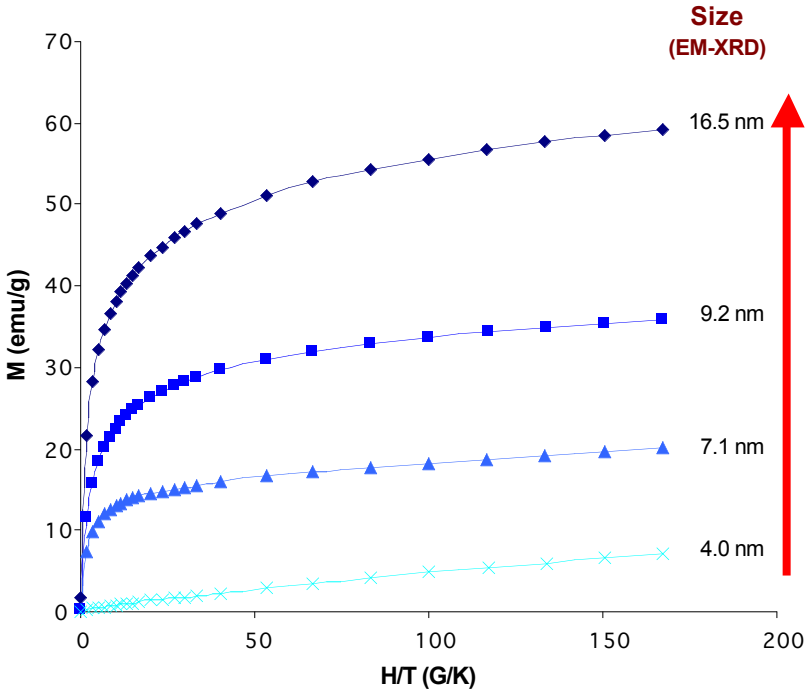
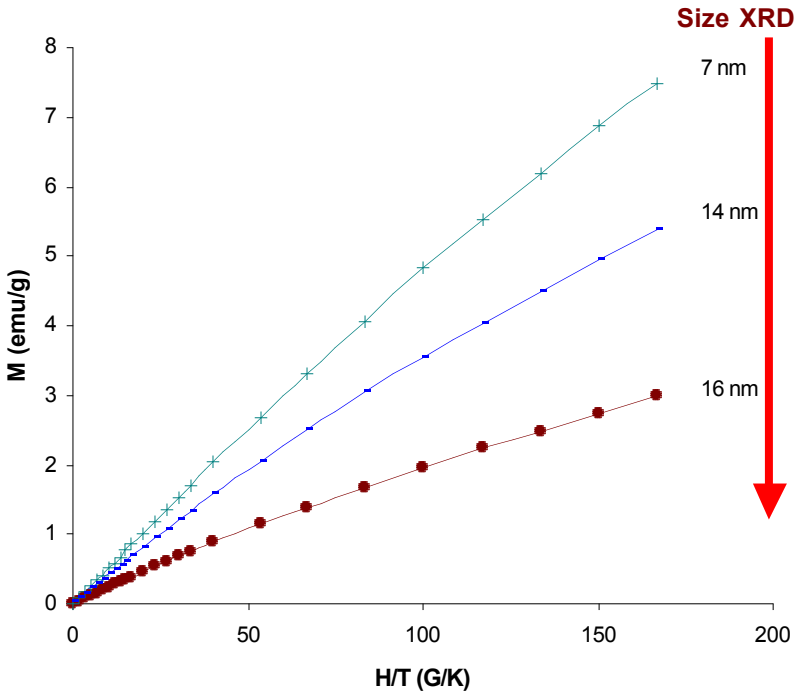
Surface effects

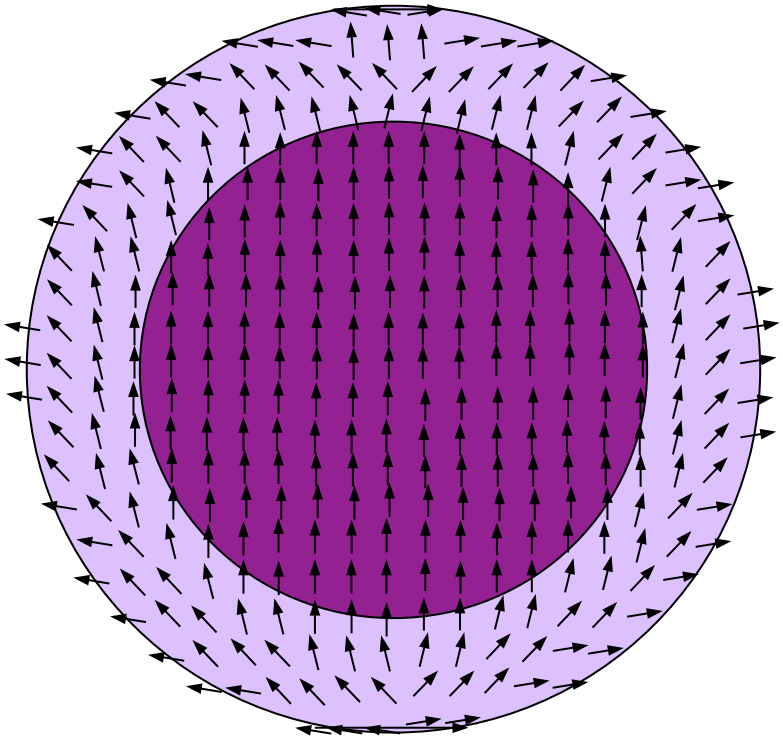
Maghemite



Goethite



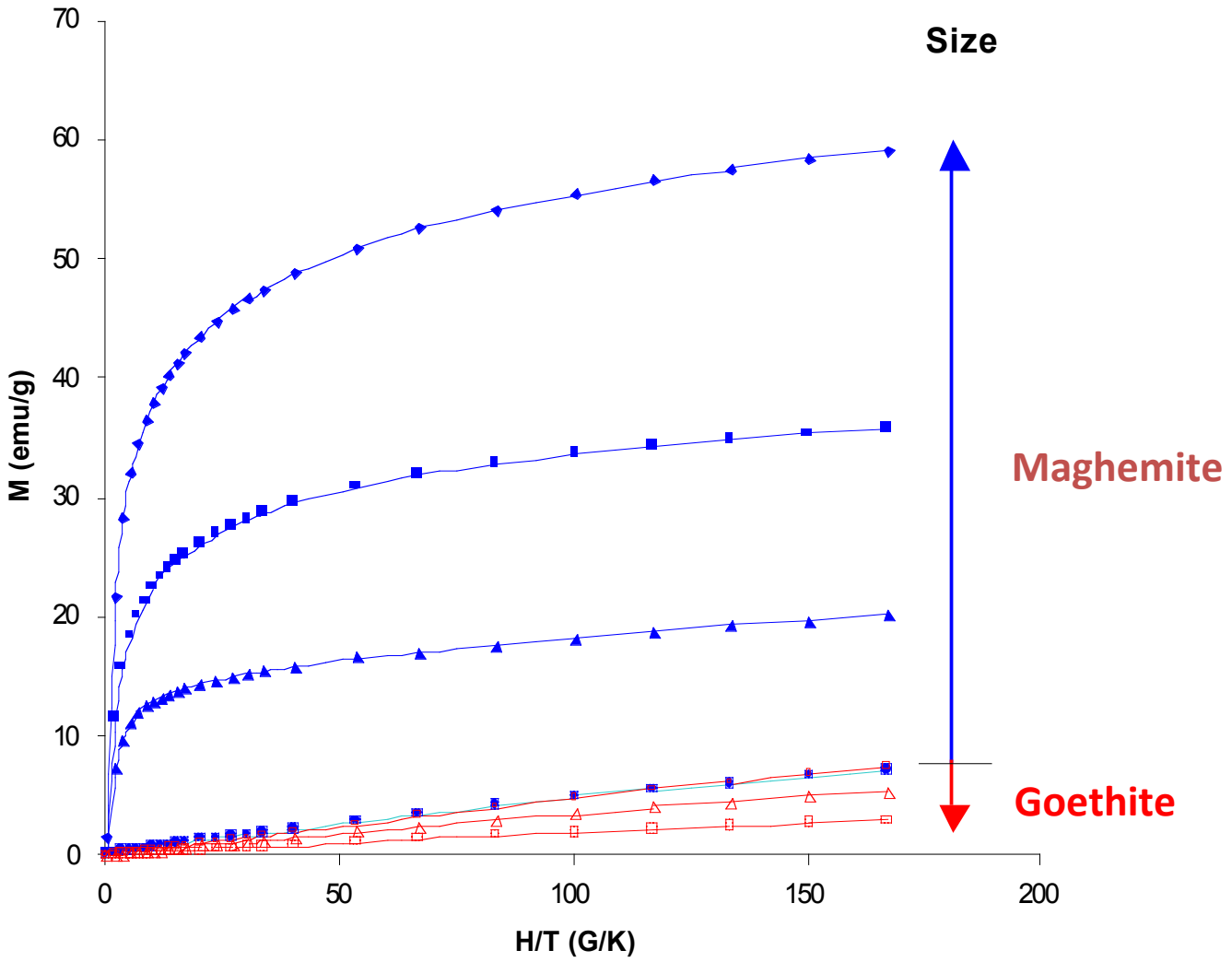
Surface effects



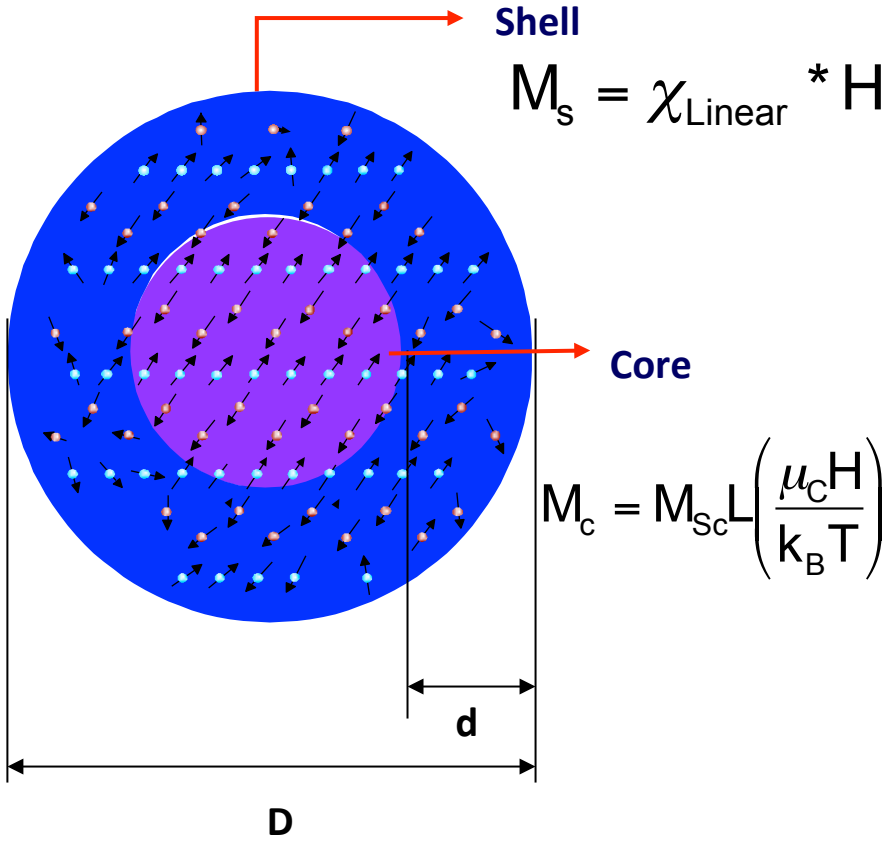
As D decreases the proportion of ions closed to the surface increases, then

- **magnetocristalline anisotropy changes**
- **canting and disordered in m appears**
- **Ms decreases (ferrimagnets)**
- **Ms appears and increases (antiferromagnets)**

Surface effects

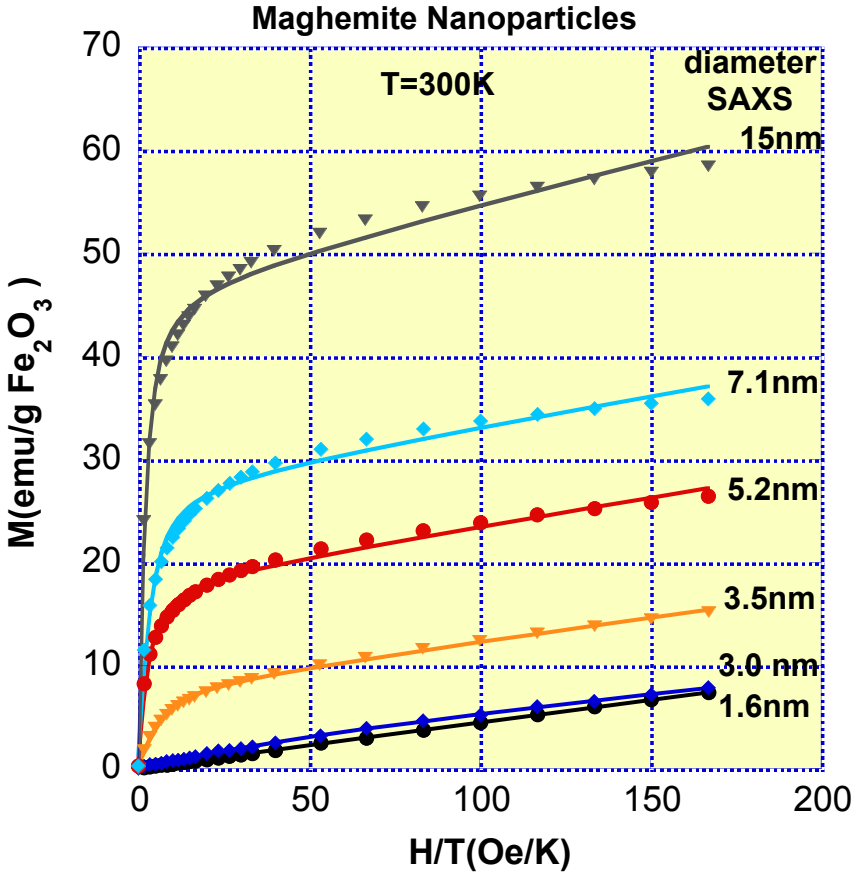


Surface thickness



$$M_s = \chi_{Linear} * H$$

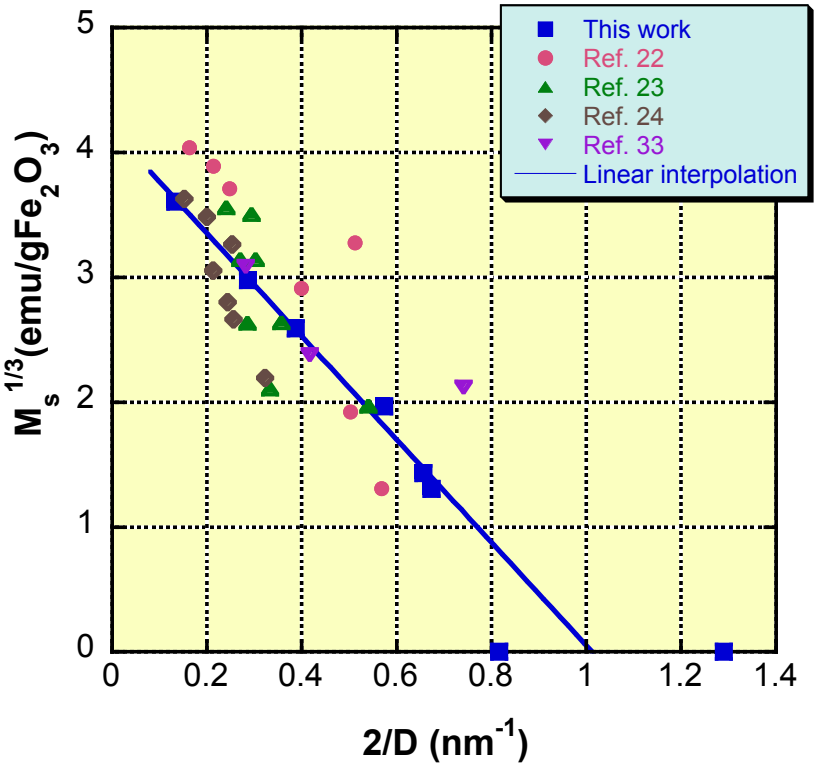
$$M_c = M_{Sc} L\left(\frac{\mu_C H}{k_B T}\right)$$



$$M_S = M_{S0}\left(\frac{(D/2) - d}{D/2}\right)^3$$

$$M = M_S L\left(\frac{\mu_C H}{k_B T}\right) + \chi_{Linear} H$$

Surface thickness



d ≈ 1 nm

Ref. 22 M.P. Morales et al., J. Magn. Magn. Mater. **203** (1999) 146
Ref. 23 N. Feltin et al., Langmuir, **13** (1997) 3927
Ref. 24 E.M. Moreno et al., Langmuir **18** (2002) 4972
Ref. 33 O. Iglesias et al., in "Surface Effects in Magnetic Nanoparticles", Ed. D. Fiorani, (Springer 2005) pp. 1-42.

A.Millán et el., J. Magn. Magn. Mat., **312**, L5-L9, (2007).

Outline P.1

In this 1st part we will cover:

- Introduction
- Magnetic fields and health: any risks?
- Do animals sense magnetic fields?
- The use of magnetism in medicine
- Fundamentals of the magnetism of nanoparticles
- Preparative techniques of magnetic nanoparticles

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Fabrication methods

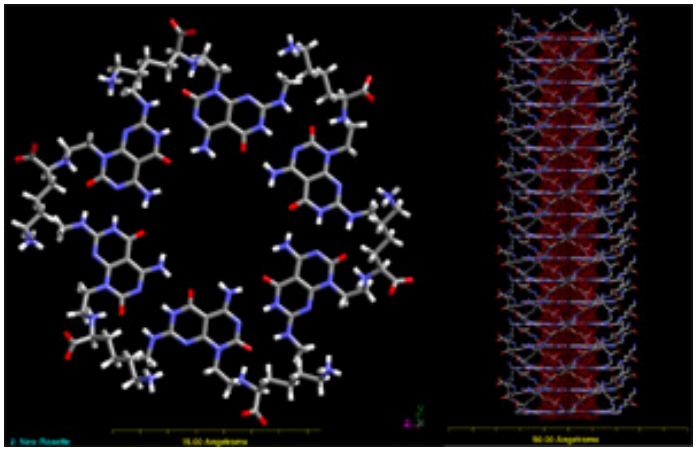
Top-down approach

It is the traditional approach: a nanosized material is obtained from a much larger source by grounding or other size-reduction actions.

Top-down approach

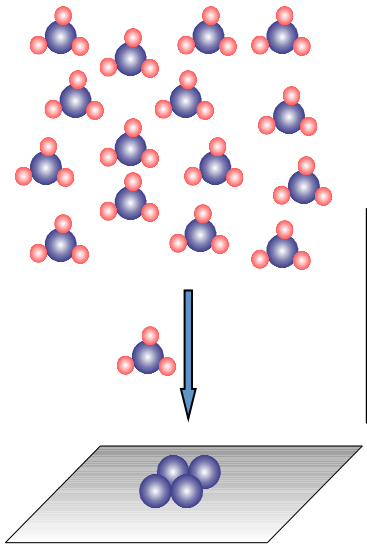
Bottom-up approach

Uses molecules or clusters and self-assemble and self-organised them like in a *Lego* toy to fabricate new materials. In many examples tends to replicate nature developing processes.



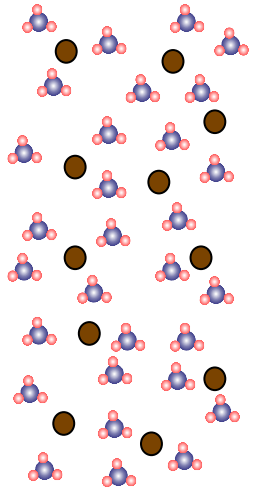
Molecular self-assembling

Preparative techniques

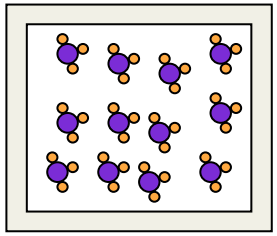


Controlled slow Transport

Extensive Nucleation

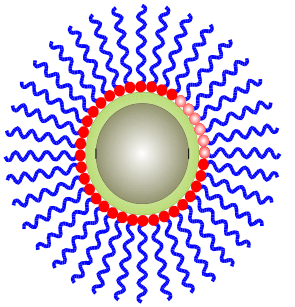


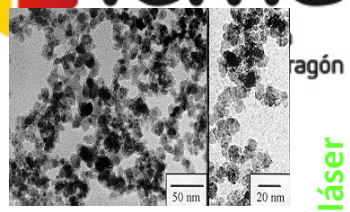
“Bottom-up”

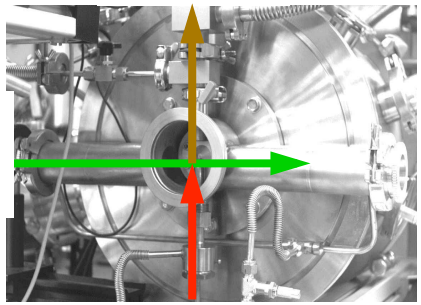


Restricted Space

Growing Inhibition







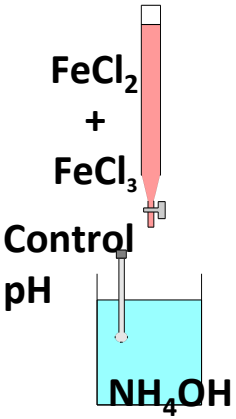
$Fe(CO)_5$, O_2

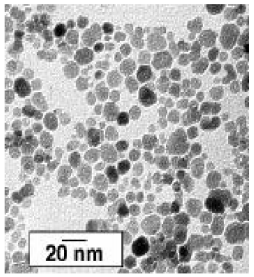
Size Control by:

- Fe/O_2 Proportion
- Laser Power

Characteristics:

- Variable Sizes (4-7 nm)
- High Yield
- Difficult coating



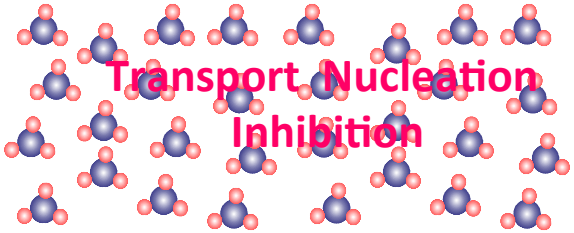


Size Control by:

- pH, cation, base

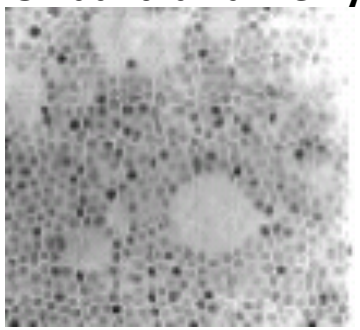
Characteristics:

- Variable Sizes (2-19 nm)
- Unexpensive
- Strong aggregation
- High size dispertion



Water

Inhibitor: Oleic ac.
Precursor: $FeCl_2$ + Fe Cl_3
Oxidant: alkaline hydroxide



Size Control by:

- pH, cation, inhibitor

Characteristics:

- Better size control
- Lower aggregation
- Difficult coating

Organic

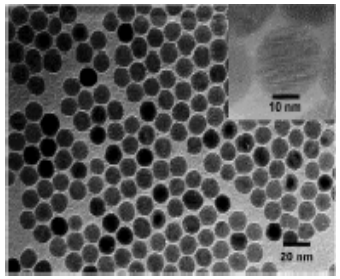
Solvent: octhyl ether
Inhibitor: Oleic ac.
Precursor: Fe(CO)5
Oxidant: O_2, trimethyl nitroxide

Size Control by:

- inhibitor, regrowing

Characteristics:

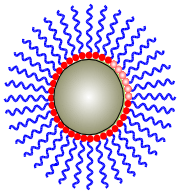
- monodispersion
- no agregation
- Difficult coating



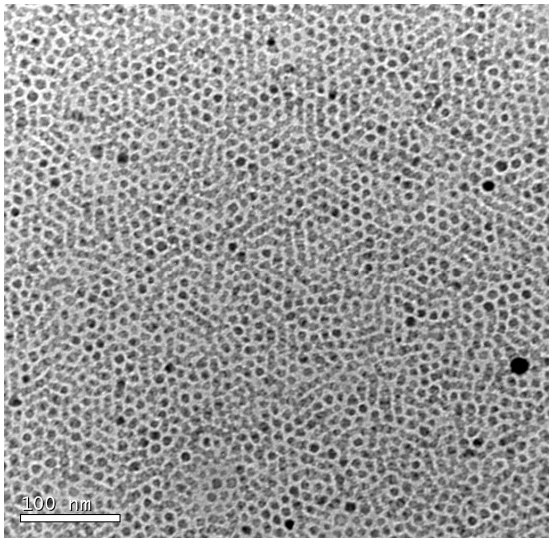
Preparative techniques

Organic

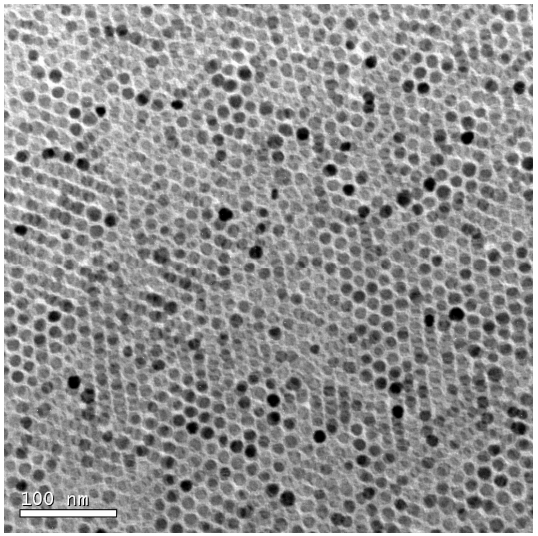
Solvent: octhyl ether

$Fe(CO)_5$ $\xrightarrow{\Delta}$ 

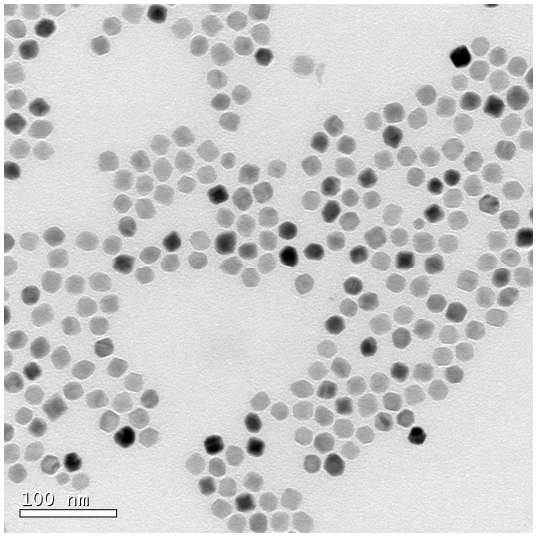
Oleic acid



Maghemite, 10 nm



Maghemite, 14 nm

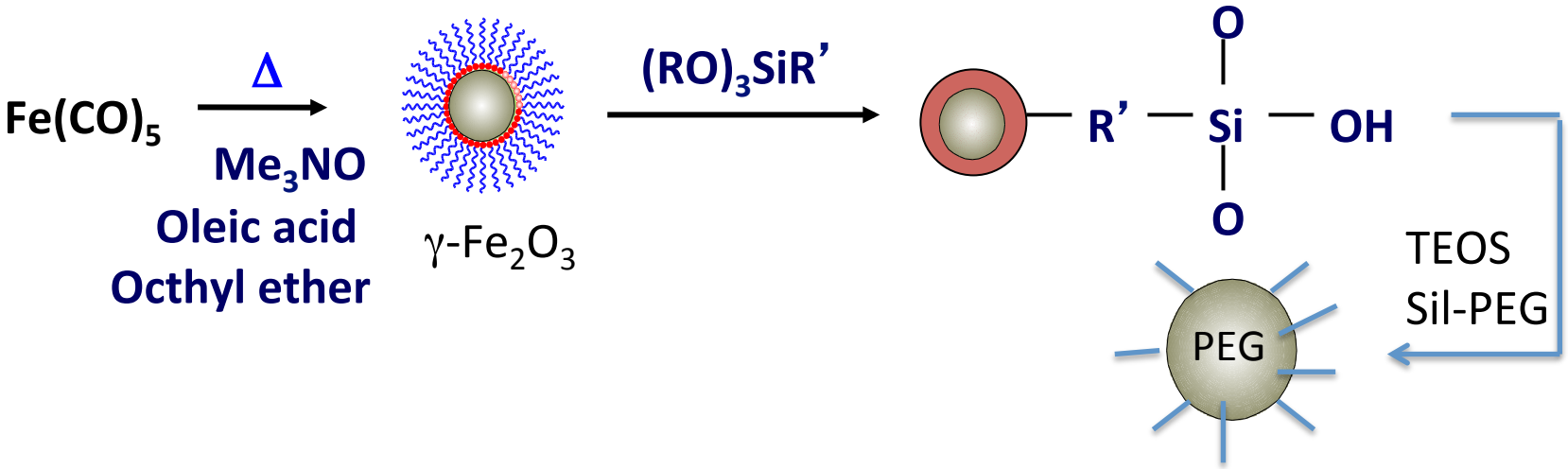


Maghemite, 20 nm

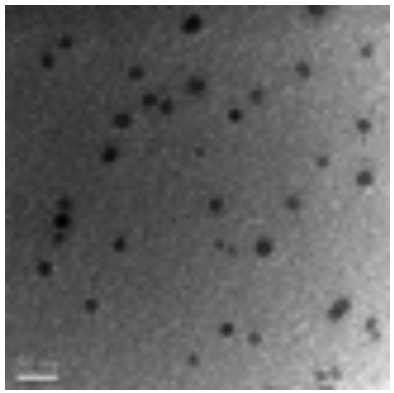
Size dispersion ≈ 5%

Size ranges: 4-20 nm

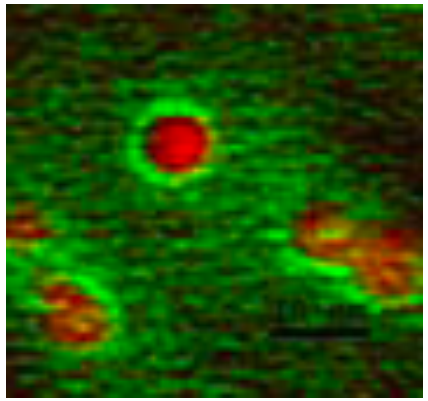
Preparative techniques

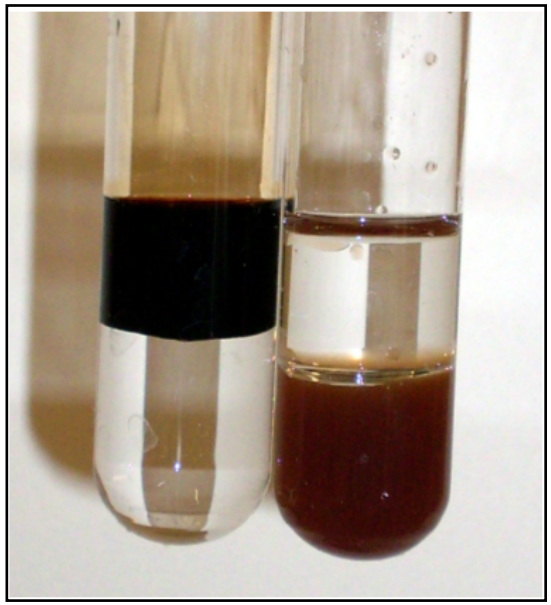


TEM



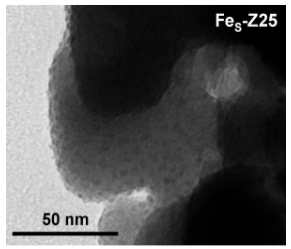
EFTEM

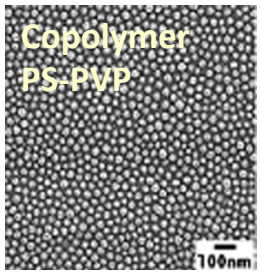


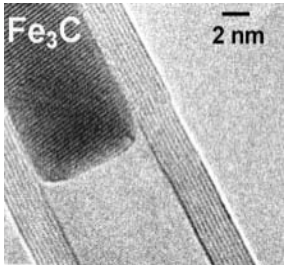


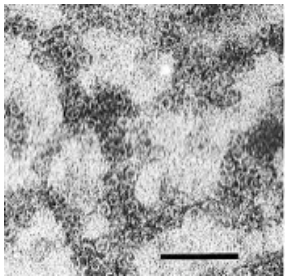
A. Arizaga et al., J. Mat. Sci. **48**, 2550-6, (2013)

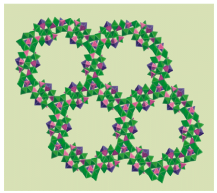
Restricted space: moulds









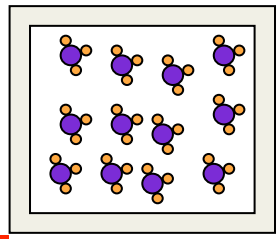


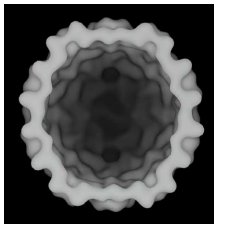
ceramic

polymer

zeolite

pores





nanotube

liposome

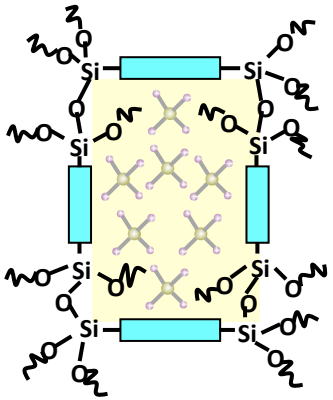
capsules

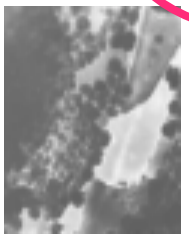
proteine

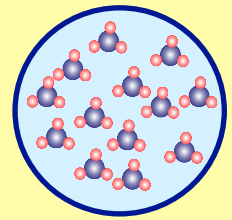
hybrid

gel

polymer





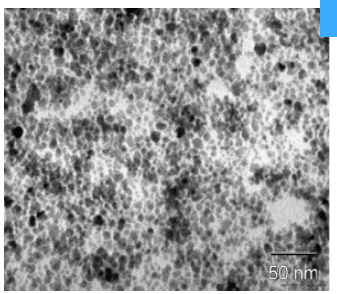


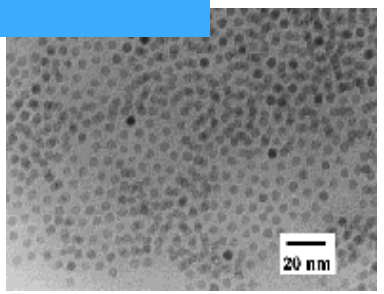
bubble

aerosol

micele

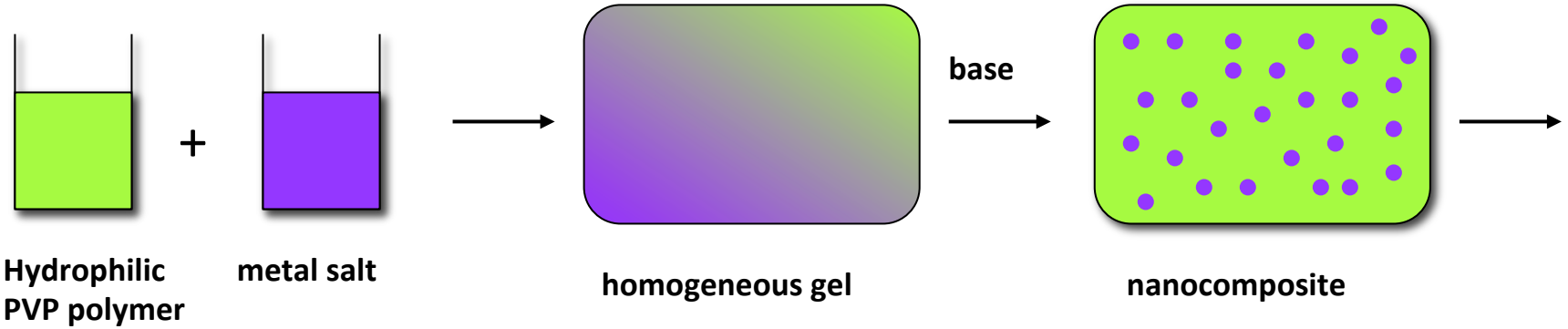
cavitation

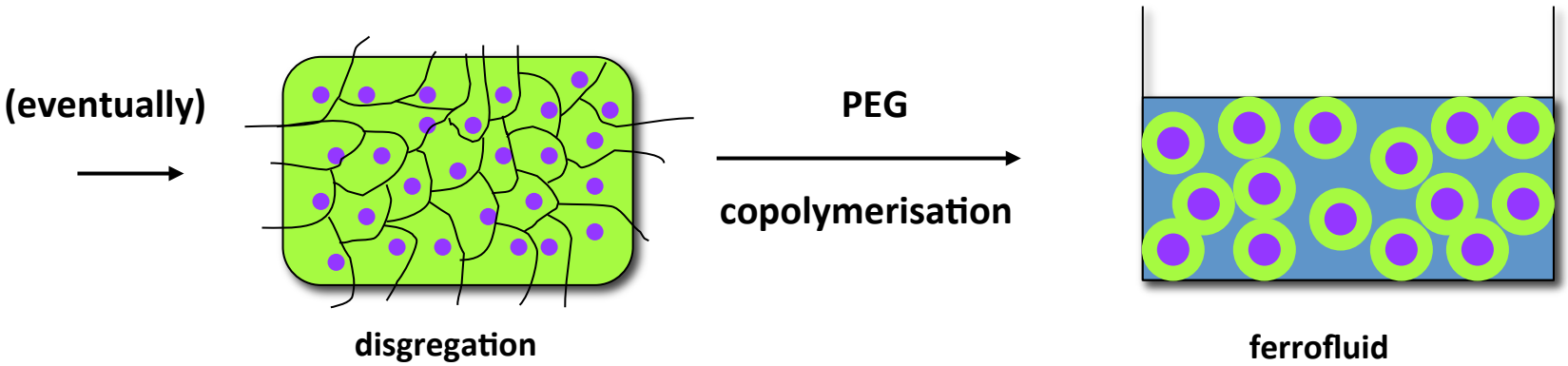




Preparative techniques

Polymeric methods





A. Millán and F. Palacio, Applied Organometallic Chemistry, **15**, 396-400 (2001)

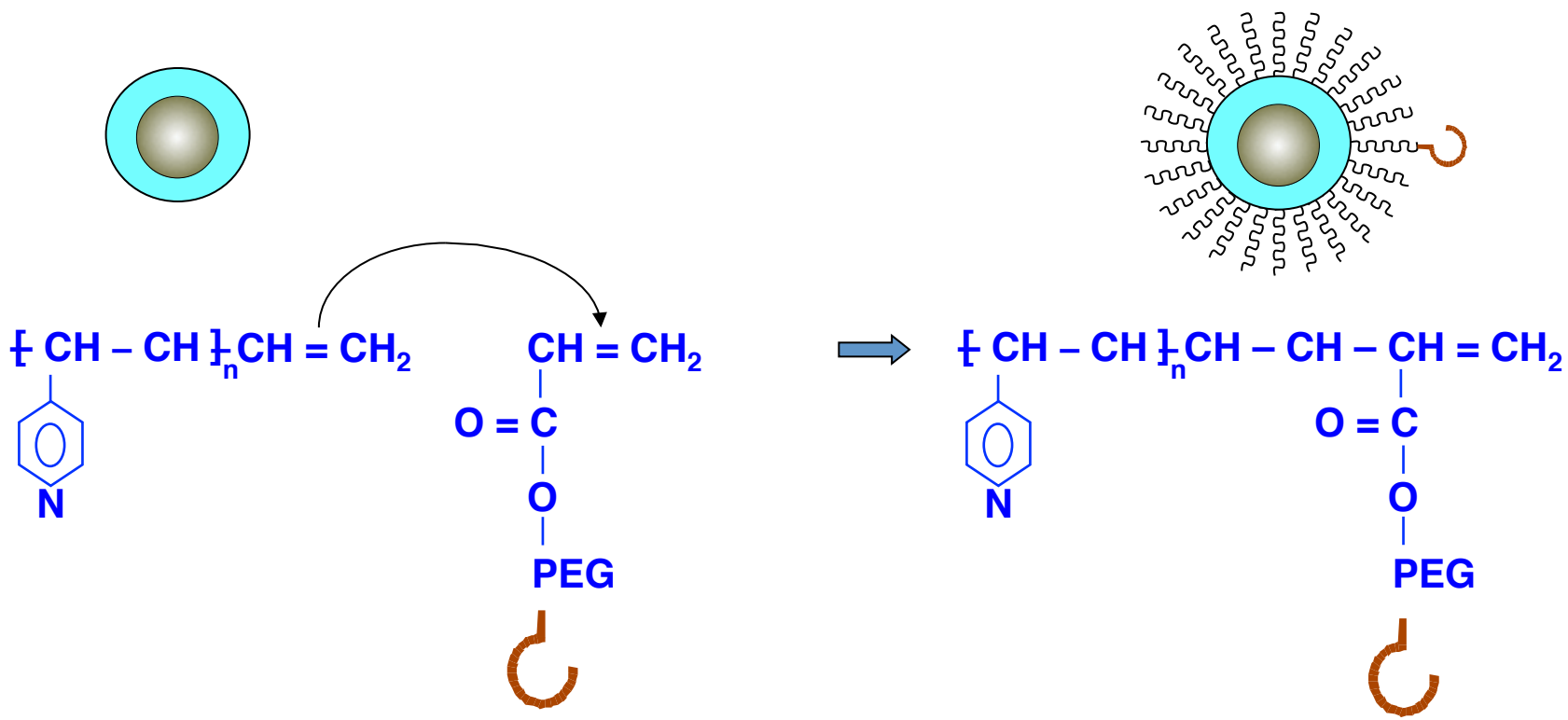
A. Millán et al., Acta Materialia **55**, 2201-9 (2007).

A. Millán, F. Palacio, G. Ibarz, Patent PCT/EP2007/058312

Preparative techniques

Polymeric methods

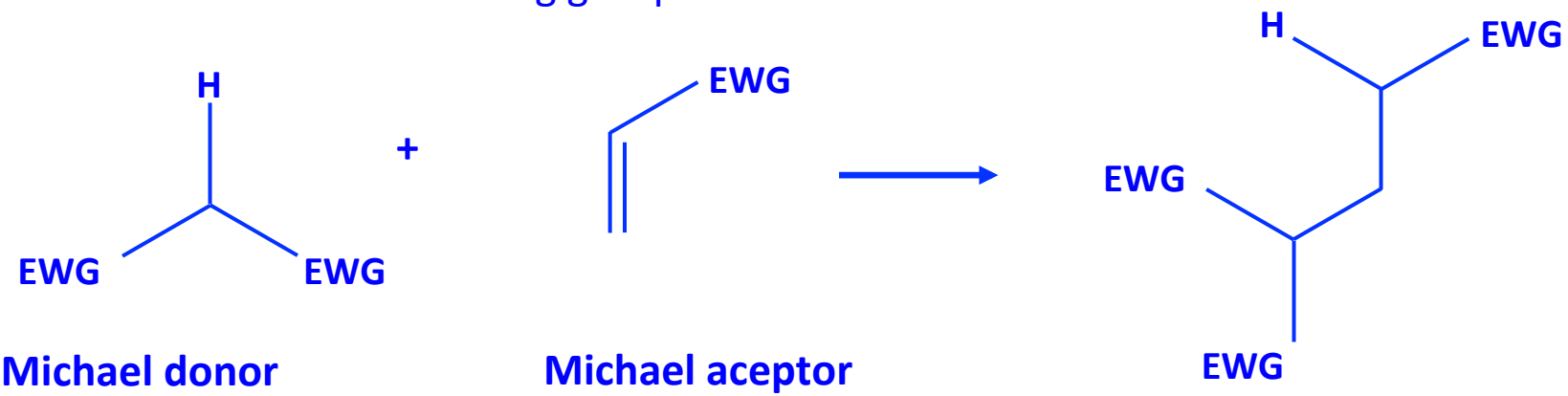
Anchoring residues by vinyl polymerization: Addition of polyetilenglicol (PEG) and linkers



Tailoring MNP with polymers

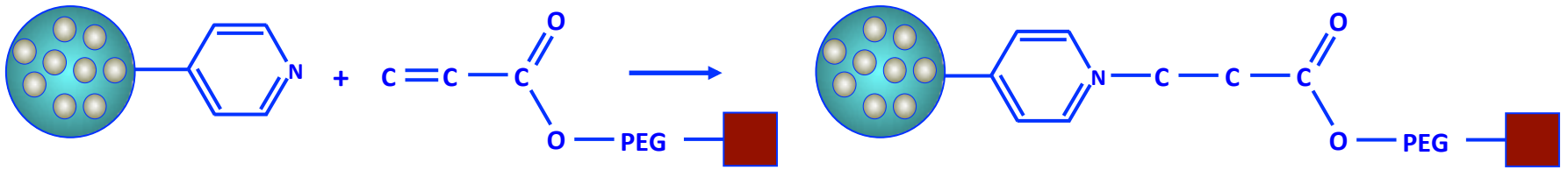
An easy route for functionalisation: Michael reaction

EWG: electron withdrawing group



Michael donor
carbanion o nucleophile

Michael aceptor
conjugated insaturated system



Physical or biological functionality

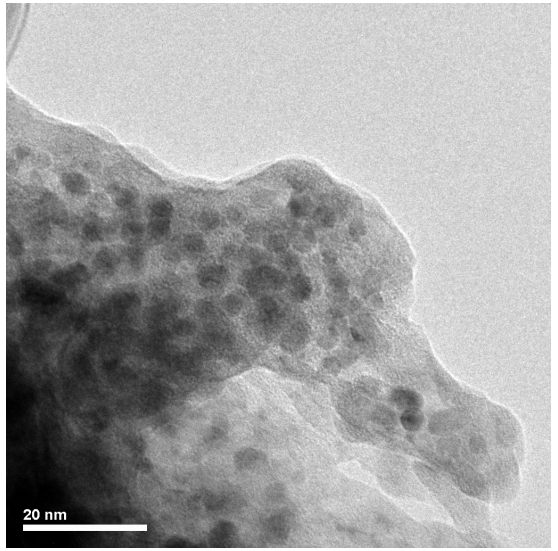
R. Piñol, A. Millán, F. Palacio et al., Patent P201031493

Tailoring MNP with polymers

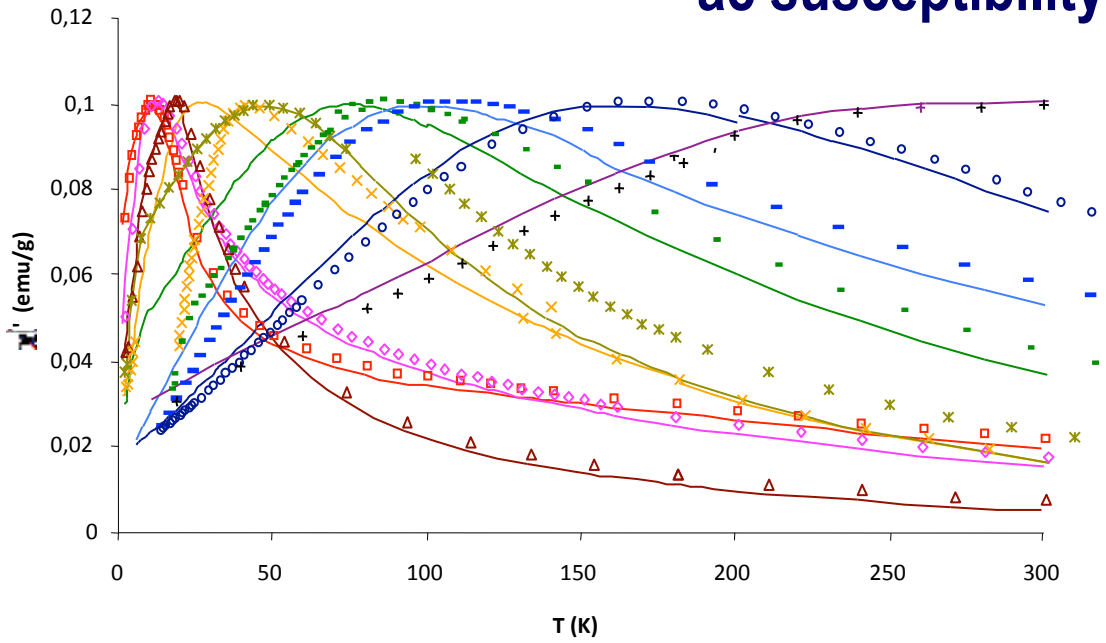
Adjustable Size

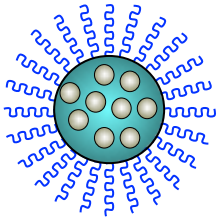
Magnetic nucleus

3 nm → 25 nm



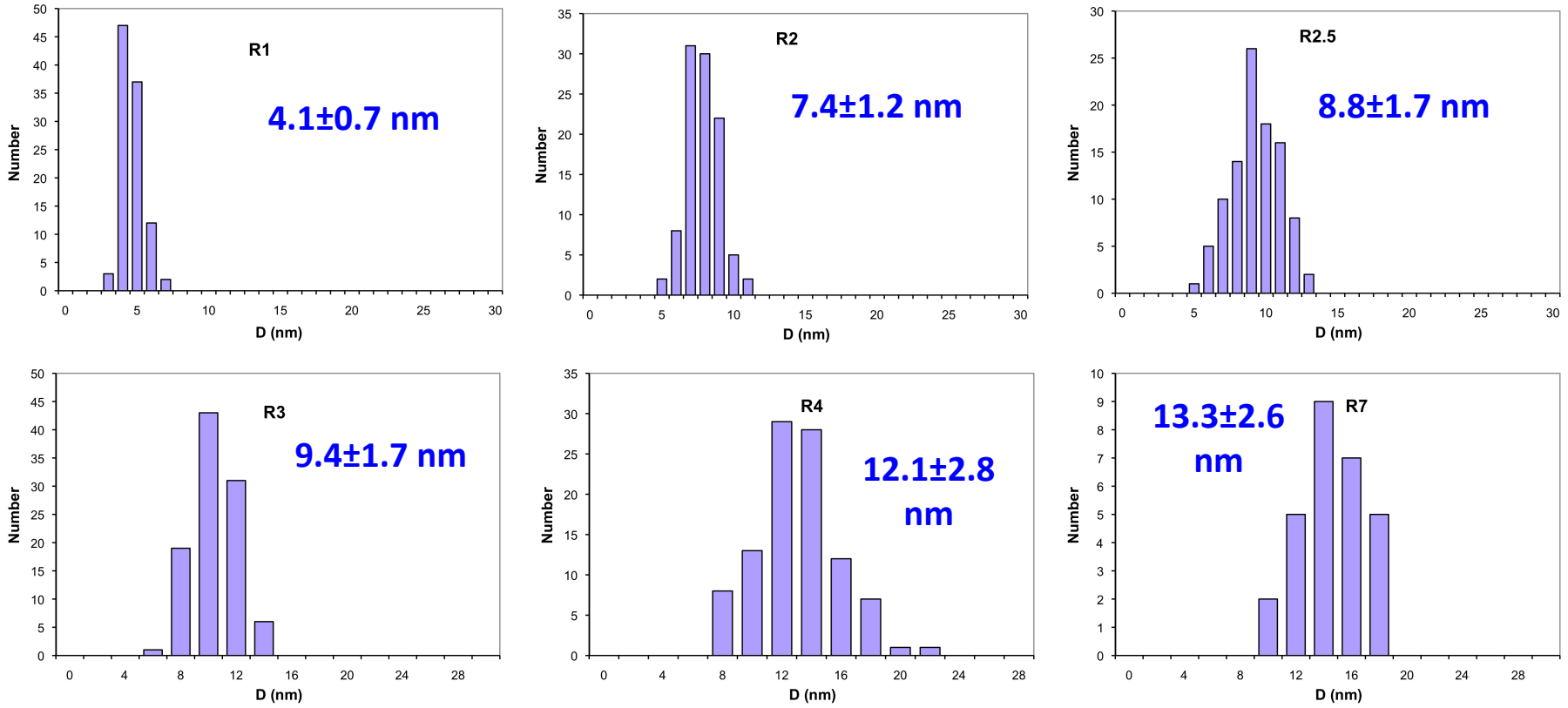
ac susceptibility





Tailoring MNP with polymers

TEM size distribution of Fe_2O_3 particles in a series of Ferrofluid samples in PBS. Same composition, but different Fe_2O_3 content

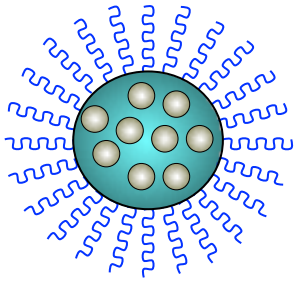


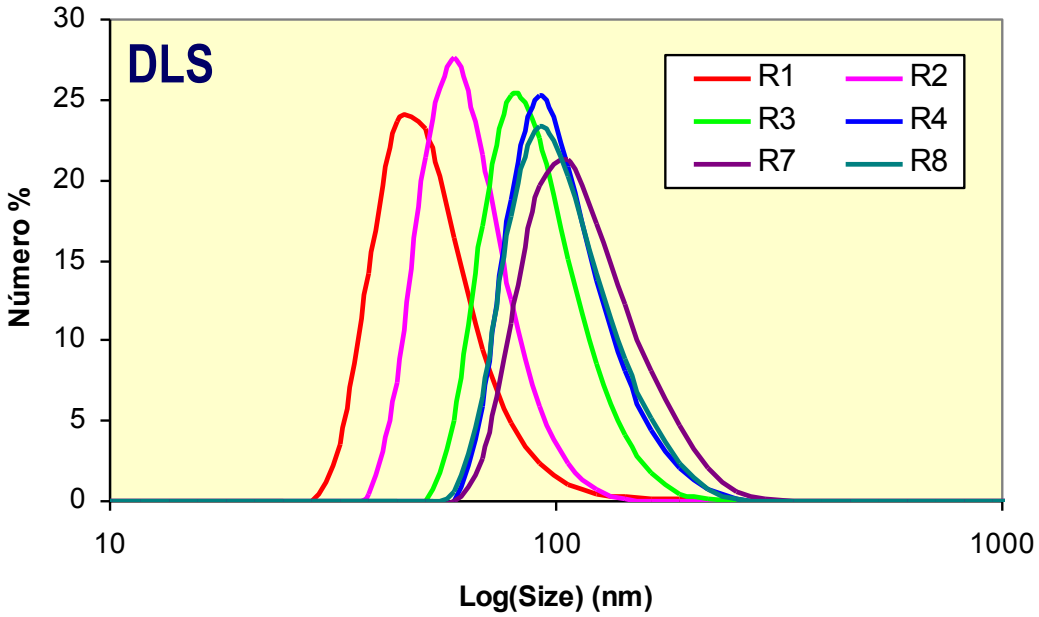
Tailoring MNP with polymers

Adjustable Size

Hydrodynamic size

30 nm → 150 nm

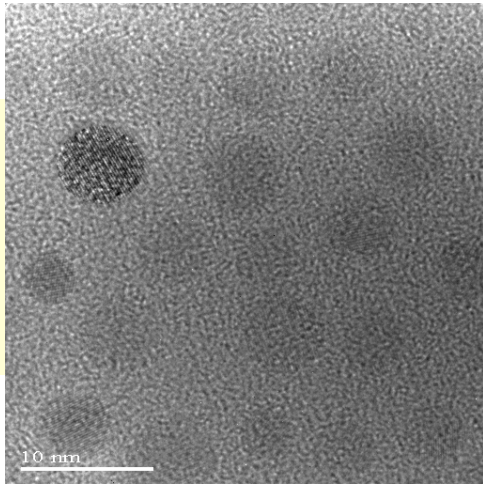


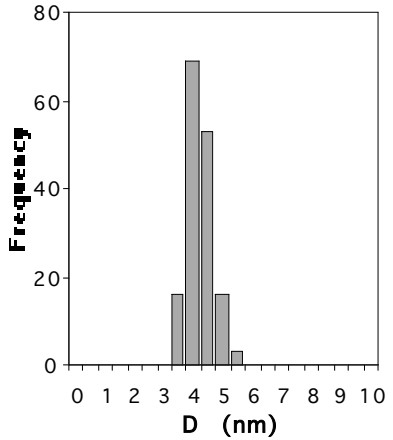


Preparative techniques

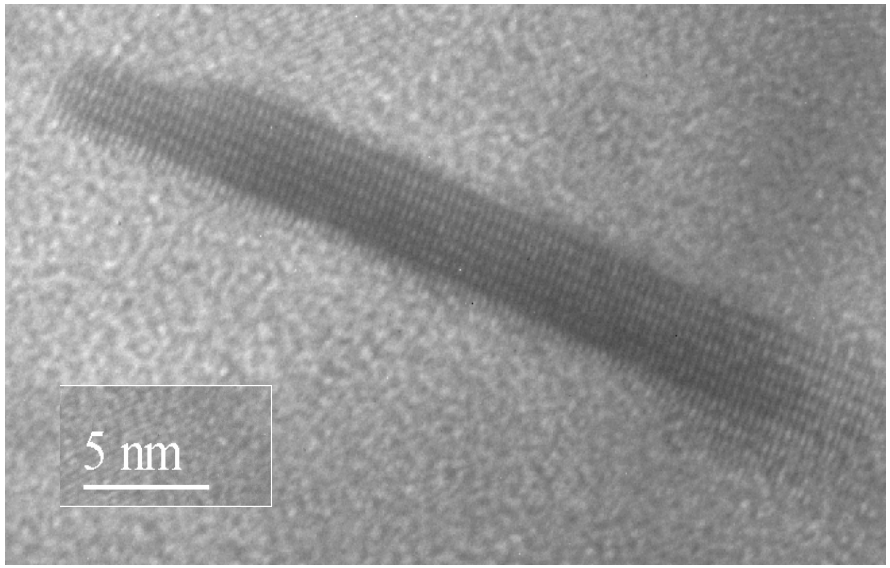
Polymeric methods

Simple and quick single-pot reaction Spheric particle sizes 2 - 15 nm
Size dispersion ±10%
No aggregation. Uniform distribution.





Either spheres and rods can be selectively prepared



Polymers can provide a way to avoid agglomeration and easy surface functionalisation

Preparative techniques

Superparamagnetic nanobeads

Stöber method