Magnetic properties of nanoparticles

J. Poltierová Vejpravová

Charles University Prague,
Faculty of Mathematics And Physics,
Department of Electronic Structures

&

Joint Laboratory for Magnetic Studies

Outline

Why nanoscale/nanoparticles ?

Magnetism - bulk vs. nano

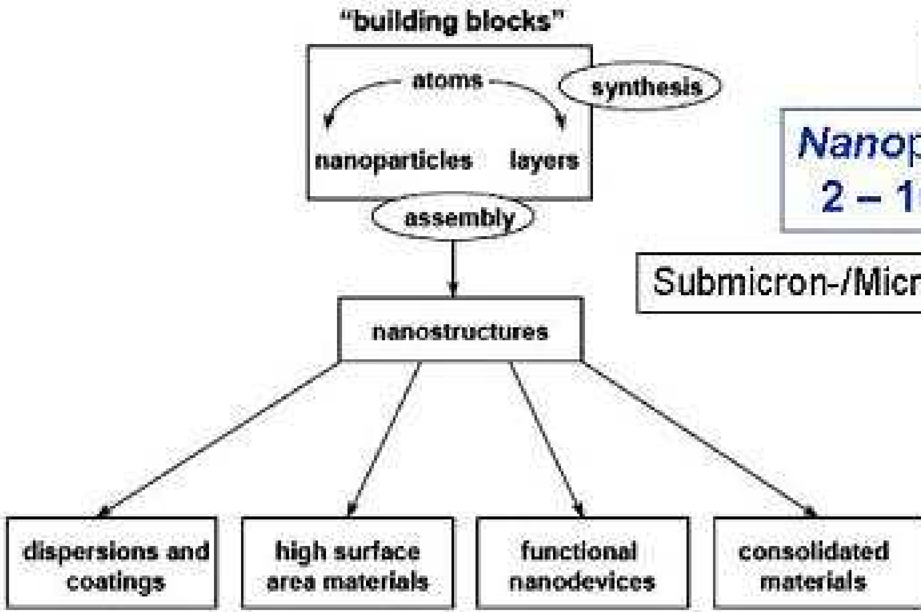
Magnetic nanoparticles – facet of reality

$CoFe_2O_4/SiO_2$ nanocomposites

Conclusions

Why nanoscale/nanoparticles ?

Bottom to top …



Clusters

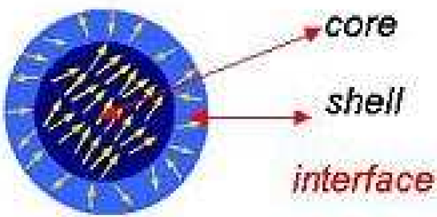
*Nano*particles
2 – 100 nm

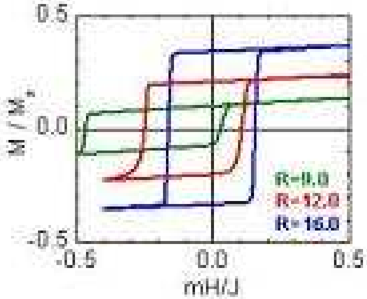
Submicron-/Microspheres

Areas of interest

Basic research

Surface-to-volume ratio (STVR) increases:
3 nm – 1400 atoms: 40% atoms at the surface!





- Surface and interface magnetism
- Control over magnetic anisotropy
- Stability and environmental compatibility

Areas of interest

Applications

Tayloring new functional materials/ functionalized surfaces

Electronics
Ultra-high density media (Tbit/inch), MRAM

Medicine, Bio –
Site-specific drug delivery, Hyperthermia - treatment for malignant cells

Other…
Hard magnets (separation), nanosensors, MCE

Dimension reduction/frustration – influence on electronic structure

Physical properties of the bulk material differ from the *nano*scaled one

Magnetism – consequence of spin and charge motion

Magnetic moment
↕
Interaction
↓
Properties

Magnetic moment

Unpaired electrons
(Hund's rules)
Paramagnetism
Curie/Curie-Weiss law

Interaction

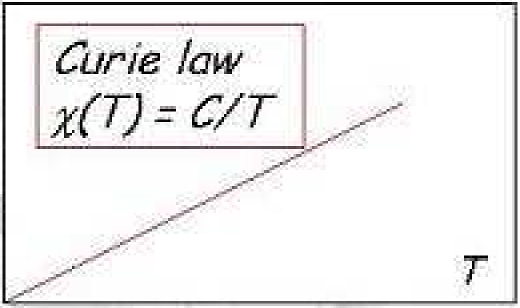
Exchange energy
Ordering temperature
Magnetic ordering – arrangement of magnetic moments: F, AF …

Properties

Spontaneous magnetization, coercivity, magnetic response …

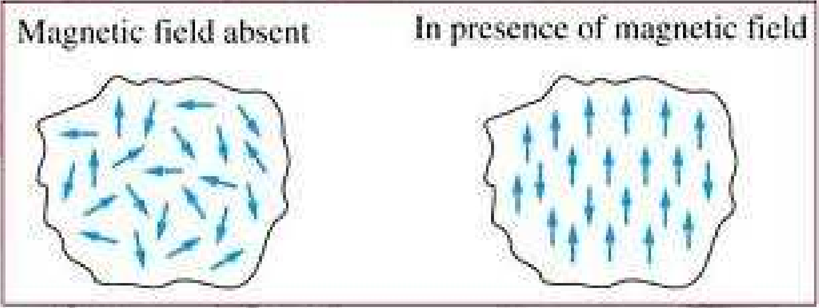
Paramagnetism:

Non-interacting moments in thermal equilibria



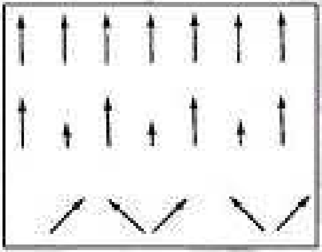
Magnetic moment

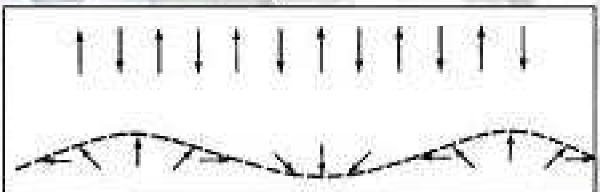
Unpaired electrons
(Hund's rules)
Paramagnetism
Curie law



Omitting paired-electron case – diamagnetism and SC

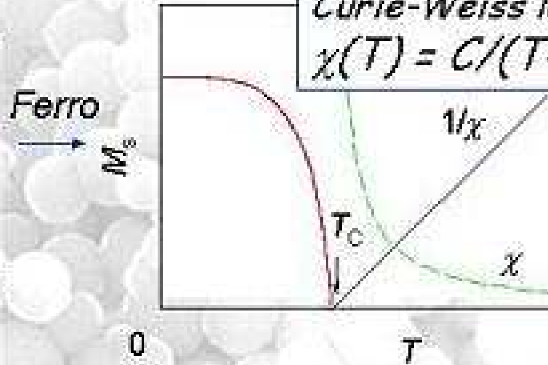
E_{ex} vs $k_B T$



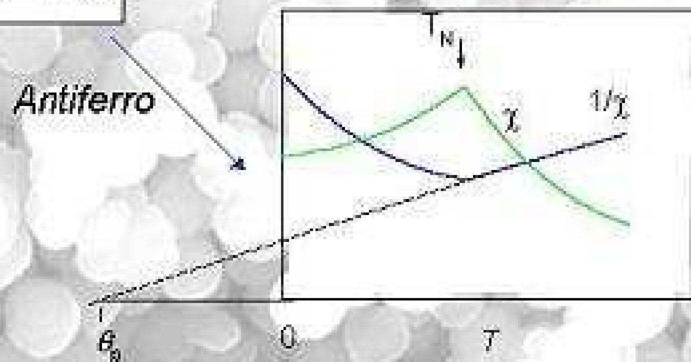


Curie-Weiss law

$\chi(T) = C/(T-\theta_p)$



!! $T > T_C/T_N$ - Para



Interaction

Exchange energy
Ordering temperature
Magnetic ordering –
– arrangement of
magnetic moments:
F, AF …

Bulk ferromagnet

↓

Nano-ferromagnet

↓

Consequences

Bulk ferromagnet

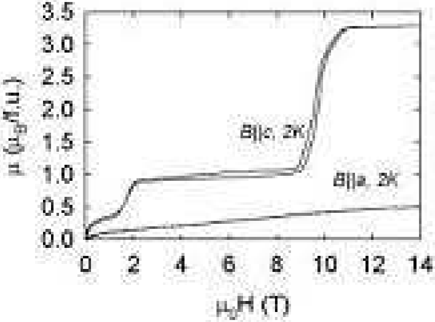
Magnetocrystalline anisotropy, magnetostatic energy&domains

***Nano*-ferromagnet**

Single domain particle, giant moment, classical behavior

Consequences

Change of magnetic properties
Superparamagnetism



Magnetocrystalline anisotropy (energy)

- spin direction with respect to crystal axes influence exchange energy
- easy/hard direction

Bulk ferromagnet

Magnetocrystalline anisotropy, magnetostatic energy&domains

Electron density anisotropy (electronic structure, crystal lattice)

↕

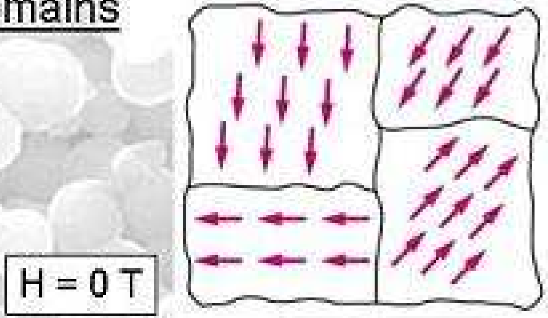
Orbital overlap

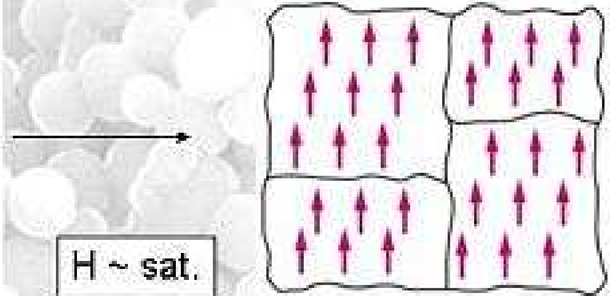
↕ ← *Spin-orbital interaction*

Magnetization - spin direction (unpaired electron/s)

Ferromagnetism

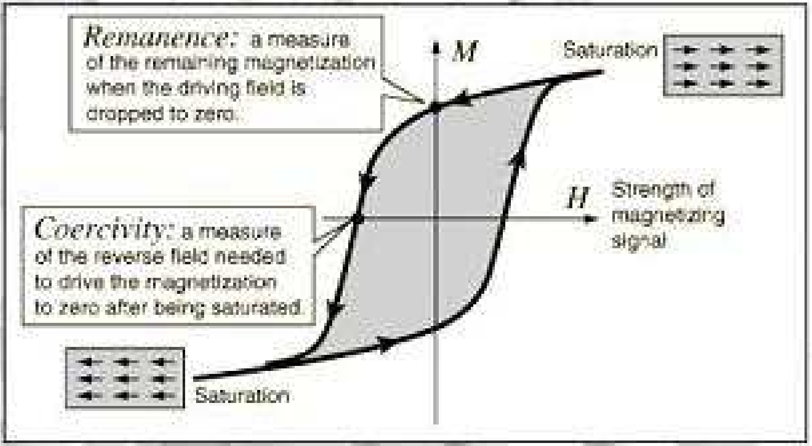
domains



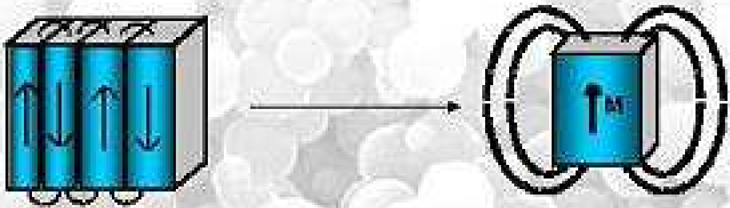


Bulk ferromagnet

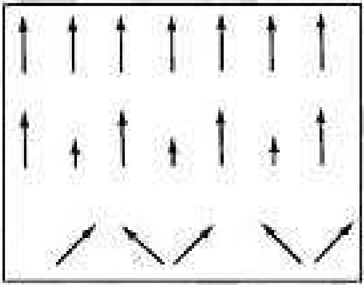
Magnetocrystalline anisotropy, magnetostatic energy&domains

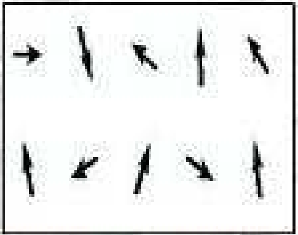


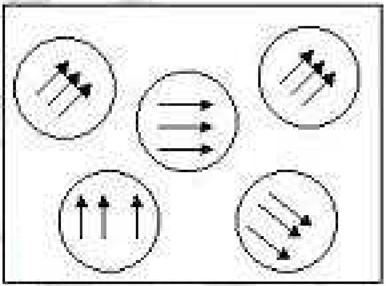
Magnetism - bulk vs. nano



Fe ~ 30 nm
Co ~ 70 nm
$SmCo_5$ ~1500nm







***Nano*-ferromagnet**

Single domain particle,
giant moment,
classical behavior

$$E = K_U V \sin^2\varphi - HM_S V \cos(\varphi - \vartheta)$$

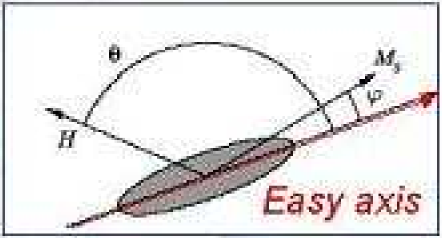
Superparamagnetism

Elmore (1938), colloidal Fe-oxide

Stoner-Wohlfarth

- no hysteresis
- no intrinsic anisotropy

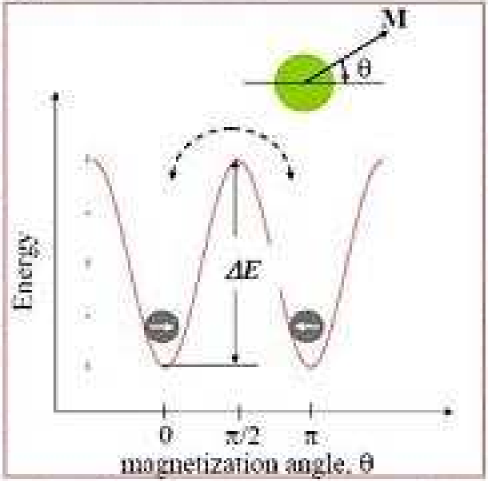
paramagnet with a huge moment



Definition – ensemble of giant moments without interaction and no effective anisotropy: Curie law, Langevin isotherm

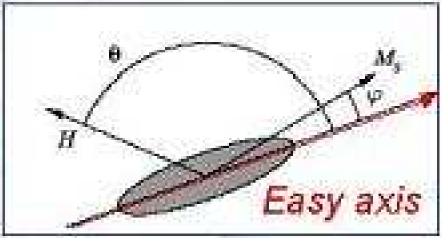
Blocked state	$T < T_B$	T_B	$T > T_B$	SPM state
$H_C \neq 0$, $K_U V > k_B T$ • rotation of M from the H direction back to the nearest easy axis		$K_U V \sim k_B T$		$H_C = 0$, $K_U V < k_B T$ • coherent rotation of M, $\langle M \rangle = 0$

Magnetism - bulk vs. nano



$$E = K_U V \sin^2\varphi - HM_S V \cos(\varphi - \vartheta)$$

$E_a \sim K_U V$



10 years of stability:

- *$K_U V / k_B T \sim 40$*
- *typically ~25*

Blocked state $T < T_B$

$H_C \neq 0$, $K_U V > k_B T$

- rotation of M from the H direction back to the nearest easy axis

T_B

$K_U V \sim k_B T$

SPM state $T > T_B$

$H_C = 0$, $K_U V < k_B T$

- coherent rotation of M, $\langle M \rangle = 0$

Is there the only *characteristic* T_B ?

Depends on the volume and magnetic anisotropy (τ = 72 s)

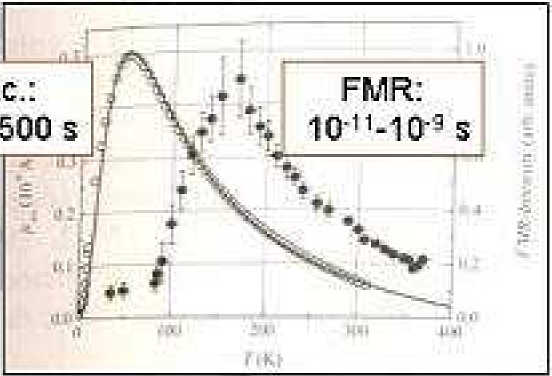
V (Ø nm)	K_{eff} (J/m³)	T_B (K)
10	10^6	1520
4	10^6	96
4	10^5	9

$$T_B = \frac{K < V >}{25 k_B}$$

Depends on the **time window** t_m of the measurement:

$t_m > \tau_r$
thermodynamic relaxation - SPM

$t_m < \tau_r$
non-equilibrium state – blocked state



V (Ø nm)	K_{eff} (J/m³)	T_B (K)	τ (sec)
10	10^6	1900	1 sec
4	10^6	120	1 sec
4	10^6	173	1 msec
4	10^6	1043	**10 nsec**

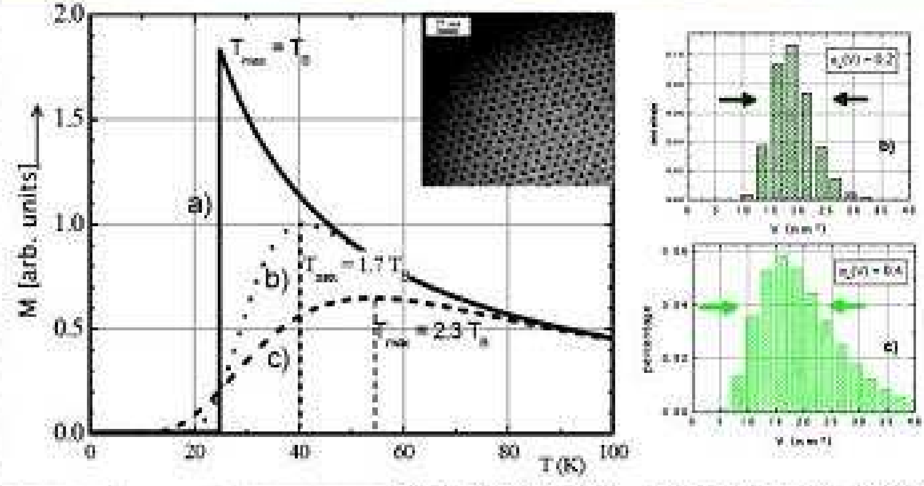
Relaxation

1. Brownian
2. **Nèel**

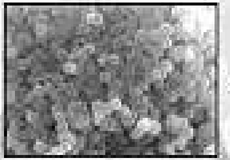
$\tau = \tau_0 \exp[E_a / k_B T]$

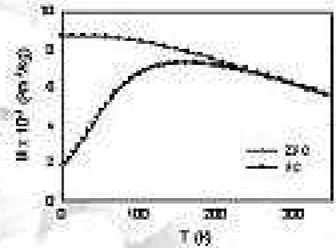
Real system:

- Interactions between particles (reduction of K_U, change of T_B …)
- Size distribution
- Shape anisotropy



C. Antoniak et al., Europhys. Lett. (2005)





How to deal with experimental results ?

Model system: $CoFe_2O_4/SiO_2$ nanocomposites
ensemble of monodisperse, noninteracting and monodomain particles embedded in magnetically inert matrix.

Series of samples: **S800 – S1100**, particle diameter increases with the annealing temperature from ~ 2 up to ~ 8 nm

Motivation:

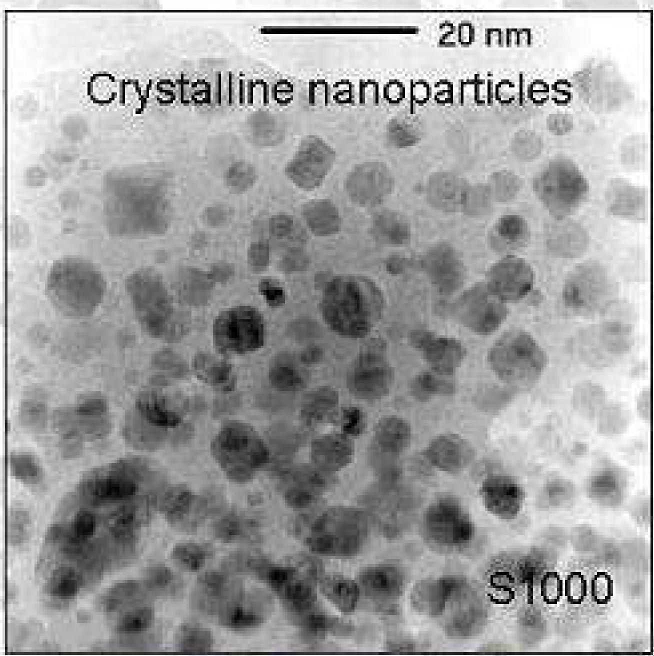
- Numerous studies of Fe, Ni or Co nanosystems [1, 2, 3]
- Ferrite particles – rich **chemistry** and **physics**
- Previous studies on Ni/Zn (Cu), Mn/Zn ferrites [4]

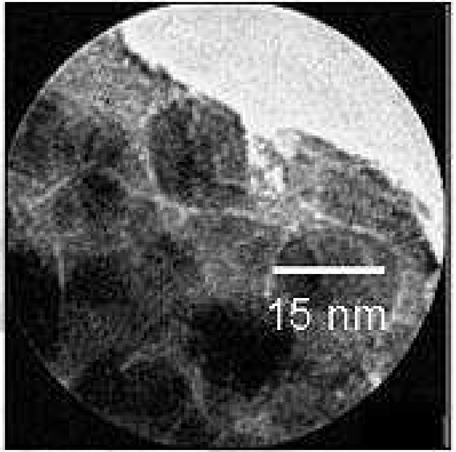
Co/Fe – ferrite:

- High values of H_C and M_S in bulk
- Convenient fabrication techniques [5]

[1] F.C. Fonseca et al., PRB 66, 104406 (2002).
[2] A. Fnidiki et al., JMMM 262, 368 (2003).
[3] D. Kumar, JMMM 232, 161 (2001)
[4] E. C. Snelling, *Soft Ferrites: Properties and Applications* ~Butterworths, London, (1988).
[5] A. Hutlova et al, Advanced Matt. 19, c5305 (2003).

$CoFe_2O_4/SiO_2$ nanocomposites





HR TEM:
Topcon; Scion Images software

Average particle size (radius):

S1100	7.5 nm
S1000	6.5 nm
S900	2.0 nm
S800	1.5 nm

Magnetization ZFC-FC

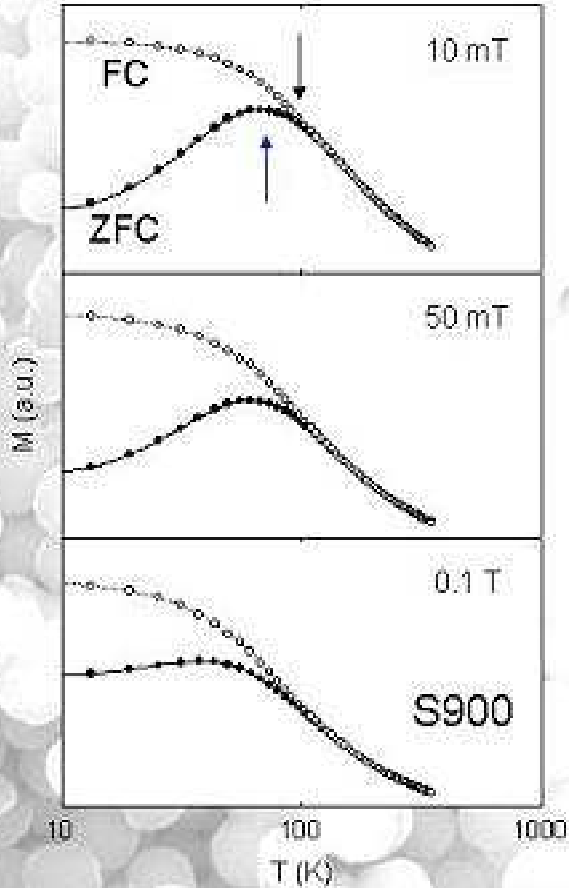
- maximum on ZFC curve ?
- particle size distribution, $T_{diff} > T_{max}$

Estimation of particle diameter from T_B:

$$T_B = \frac{K < V >}{25 k_B}$$

	T_{diff}	T_{max}	<r>*
S800	92	50	3.0
S900	116	60	3.3
S1000	305	180	4.5
S1100	350	-	5.0

ZFC – zero-field cooled
FC – field-cooled magnetization
PPMS – Quantum Design

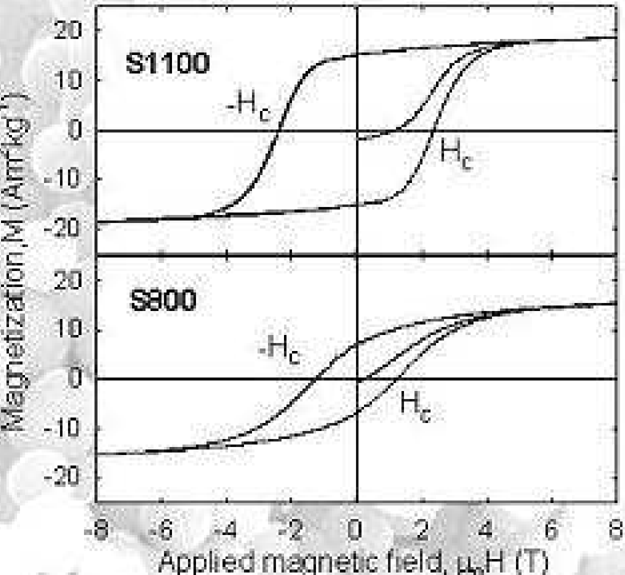


Magnetization below T_B

Coercivity, H_C

H_C enhancement due to:

- intrinsic anisotropy of particles (surface effects)
- inter-particle (dipolar) interactions
- shape anisotropy field



	M_S (Am^2kg^{-1})	H_C (T)
S800	15	1.5
S900	17	1.6
S1000	18	1.9
S1100	19	2.5

M_S increases with particle size

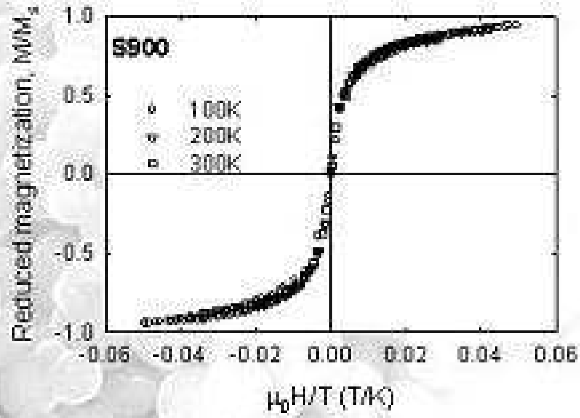
$CoFe_2O_4/SiO_2$ nanocomposites

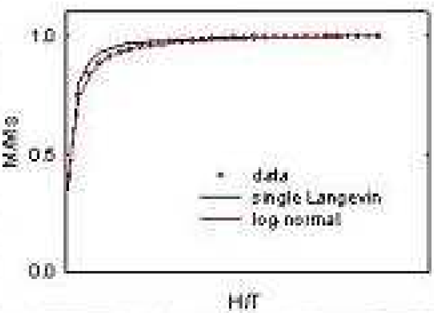
Magnetization above T_B

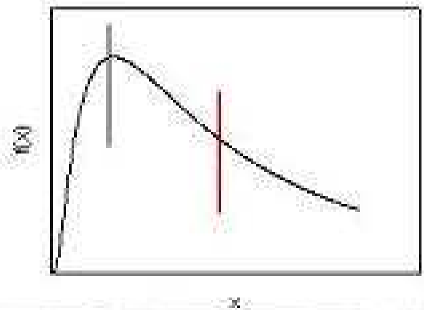
Generalized *Langevin scaling*

M/M_s vs. H/T

- no hysteresis above T_B
- generalized Langevin scaling
- description by a single Langevin function fails
- log-normal distribution of *magnetic moments or particle volumes*







	μ_m (μ_B)/r_m
S800	4700/3.0
S900	5700/3.7
S1000	8100/6.2
S1100	5700/6.8

A.c. susceptibility as a dynamic probe

$t_m > \tau_r$
thermodynamic relaxation - SPM

$t_m < \tau_r$
non-equilibrium state – blocked state

probing field: $H \sim H_A.\hat{H}(\omega t)$

$\tau = \tau_0 \exp[E_a / k_B T]$

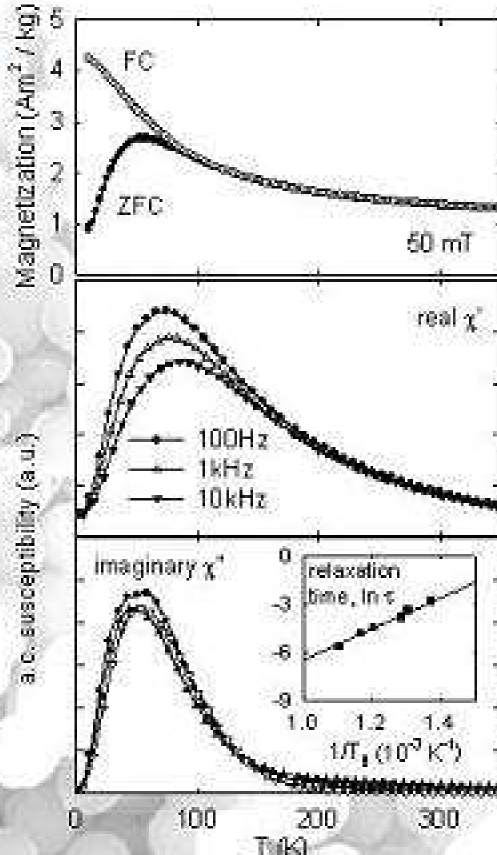
	$\tau_0 \times 10^8$ (s)	E_a (K)	$K \times 10^{-6}$ ($J.\,m^3$)
S900	1.8	1227	4
S800	1.3	920	3

$$\Phi = \frac{\Delta T_f}{T_f \Delta \log_{10}(f)}$$

$\Phi \sim 0.09$

*G.F. Goya et al, JAP 94, 3520 (2003)

H_A = *10 Oe, f = 10 – 10^4 Hz*
PPMS – Quantum Design



Conclusions

- ✓ *Nanoscale opens new areas of interest*
- ✓ *Magnetism is driven by system dimensions*
- ✓ *There are relevant models to describe behavior of nanoparticle systems …*
- ✓ *but real effects must be taken into account*
- ✓ *Observed phenomena depends on probing technique*
- ✓ *Magnetic behavior of the $CoFe_2O_4$ nanocomposites can be well described by the single-domain particle theory; at least distribution of particle sizes must be involved!*

Joint Laboratory for Magnetic Studies

Experiments available in magnetic fields up to 14 T:

- ✓ Heat capacity (0.4 – 400 K)
- ✓ Thermal conductivity (2 – 400 K)
- ✓ Thermopower (2 – 400 K)
- ✓ Magnetization (2 – 1000 K)
- ✓ Dilatometry (capacitance cell) (2 – 350 K)

and pressures up to 2.0 GPa…

- ✓ Magnetization (2 – 350 K)
- ✓ a.c. susceptibility (2 – 350 K, 1 – 10 kHz)
- ✓ Electrical and Hall resistivity (0.4 – 400 K)
- ✓ Dilatometry (strain gauge) (2 – 350 K)

http://kfes-80.karlov.mff.cuni.cz/jlms/CZ/Default_cz.htm

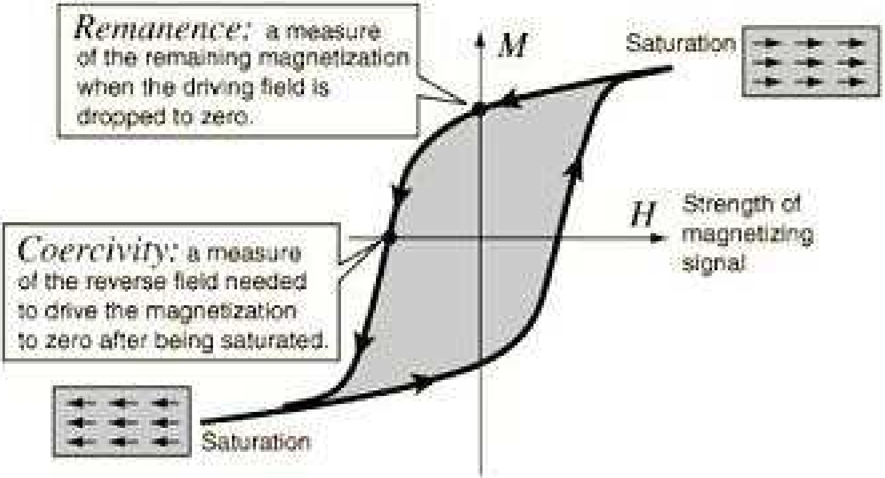
http://kfes-80.karlov.mff.cuni.cz/kfes/lide/jana.php

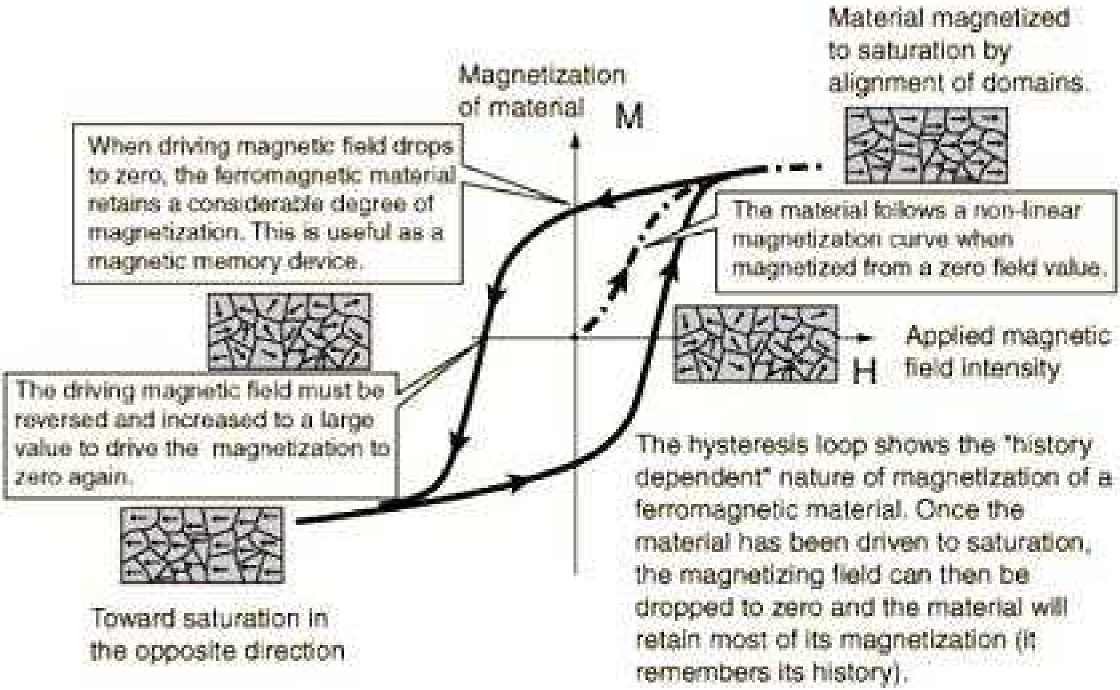
http://kfes-80.karlov.mff.cuni.cz/kfes/index.html

Many thanks to:

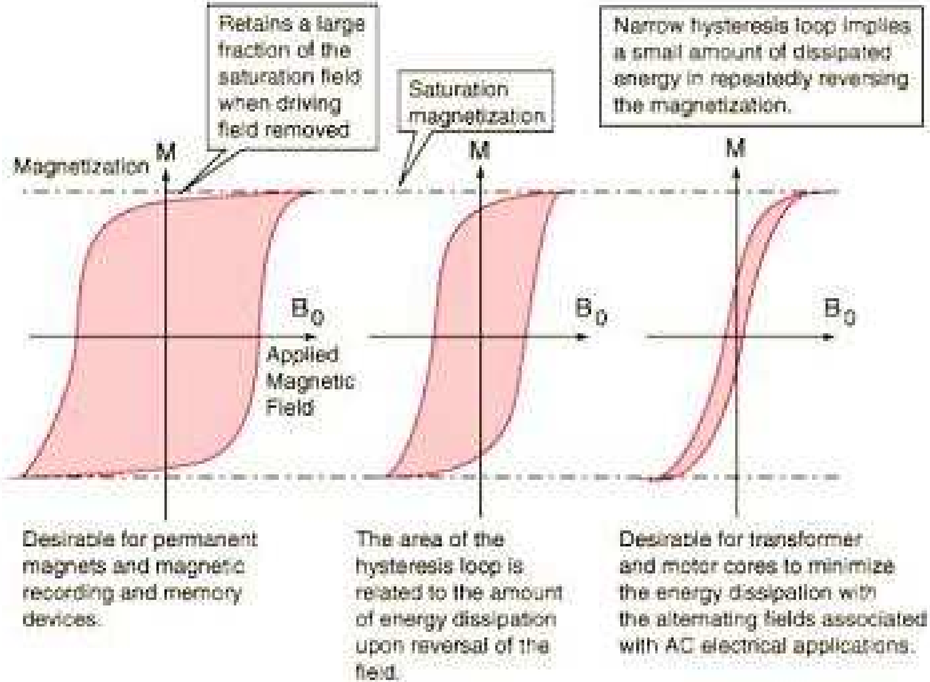
J. Plocek, D. Nižňanský
Charles University in Prague, Faculty of Natural Sciences,
Department of Inorganic Chemistry
A. Hutlová
Czech Academy of Sciences, *Institute of Inorganic Chemistry*
J.-L. Rehspringer
I.P.C.M.S., *Groupe des Matériaux Inorganiques*
V. Sechovský
Charles University in Prague, Faculty of Mathematics And Physics,
Department of Electronic Structures

Thank you for your attention !


Remanence: a measure of the remaining magnetization when the driving field is dropped to zero.
M
Saturation
H
Strength of magnetizing signal
Coercivity: a measure of the reverse field needed to drive the magnetization to zero after being saturated.
Saturation



Material magnetized to saturation by alignment of domains.
Magnetization of material
M
When driving magnetic field drops to zero, the ferromagnetic material retains a considerable degree of magnetization. This is useful as a magnetic memory device.
The material follows a non-linear magnetization curve when magnetized from a zero field value.
Applied magnetic field intensity
H
The driving magnetic field must be reversed and increased to a large value to drive the magnetization to zero again.
The hysteresis loop shows the "history dependent" nature of magnetization of a ferromagnetic material. Once the material has been driven to saturation, the magnetizing field can then be dropped to zero and the material will retain most of its magnetization (it remembers its history).
Toward saturation in the opposite direction


Retains a large fraction of the saturation field when driving field removed
Saturation magnetization
Narrow hysteresis loop implies a small amount of dissipated energy in repeatedly reversing the magnetization.
Magnetization
M
M
M
B_0
B_0
B_0
Applied Magnetic Field
Desirable for permanent magnets and magnetic recording and memory devices.
The area of the hysteresis loop is related to the amount of energy dissipation upon reversal of the field.
Desirable for transformer and motor cores to minimize the energy dissipation with the alternating fields associated with AC electrical applications.

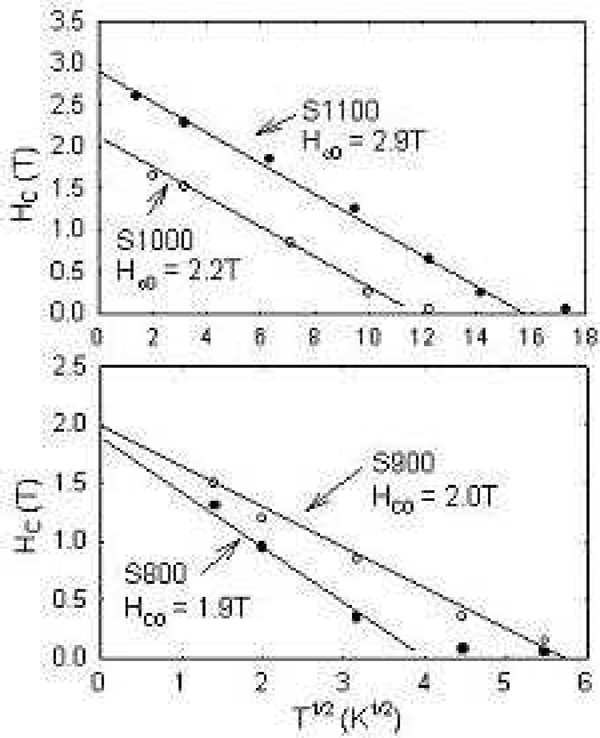
Magnetization $T < T_B$

$$H_C(T) = H_{C0}\left[1 - \left(\frac{T}{T_B}\right)^{1/2}\right]$$

	T_B (K)	H_{C0} (T)
S800	80	1.9
S900	105	2.0
S1000	270	2.2
S1100	295	2.9

Effect of particle size distribution close to the blocking region

DC magnetization
PPMS – Quantum Design



Summary

Sample	T_B(K) AC	T_B(K) T_{diff}	T_B(K) T_{max}	T_B(K) eq. (1)	$\mu_m(\mu_B)$ L	R (nm) L	R (nm) TEM/FWHM	H_{C0} eq. (1)
S800	87	92	50	80	4700	1.5	1.5/2.0	1.9
S900	107	116	60	105	5700	2	2.0/3.0	1.8
S1000	290	305	180	275	8100	5.5	5.5/4.0	2.2
S1100	x	350	300	295	x	7.5	x/8.0	2.9

Magnetic properties of nanoparticles

J. Poltierová Vejpravová

Charles University Prague,
Faculty of Mathematics And Physics,
Department of Electronic Structures

&

Joint Laboratory for Magnetic Studies

Outline

Why nanoscale/nanoparticles ?

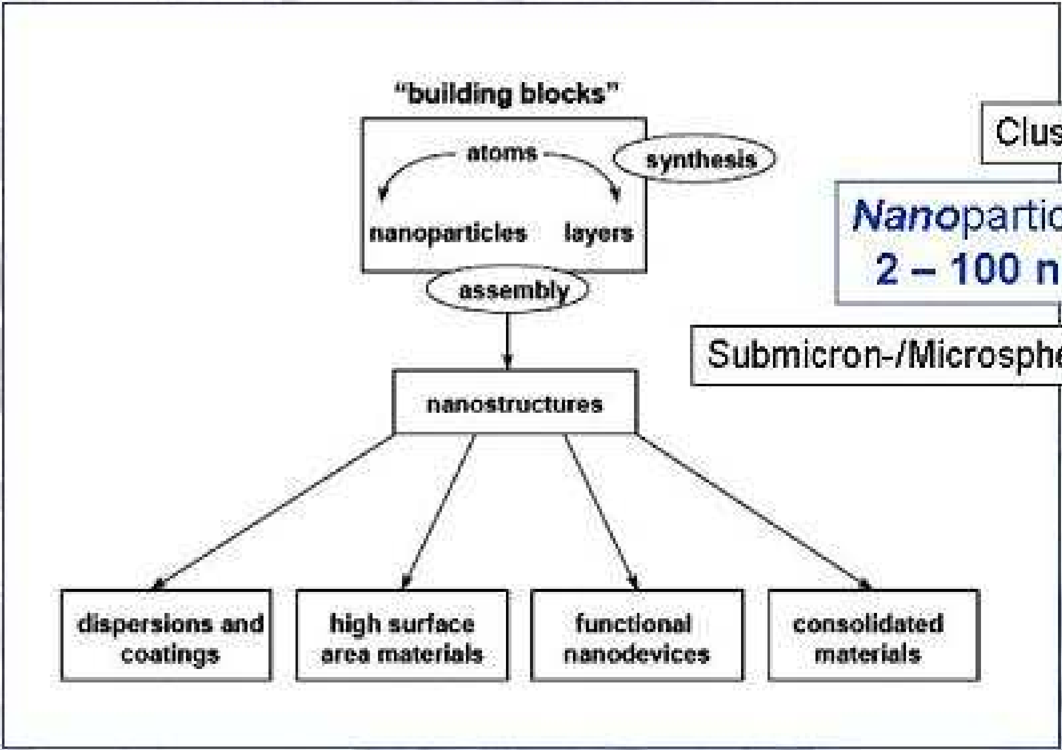
Magnetism - bulk vs. nano

Magnetic nanoparticles – facet of reality

$CoFe_2O_4/SiO_2$ nanocomposites

Conclusions

Bottom to top …



Clusters

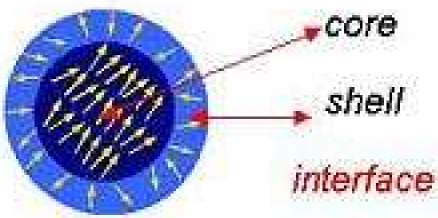
*Nano*particles
2 – 100 nm

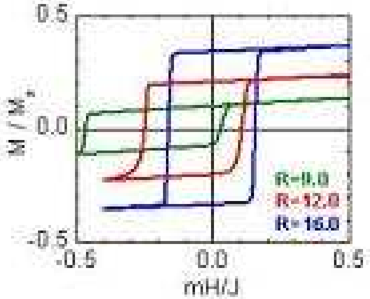
Submicron-/Microspheres

Areas of interest

Basic research

Surface-to-volume ratio (STVR) increases:
3 nm – 1400 atoms: 40% atoms at the surface!





- Surface and interface magnetism
- Control over magnetic anisotropy
- Stability and environmental compatibility

Areas of interest

Applications

Tayloring new functional materials/ functionalized surfaces

Electronics
Ultra-high density media (Tbit/inch), MRAM

Medicine, Bio –
Site-specific drug delivery, Hyperthermia - treatment for malignant cells

Other…
Hard magnets (separation), nanosensors, MCE

Dimension reduction/frustration – influence on electronic structure

Physical properties of the bulk material differ from the *nano*scaled one

Magnetism – *consequence of spin and charge motion*

Magnetic moment
↕
Interaction
↓
Properties

Magnetic moment

Unpaired electrons
(Hund's rules)
Paramagnetism
Curie/Curie-Weiss law

Interaction

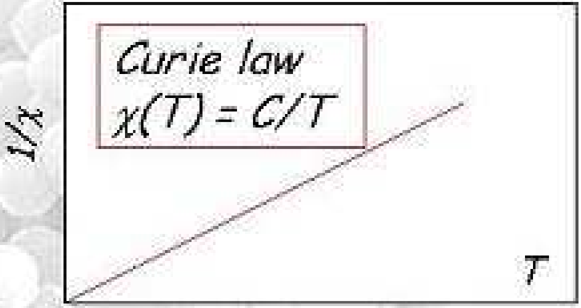
Exchange energy
Ordering temperature
Magnetic ordering – arrangement of magnetic moments:
F, AF …

Properties

Spontaneous magnetization,
coercivity,
magnetic response …

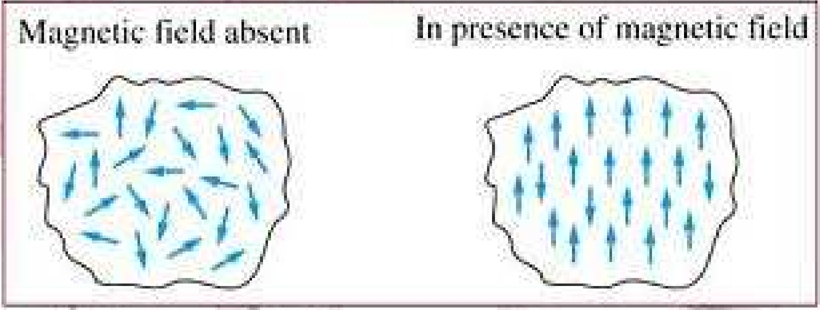
Paramagnetism:

Non-interacting moments in thermal equilibria



Magnetic moment

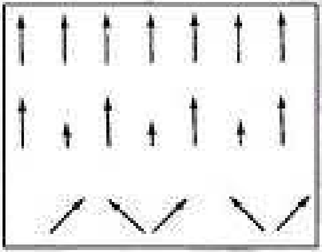
Unpaired electrons
(Hund's rules)
Paramagnetism
Curie law

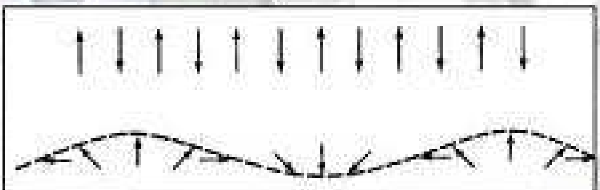


Omitting paired-electron case – diamagnetism and SC

Magnetism - bulk vs. nano

E_{ex} vs k_BT

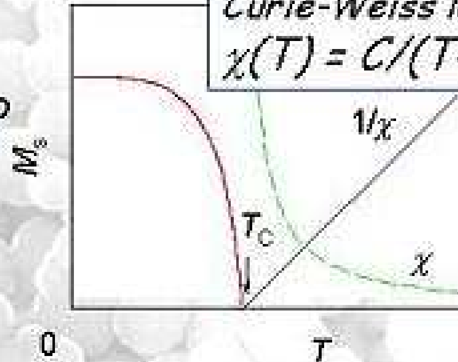




Ferro

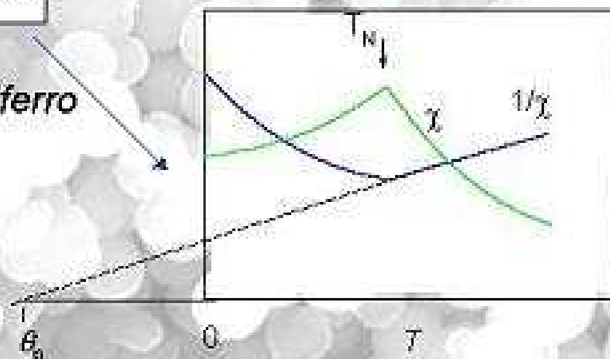
Curie-Weiss law

$\chi(T) = C/(T-\theta_p)$



!! $T > T_C/T_N$ - Para

Antiferro



Interaction

Exchange energy
Ordering temperature
Magnetic ordering –
– arrangement of
magnetic moments:
F, AF …

Bulk ferromagnet
↓
Nano-ferromagnet
↓
Consequences

Bulk ferromagnet

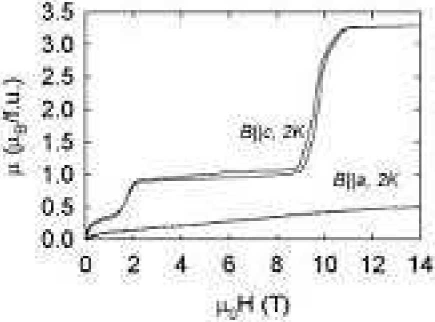
Magnetocrystalline anisotropy, magnetostatic energy&domains

***Nano*-ferromagnet**

Single domain particle, giant moment, classical behavior

Consequences

Change of magnetic properties
Superparamagnetism



Magnetocrystalline anisotropy (energy)

- spin direction with respect to crystal axes influence exchange energy
- easy/hard direction

Electron density anisotropy
(electronic structure, crystal lattice)

↕

Orbital overlap

↕ ← *Spin-orbital interaction*

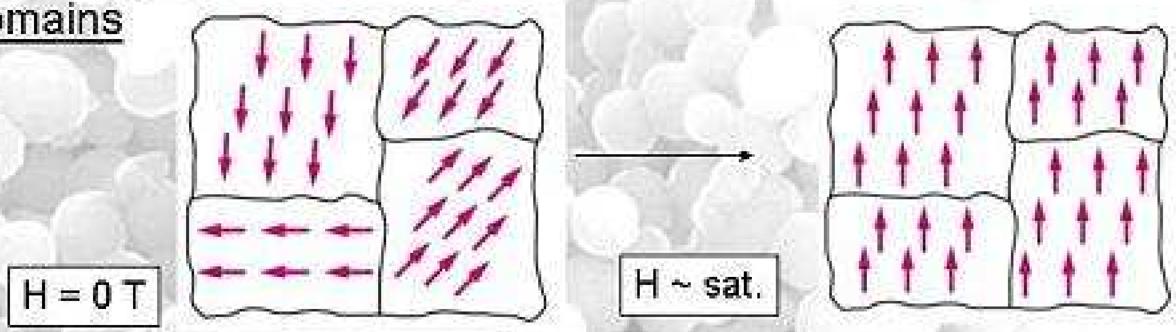
Magnetization - spin direction
(unpaired electron/s)

Bulk ferromagnet

Magnetocrystalline anisotropy, magnetostatic energy&domains

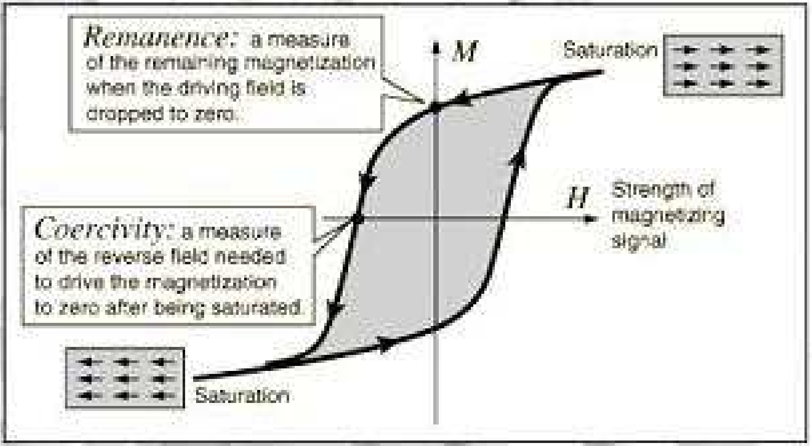
Ferromagnetism

domains

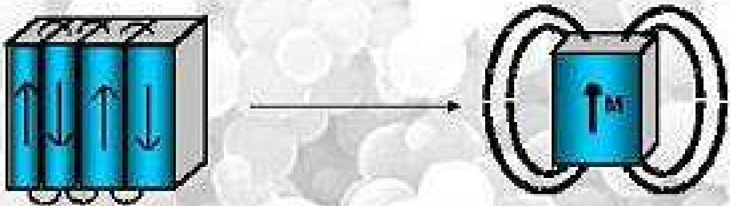


Bulk ferromagnet

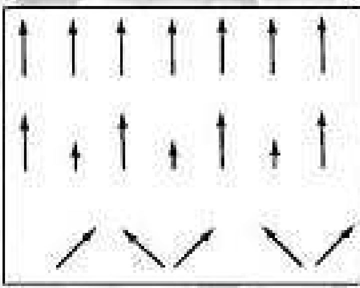
Magnetocrystalline anisotropy, magnetostatic energy&domains

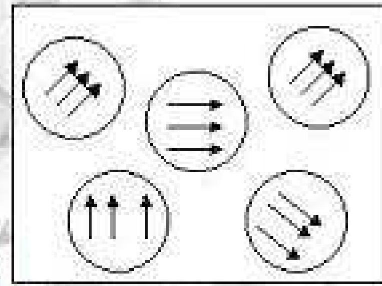


Magnetism - bulk vs. nano



Fe ~ 30 nm
Co ~ 70 nm
$SmCo_5$ ~1500nm





***Nano*-ferromagnet**

Single domain particle,
giant moment,
classical behavior

$$E = K_U V \sin^2 \varphi - H M_S V \cos(\varphi - \vartheta)$$

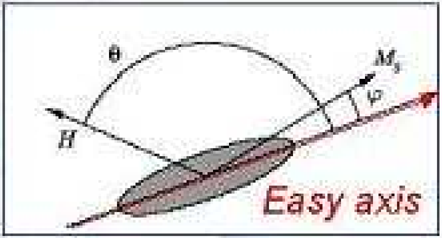
Superparamagnetism

Elmore (1938), colloidal Fe-oxide

Stoner-Wohlfarth

- no hysteresis
- no intrinsic anisotropy

paramagnet with a huge moment



Definition – ensemble of giant moments without interaction and no effective anisotropy: Curie law, Langevin isotherm

Blocked state $T < T_B$

$H_C \neq 0$, $K_U V > k_B T$

- rotation of M from the H direction back to the nearest easy axis

T_B

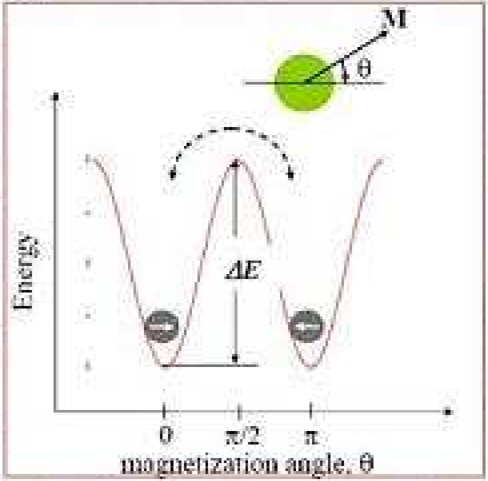
$K_U V \sim k_B T$

SPM state $T > T_B$

$H_C = 0$, $K_U V < k_B T$

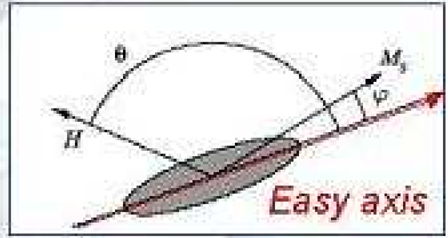
- coherent rotation of M, $\langle M \rangle = 0$

Magnetism - bulk vs. nano



$$E = K_U V \sin^2\varphi - HM_s V\cos(\varphi - \vartheta)$$

$E_a \sim K_U V$



10 years of stability:

- $K_U V/k_B T \sim 40$

- typically ~25

Blocked state $T < T_B$

$H_C \neq 0$, $K_U V > k_B T$

- rotation of M from the H direction back to the nearest easy axis

T_B

$K_U V \sim k_B T$

SPM state $T > T_B$

$H_C = 0$, $K_U V < k_B T$

- coherent rotation of M, $\langle M \rangle = 0$

Is there the only *characteristic* T_B ?

Depends on the volume and magnetic anisotropy (τ = 72 s)

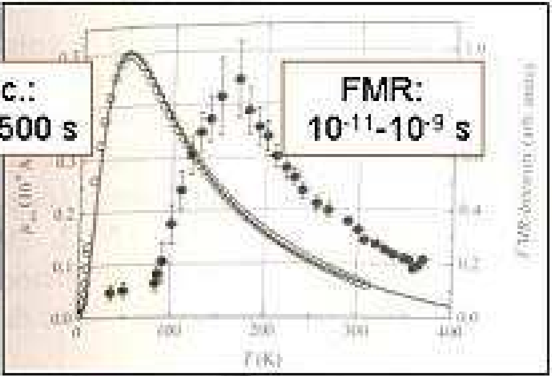
V (Ø nm)	K_{eff} (J/m³)	T_B (K)
10	10^6	1520
4	10^6	96
4	10^5	9

$$T_B = \frac{K < V >}{25 k_B}$$

Depends on the **time window** t_m of the measurement:

$t_m > \tau_r$
thermodynamic relaxation - SPM

$t_m < \tau_r$
non-equilibrium state – blocked state



V (Ø nm)	K_{eff} (J/m³)	T_B (K)	τ (sec)
10	10^6	1900	1 sec
4	10^6	120	1 sec
4	10^6	173	1 msec
4	10^6	1043	**10 nsec**

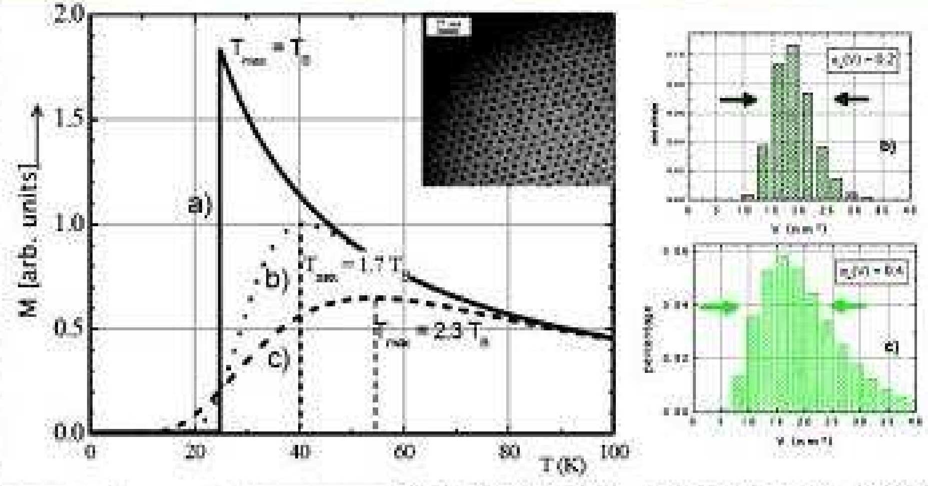
Relaxation

1. Brownian
2. **Nèel**

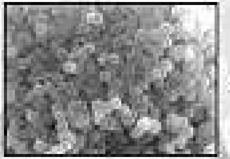
$\tau = \tau_0 \exp[E_a / k_B T]$

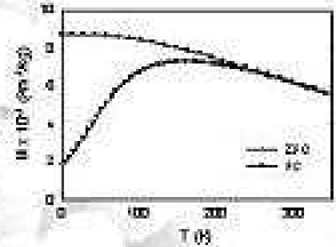
Real system:

- Interactions between particles (reduction of K_U, change of T_B …)
- Size distribution
- Shape anisotropy



C. Antoniak et al., Europhys. Lett. (2005)





How to deal with experimental results ?

Model system: $CoFe_2O_4/SiO_2$ nanocomposites
ensemble of monodisperse, noninteracting and monodomain particles embedded in magnetically inert matrix.

Series of samples: **S800 – S1100**, particle diameter increases with the annealing temperature from ~ 2 up to ~ 8 nm

$CoFe_2O_4/SiO_2$ nanocomposites

Motivation:

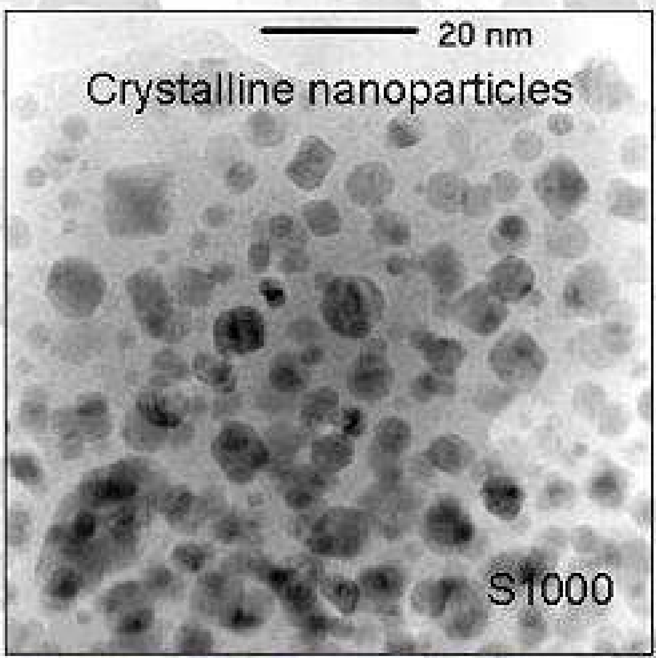
- Numerous studies of Fe, Ni or Co nanosystems [1, 2, 3]
- Ferrite particles – rich **chemistry** and **physics**
- Previous studies on Ni/Zn (Cu), Mn/Zn ferrites [4]

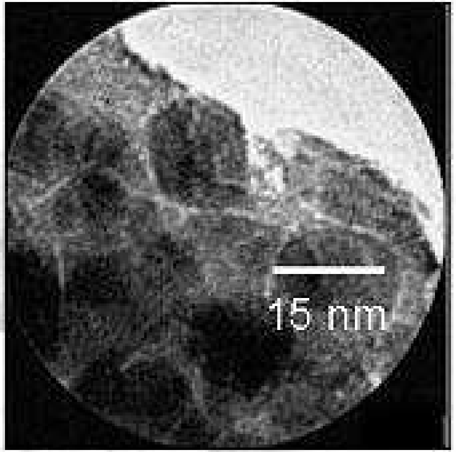
Co/Fe – ferrite:

- High values of H_C and M_S in bulk
- Convenient fabrication techniques [5]

[1] F.C. Fonseca et al., PRB 66, 104406 (2002).
[2] A. Fnidiki et al., JMMM 262, 368 (2003).
[3] D. Kumar, JMMM 232, 161 (2001)
[4] E. C. Snelling, *Soft Ferrites: Properties and Applications* ~Butterworths, London, (1988).
[5] A. Hutlova et al, Advanced Matt. 19, c5305 (2003).

$CoFe_2O_4/SiO_2$ nanocomposites





HR TEM:
Topcon; Scion Images software

Average particle size (radius):

S1100	7.5 nm
S1000	6.5 nm
S900	2.0 nm
S800	1.5 nm

Magnetization ZFC-FC

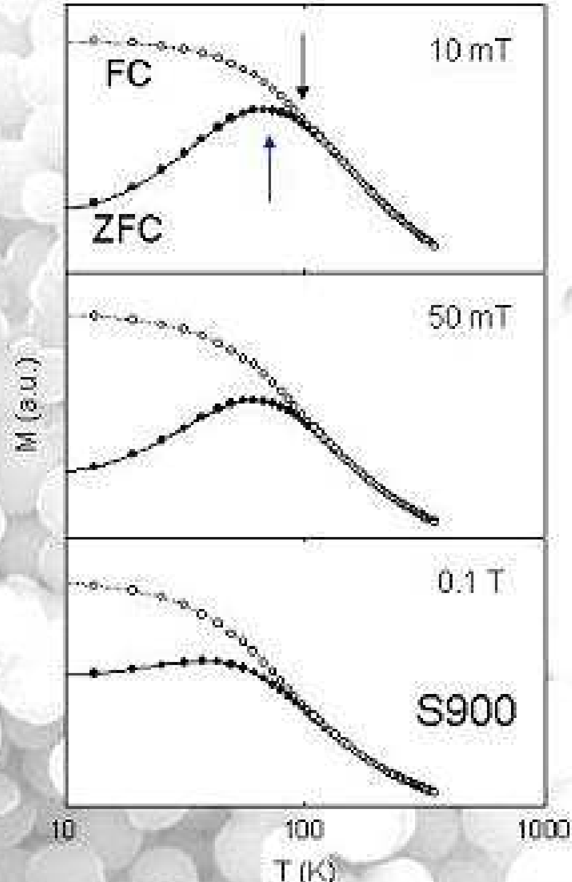
- maximum on ZFC curve ?
- particle size distribution, $T_{diff} > T_{max}$

Estimation of particle diameter from T_B:

$$T_B = \frac{K < V >}{25 k_B}$$

	T_{diff}	T_{max}	<r>*
S800	92	50	3.0
S900	116	60	3.3
S1000	305	180	4.5
S1100	350	-	5.0

ZFC – zero-field cooled
FC – field-cooled magnetization
PPMS – Quantum Design



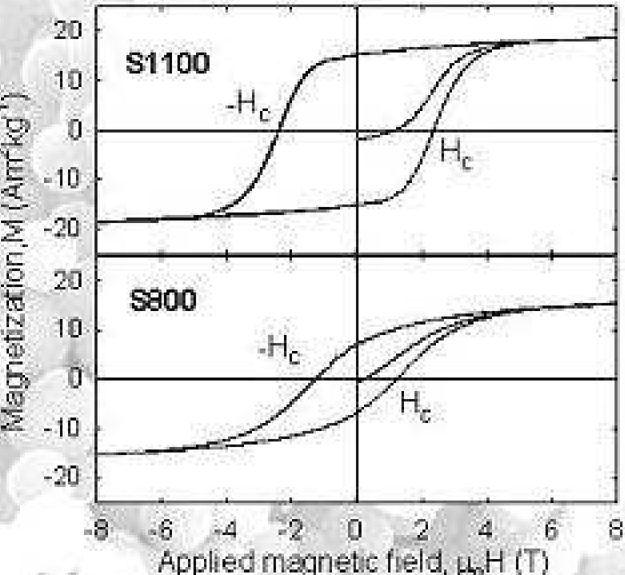
$CoFe_2O_4/SiO_2$ nanocomposites

Magnetization below T_B

Coercivity, H_C

H_C enhancement due to:

- intrinsic anisotropy of particles (surface effects)
- inter-particle (dipolar) interactions
- shape anisotropy field



	M_S (Am^2kg^{-1})	H_C (T)
S800	15	1.5
S900	17	1.6
S1000	18	1.9
S1100	19	2.5

M_S increases with particle size

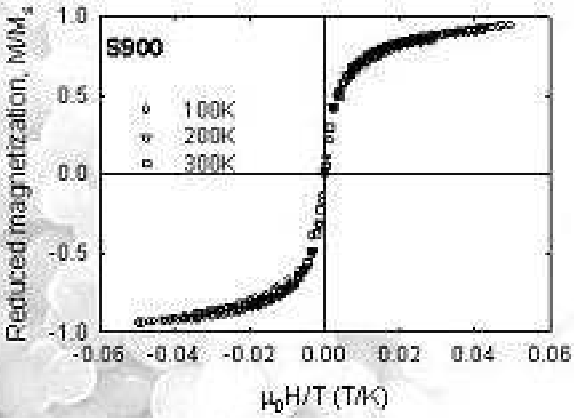
$CoFe_2O_4/SiO_2$ nanocomposites

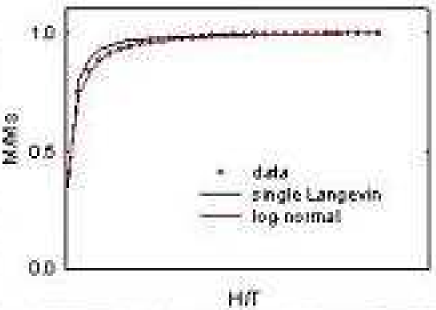
Magnetization above T_B

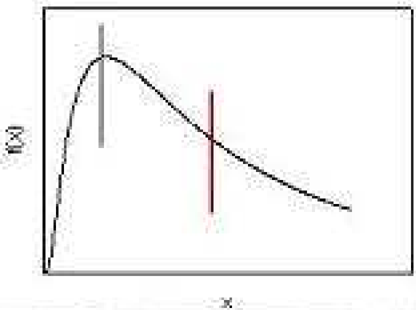
Generalized *Langevin scaling*

M/M_s vs. H/T

- no hysteresis above T_B
- generalized Langevin scaling
- description by a single Langevin function fails
- log-normal distribution of *magnetic moments or particle volumes*







	μ_m (μ_B)/r_m
S800	4700/3.0
S900	5700/3.7
S1000	8100/6.2
S1100	8700/6.3

$CoFe_2O_4/SiO_2$ nanocomposites

A.c. susceptibility as a dynamic probe

$t_m > \tau_r$
thermodynamic relaxation - SPM

$t_m < \tau_r$
non-equilibrium state – blocked state

probing field: $H \sim H_A.\hat{H}(\omega t)$

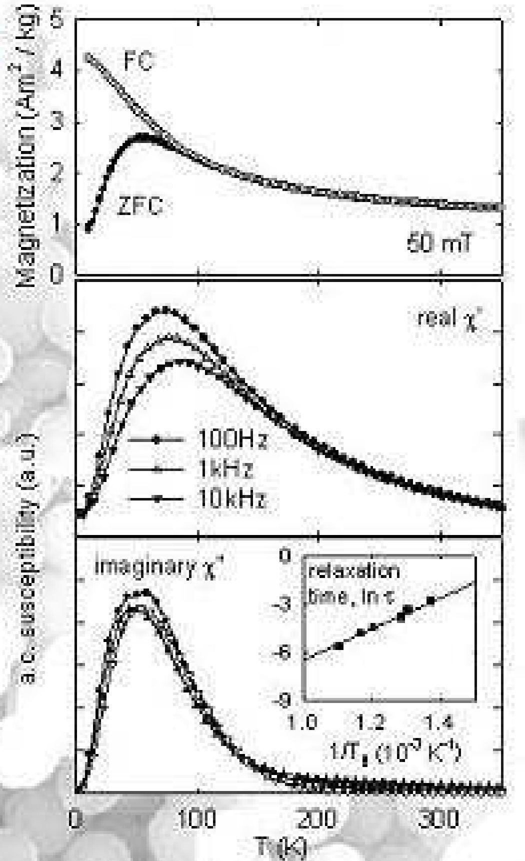
$\tau = \tau_0 \exp[E_a / k_B T]$

	$\tau_0 \times 10^8$ (s)	E_a (K)	$K \times 10^{-6}$ (J. m^3)
S900	1.8	1227	4
S800	1.3	920	3

$$\Phi = \frac{\Delta T_f}{T_f \Delta \log_{10}(f)}$$ $\Phi \sim 0.09$

*G.F. Goya et al, JAP 94, 3520 (2003)

H_A = *10 Oe, f = 10 – 10^4 Hz*
PPMS – Quantum Design



Conclusions

- ✓ *Nanoscale opens new areas of interest*
- ✓ *Magnetism is driven by system dimensions*
- ✓ *There are relevant models to describe behavior of nanoparticle systems …*
- ✓ *but real effects must be taken into account*
- ✓ *Observed phenomena depends on probing technique*
- ✓ *Magnetic behavior of the $CoFe_2O_4$ nanocomposites can be well described by the single-domain particle theory; at least distribution of particle sizes must be involved!*

Joint Laboratory for Magnetic Studies

Experiments available in magnetic fields up to 14 T:

- ✓ Heat capacity (0.4 – 400 K)
- ✓ Thermal conductivity (2 – 400 K)
- ✓ Thermopower (2 – 400 K)
- ✓ Magnetization (2 – 1000 K)
- ✓ Dilatometry (capacitance cell) (2 – 350 K)

and pressures up to 2.0 GPa…

- ✓ Magnetization (2 – 350 K)
- ✓ a.c. susceptibility (2 – 350 K, 1 – 10 kHz)
- ✓ Electrical and Hall resistivity (0.4 – 400 K)
- ✓ Dilatometry (strain gauge) (2 – 350 K)

http://kfes-80.karlov.mff.cuni.cz/jlms/CZ/Default_cz.htm

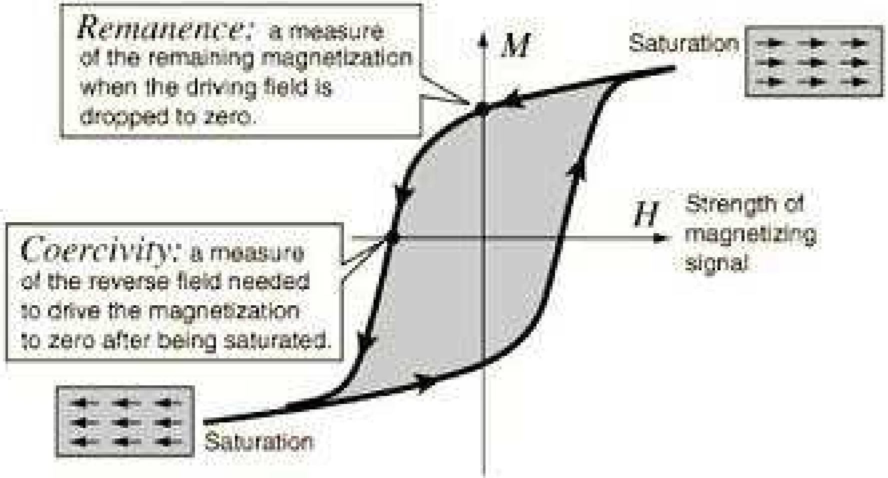
http://kfes-80.karlov.mff.cuni.cz/kfes/lide/jana.php

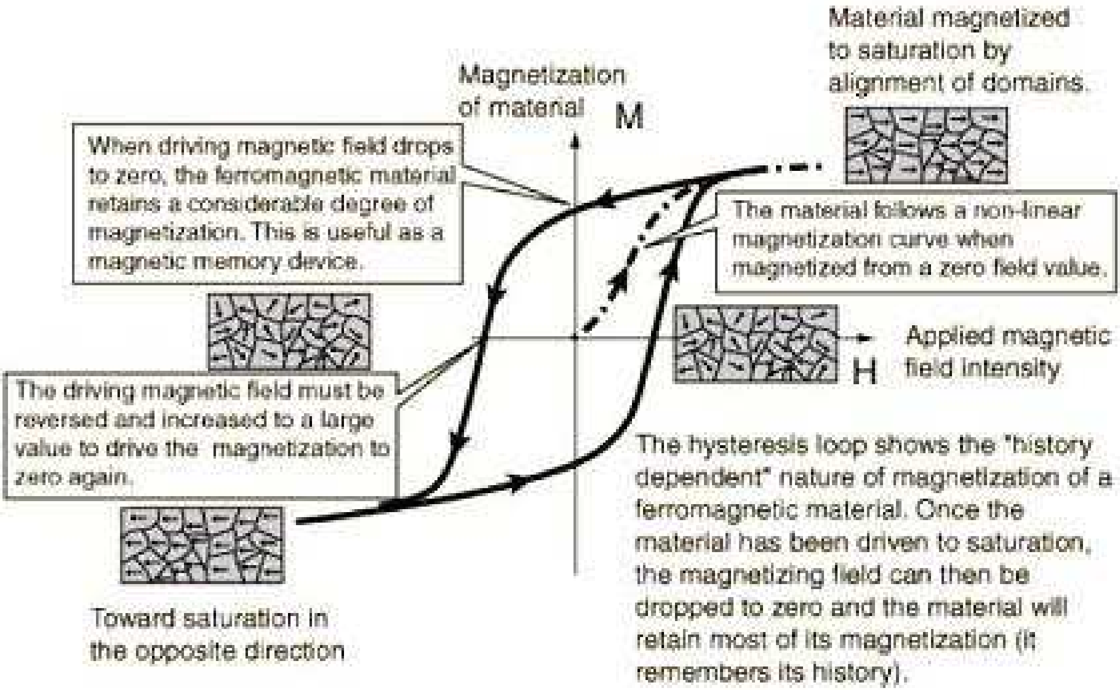
http://kfes-80.karlov.mff.cuni.cz/kfes/index.html

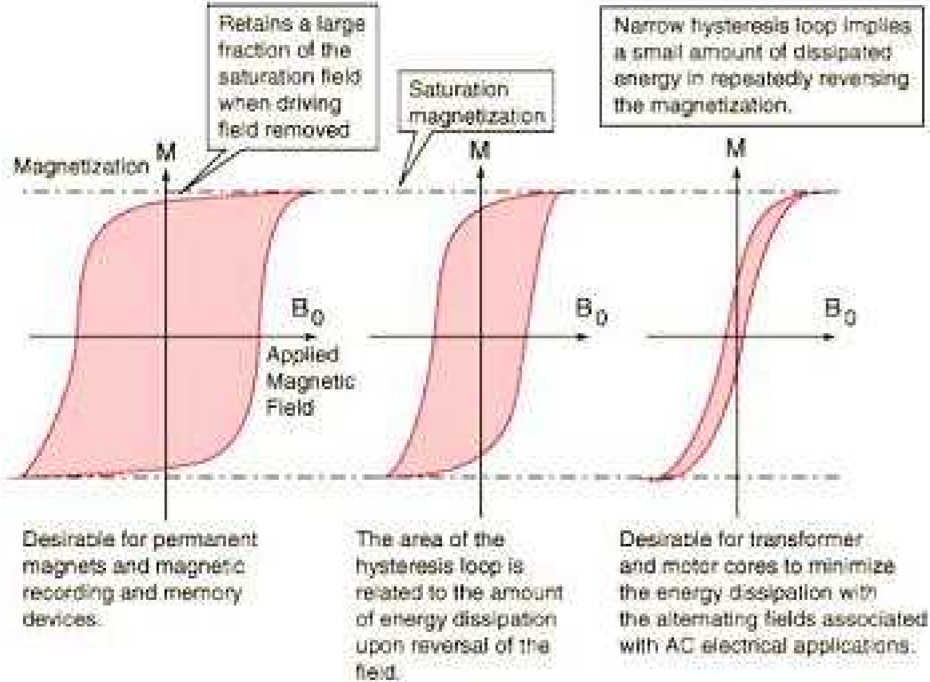
Many thanks to:

J. Plocek, D. Nižňanský
Charles University in Prague, Faculty of Natural Sciences,
Department of Inorganic Chemistry
A. Hutlová
Czech Academy of Sciences, *Institute of Inorganic Chemistry*
J.-L. Rehspringer
I.P.C.M.S., *Groupe des Matériaux Inorganiques*
V. Sechovský
Charles University in Prague, Faculty of Mathematics And Physics,
Department of Electronic Structures

Thank you for your attention !


Remanence: a measure of the remaining magnetization when the driving field is dropped to zero.
M
Saturation
H
Strength of magnetizing signal
Coercivity: a measure of the reverse field needed to drive the magnetization to zero after being saturated.
Saturation


Material magnetized
to saturation by
alignment of domains.
Magnetization
of material
M
When driving magnetic field drops to zero, the ferromagnetic material retains a considerable degree of magnetization. This is useful as a magnetic memory device.
The material follows a non-linear magnetization curve when magnetized from a zero field value.
Applied magnetic
field intensity
H
The driving magnetic field must be reversed and increased to a large value to drive the magnetization to zero again.
The hysteresis loop shows the "history dependent" nature of magnetization of a ferromagnetic material. Once the material has been driven to saturation, the magnetizing field can then be dropped to zero and the material will retain most of its magnetization (it remembers its history).
Toward saturation in
the opposite direction



Retains a large fraction of the saturation field when driving field removed
Saturation magnetization
Narrow hysteresis loop implies a small amount of dissipated energy in repeatedly reversing the magnetization.
Magnetization
M
M
M
B0
Applied Magnetic Field
B0
B0
Desirable for permanent magnets and magnetic recording and memory devices.
The area of the hysteresis loop is related to the amount of energy dissipation upon reversal of the field.
Desirable for transformer and motor cores to minimize the energy dissipation with the alternating fields associated with AC electrical applications.

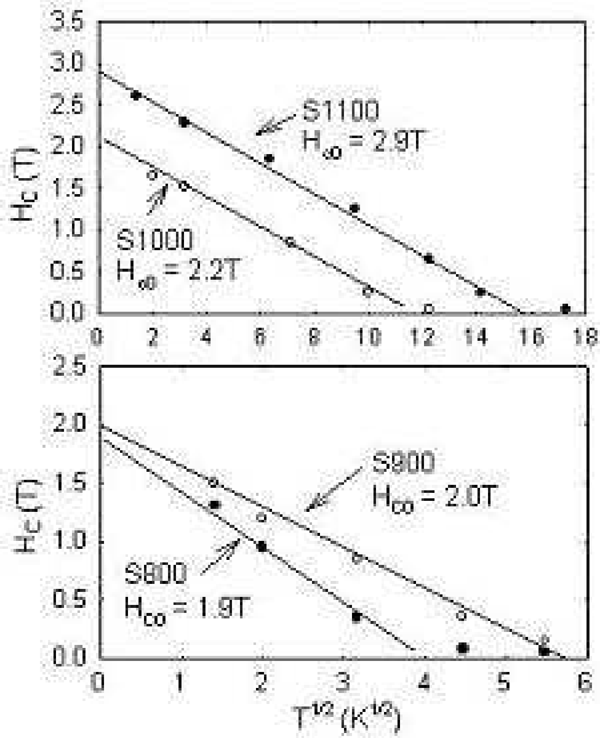
Magnetization $T < T_B$

$$H_C(T) = H_{C0}\left[1-\left(\frac{T}{T_B}\right)^{1/2}\right]$$

	T_B (K)	H_{C0} (T)
S800	80	1.9
S900	105	2.0
S1000	270	2.2
S1100	295	2.9

Effect of particle size distribution close to the blocking region

DC magnetization
PPMS – Quantum Design



Summary

Sample	T_B(K) AC	T_B(K) T_{diff}	T_B(K) T_{max}	T_B(K) eq. (1)	$\mu_m(\mu_B)$ L	R (nm) L	R (nm) TEM/FWHM	H_{C0} eq. (1)
S800	87	92	50	80	4700	1.5	1.5/2.0	1.9
S900	107	116	60	105	5700	2	2.0/3.0	1.8
S1000	290	305	180	275	8100	5.5	5.5/4.0	2.2
S1100	x	350	300	295	x	7.5	x/8.0	2.9