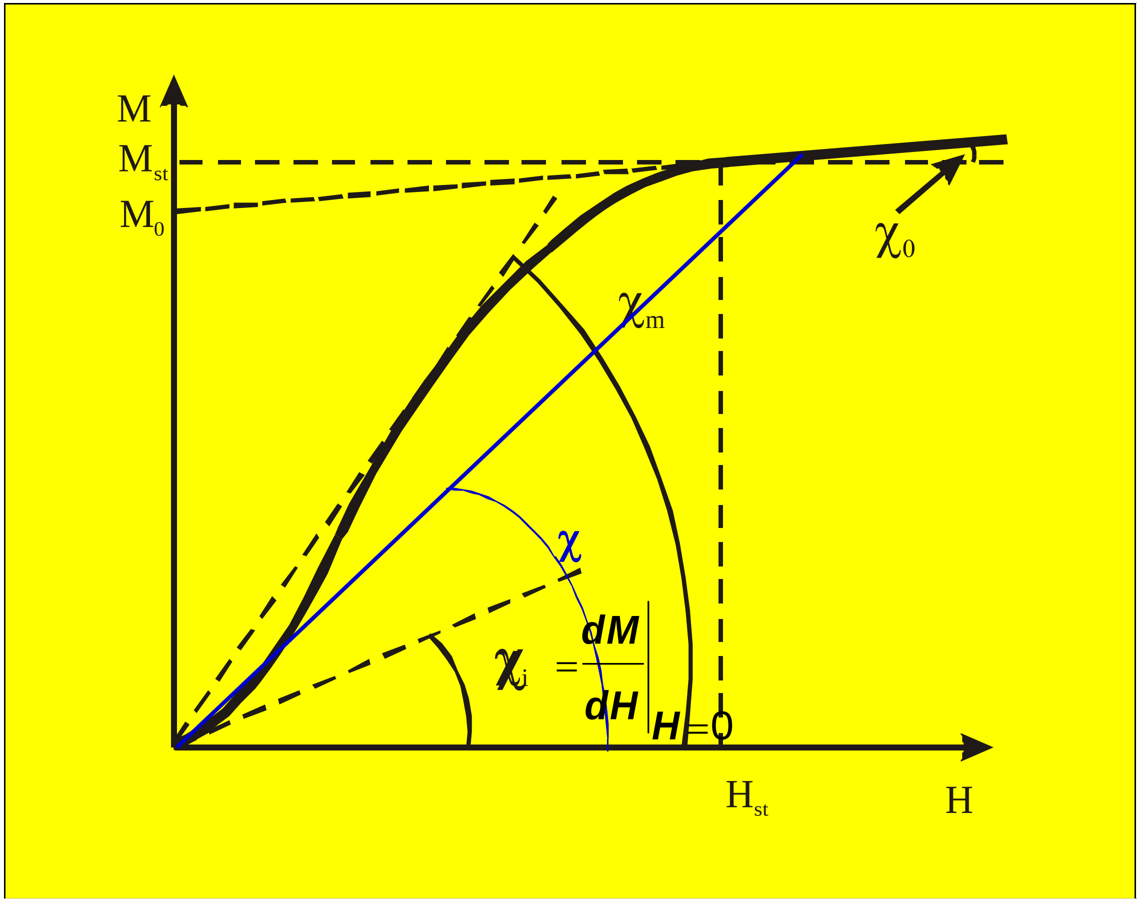
What is the susceptibility ?

Answer which one?

Initial susceptibility

Mean susceptibility

High field susceptibility



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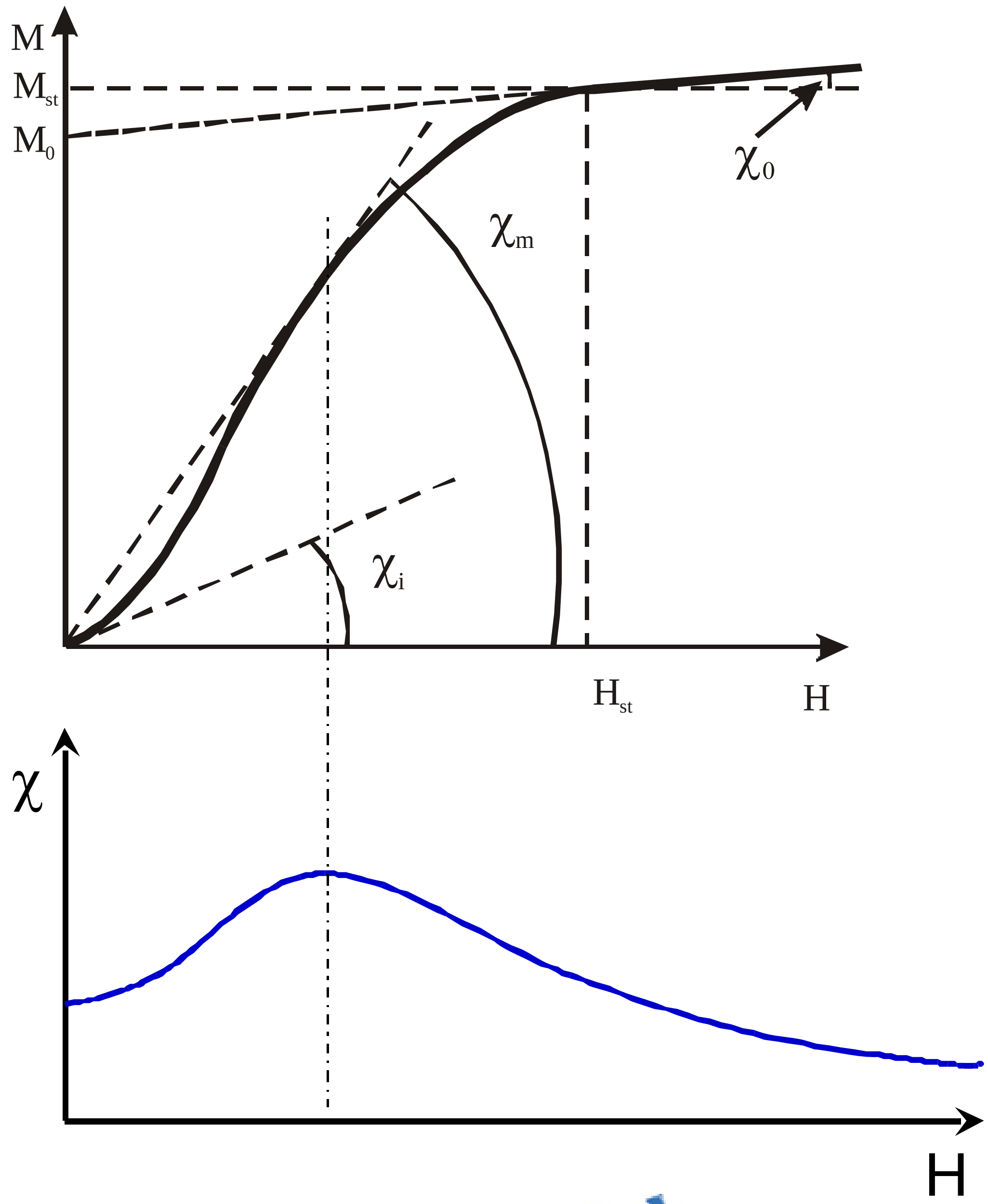


GRENOBLE 1
UNIVERSITE JOSEPH FOURIER
SCIENCES.TECHNOLOGIE.SANTÉ
Olivier ISNARD
NÉEL institut
cnrs

What is the susceptibility ?

Answer which one?

$$\chi = \frac{M}{H}$$

Susceptibility often express
/ mass or
/ volume or
/ molecule

Initial susceptibility

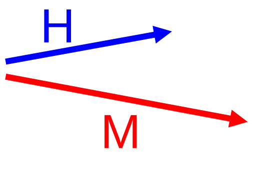
Mean susceptibility

High field susceptibility

Tensor of susceptibility $\vec{M} = \chi \vec{H}$

$$\begin{pmatrix} \chi_{11} & \chi_{12} & \chi_{13} \\ \chi_{23} & \chi_{22} & \chi_{23} \\ \chi_{31} & \chi_{32} & \chi_{33} \end{pmatrix}$$

$$\begin{pmatrix} M_1 \\ M_2 \\ M_3 \end{pmatrix} = \begin{pmatrix} \chi_{11} & \chi_{12} & \chi_{13} \\ \chi_{21} & \chi_{22} & \chi_{23} \\ \chi_{31} & \chi_{32} & \chi_{33} \end{pmatrix} \begin{pmatrix} H_1 \\ H_2 \\ H_3 \end{pmatrix}$$



Differential susceptibility $\chi_{ij}^{d} = \frac{\partial M_{ij}}{\partial H_{ij}}$

dc or ac susceptibility $\chi = \chi' - i\,\chi''$

…

$$\chi_{material} = f(\omega, T, H)$$

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What is the physical meaning of real and imaginary part of susceptibility ?

$$\chi = \chi' - i\,\chi''$$

$$H(t) = H + H_{ac}\cos\omega t$$

$$M(t) = M + M_{ac}\cos(\omega t - \phi)$$

$$M(t) = M + M_{ac}(\cos\omega t\cos\phi - \sin\omega t\sin\phi)$$

$\chi = \chi' - i\,\chi''$ Phase shift ⟹ $\chi' = \dfrac{M_{ac}\cos\phi}{H_{ac}}$ and $\chi'' = \dfrac{M_{ac}\sin\phi}{H_{ac}}$

$$H(t) = H + H_{ac}\exp(i\omega t) \qquad M(t) = M + \chi_{ac} M_{ac}\exp(i\omega t)$$

power absorbed per unit volume $P = \dfrac{1}{2}\omega\chi''_{ac} H_{ac}^2$

What is the physical meaning of real and imaginary part of susceptibility ?

Real part

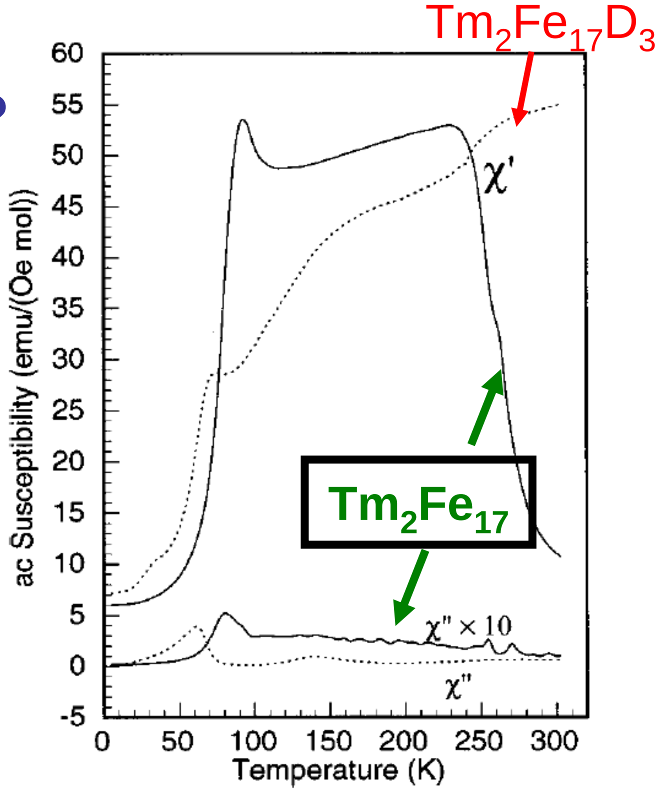
$$\chi' = \frac{M_{ac} \cos\phi}{H_{ac}}$$

Reflects sensitivity of material to H applied
Eventually in the different directions (tensor rank 2)

Imaginary part

$$\chi'' = \frac{M_{ac} \sin\phi}{H_{ac}}$$

Reflects :
- phase shift of H applied
- dissipation energy lost absorption of energy



PHYSICAL REVIEW B, VOLUME 65, 064429
F. Grandjean, O. Isnard, G.J. Long

Non zero values of χ'' related to dispersion centered at a frequency of $\omega_\tau = 1/\tau$ τ being a relaxation time ie: domain wall motions, relaxation irreversibility, magnetic phase transition, Tc, spin reorientation …

Remember $\chi_{material} = f(\omega, T, H)$ From Hz to 10 KHz…

Ac susceptibility is a very sensitive technique !!

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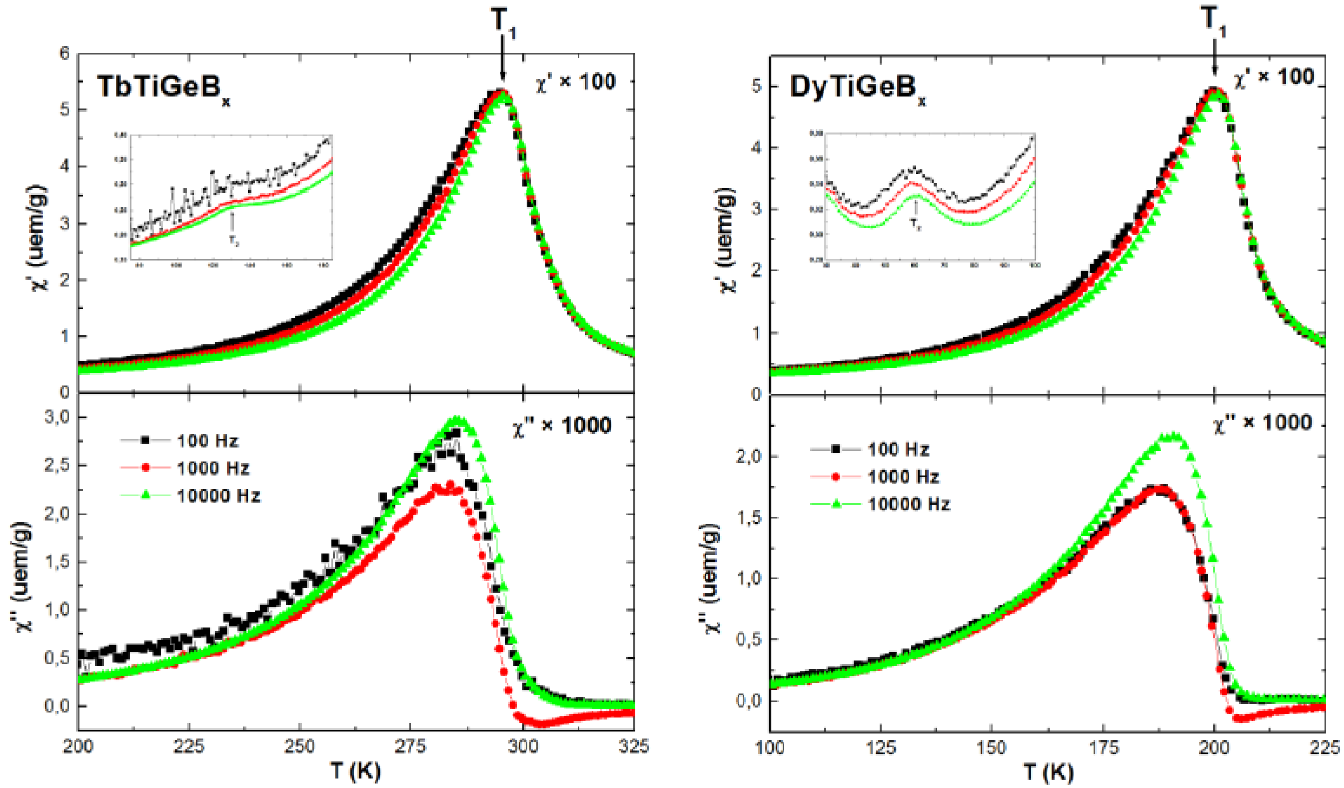


Figure 4.7 : Variation thermique de la partie réelle χ' et imaginaire χ'' de l'aimantation des composés $TbTiGeB_x$ et $DyTiGeB_x$ (H_{AC} = 5 Oe ; ν = 100, 1000 et 10000 Hz).

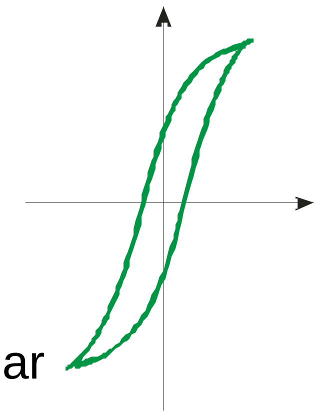
After Lemoine thesis
Univ. Nancy

Signal at the ordering of the rare earth

What is the susceptibility ?

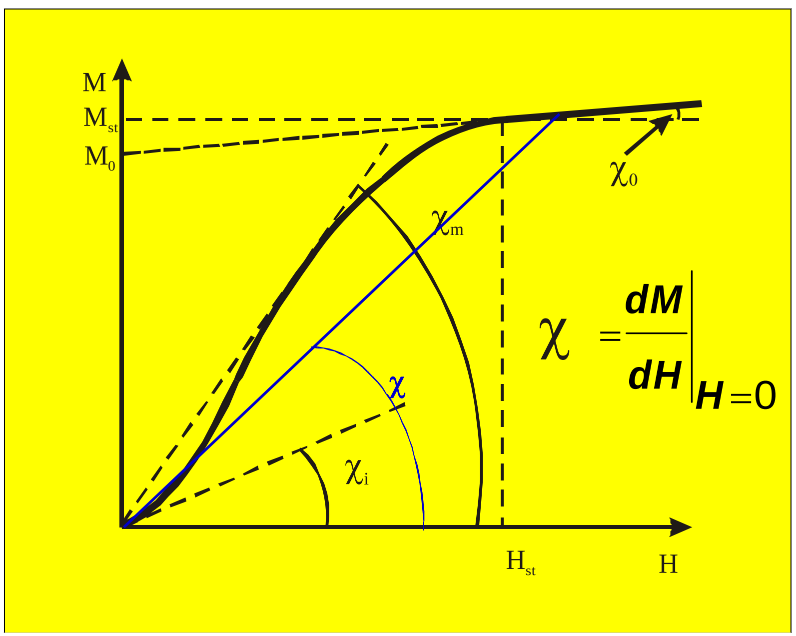
Differential susceptibility

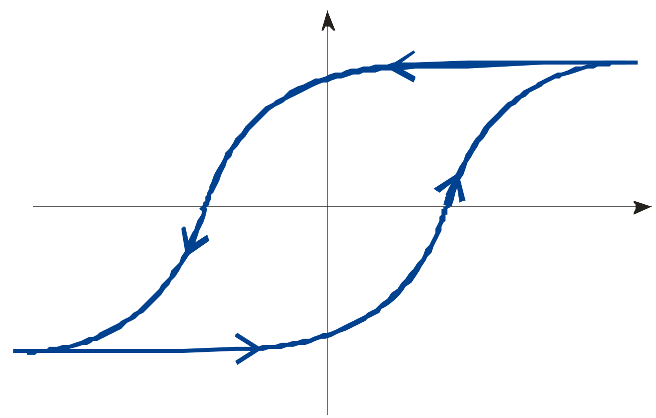
$$\chi_{ij}^{d} = \frac{\partial M_{ij}}{\partial H_{ij}}$$



In ferromagnetic materials the relation between M and H is not linear

Differential susceptibility also referred to





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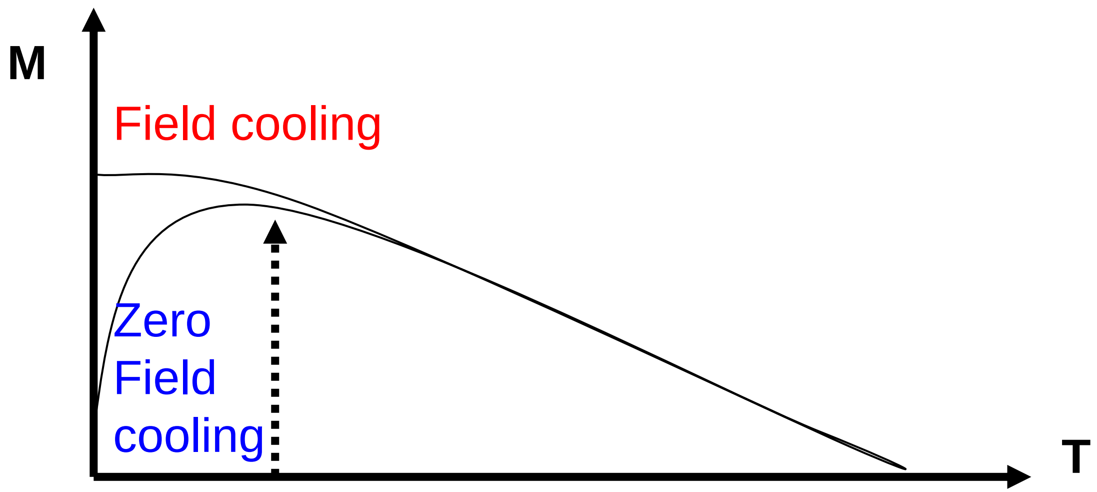
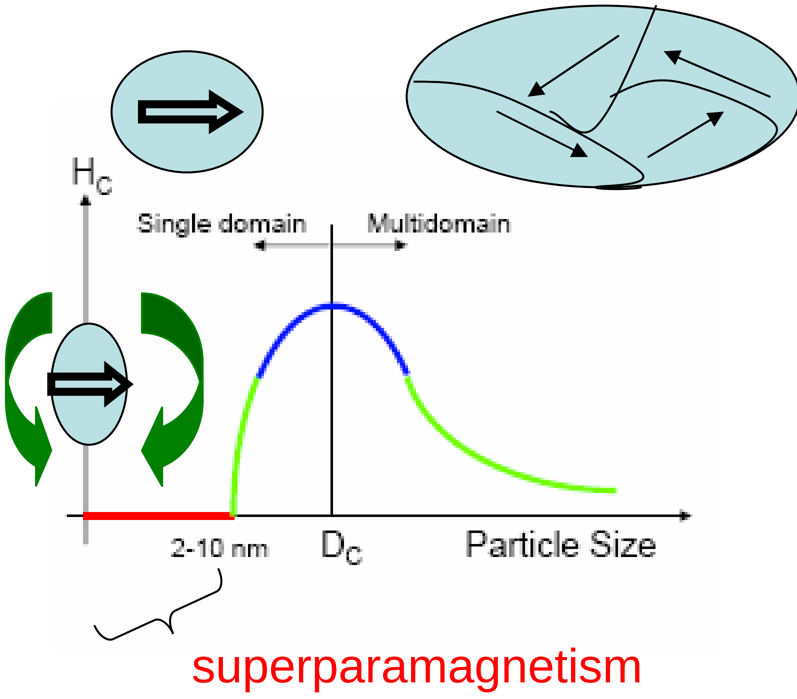
In which measurement can you see difference between superparamagnetism and spin glass behaviour?

What is spin glass ?

What is superparamagnetism ?

Similar behaviour from magnetization measurements





T critical = T blocking or T freezing

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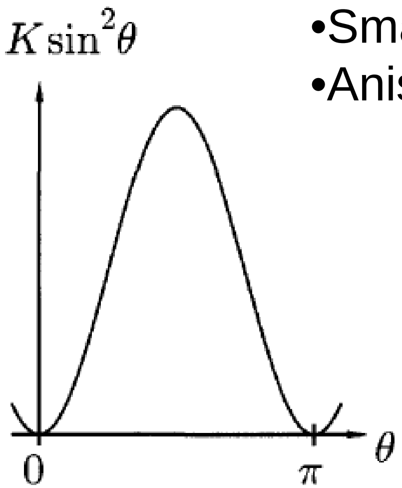
Superparamagnetism



•Ferromagnetic particles => J>0
•Small particles => single domain (cf lecture Olivier)
•Anisotropy M preferentially aligned along one direction energy KV

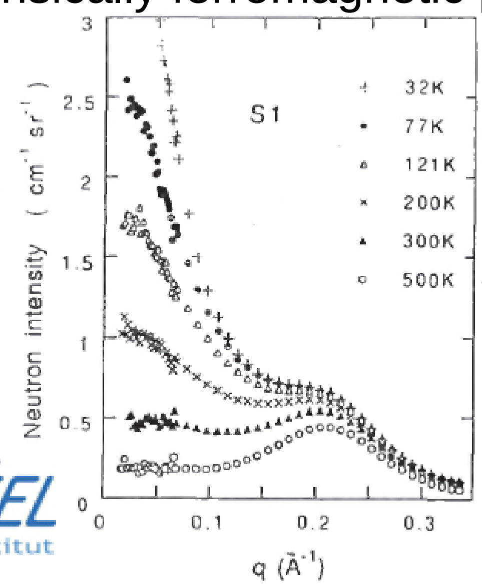
The particle behaves like a macrospin

Competition between kT and KV => limit on particle size
If V decreases then anisotropy energy also and Magnetization of the particle no longer force to be along the easy direction because of kT

⇒ Fluctuation of the magnetization direction ⬄ intrinsically ferromagnetic particles but appearing like para (superpara)

$k\,T_{blocking} \sim K\,V$

Coherence length larger than the particle size at $T > T_{blocking}$



Superpara
Fe particles

20 nm

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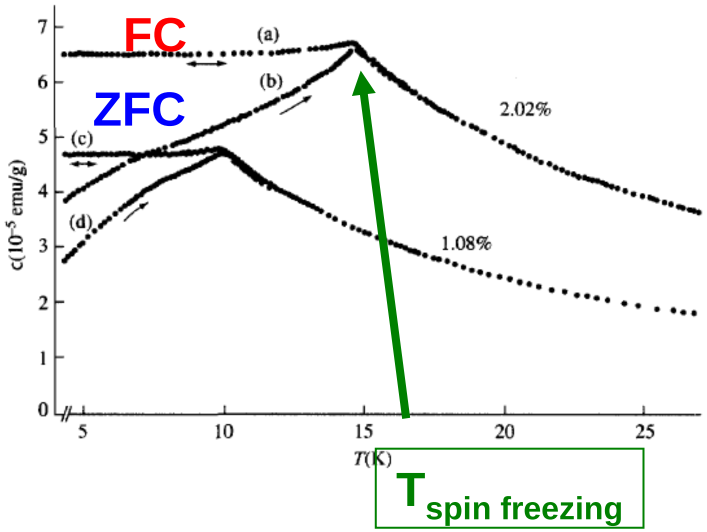
Spin glasses ie: Fe diluted in Au or $Cu_{1-x}Mn_x$ and x→0

The term "glass" comes from an analogy between the *magnetic* disorder in a spin glass and the *positional* disorder of a conventional, chemical glass



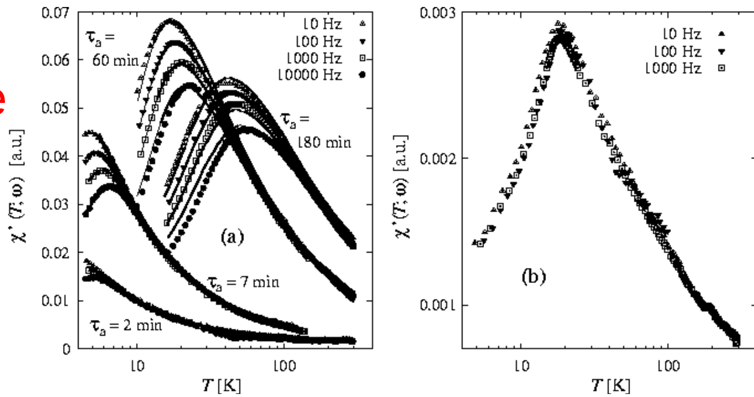
- Diluted system
- Mixed interaction competing
- J>0 and J<0 (RKKY int.)
- Random
- Transition from not ordered to low T metastable state (no long range order)

Opposite limit percolation between clusters => ordering

In which measurement can you see difference between superparamagnetism and spin glass behaviour?

superparamagnetism and spin glass exhibit similar behavior from magnetization measurements

ac susceptibility in particular frequency dependence



B. Idzikowski *et al* 1999 *Europhys. Lett.* **45** 714

For more details

J.A. Mydosh, *Spin Glasses : An experimental Introduction*, Taylor & Francis : London, 1993.

Specific heat (magnetic one) independent of T below $T_{freezing}$

Local probe of the internal magnetic field

- Mössbauer spectroscopy 10^{-7}-10^{-10}s
- Muon spectroscopy 10^{-5}-10^{-10}s
- Neutron spectroscopies 10^{-10}-10^{-12}s
- NMR …

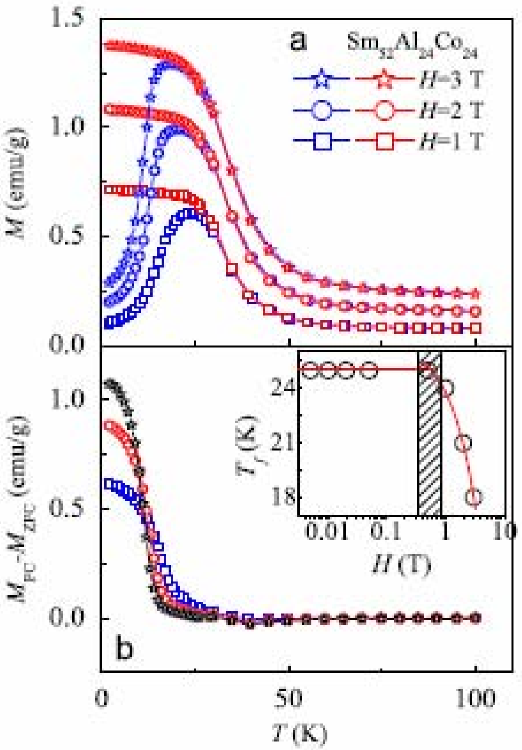
Access to relaxation time

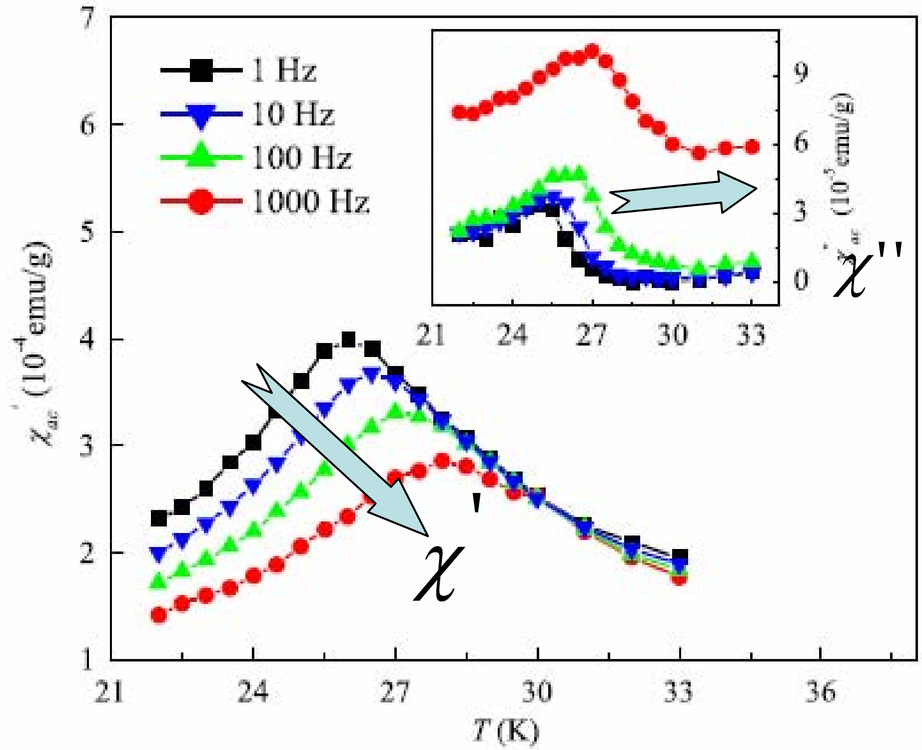
ie: Relaxation time of the moment in the superparamagnet

$$\tau = \tau_0 \exp\left(\frac{KV}{k_B T}\right)$$

Signature of Spin Glass from M(T) and Xac

C.L. Lu et al. / Journal of Magnetism and Magnetic Materials 322 (2010) 2845–2850 2847





Follow the frequency dependence

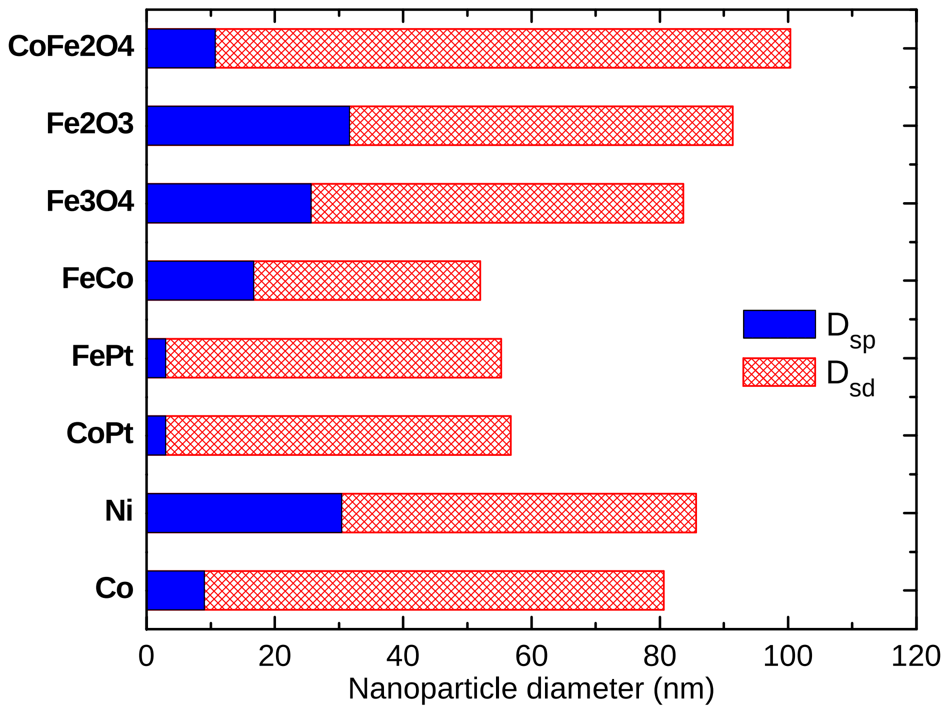
$$\chi = \chi' + i\,\chi''$$

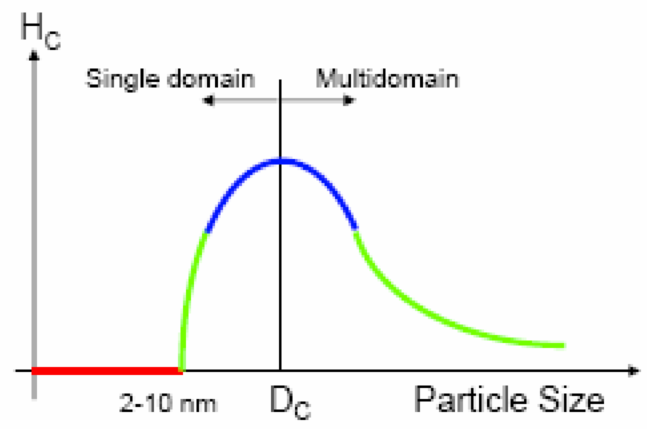
For more details

J.A. Mydosh, *Spin Glasses : An experimental Introduction*, Taylor & Francis : London, 1993.

What is superparamagnetism ?

Usuallly of interest for
Crystalline materials
Large anisotropy





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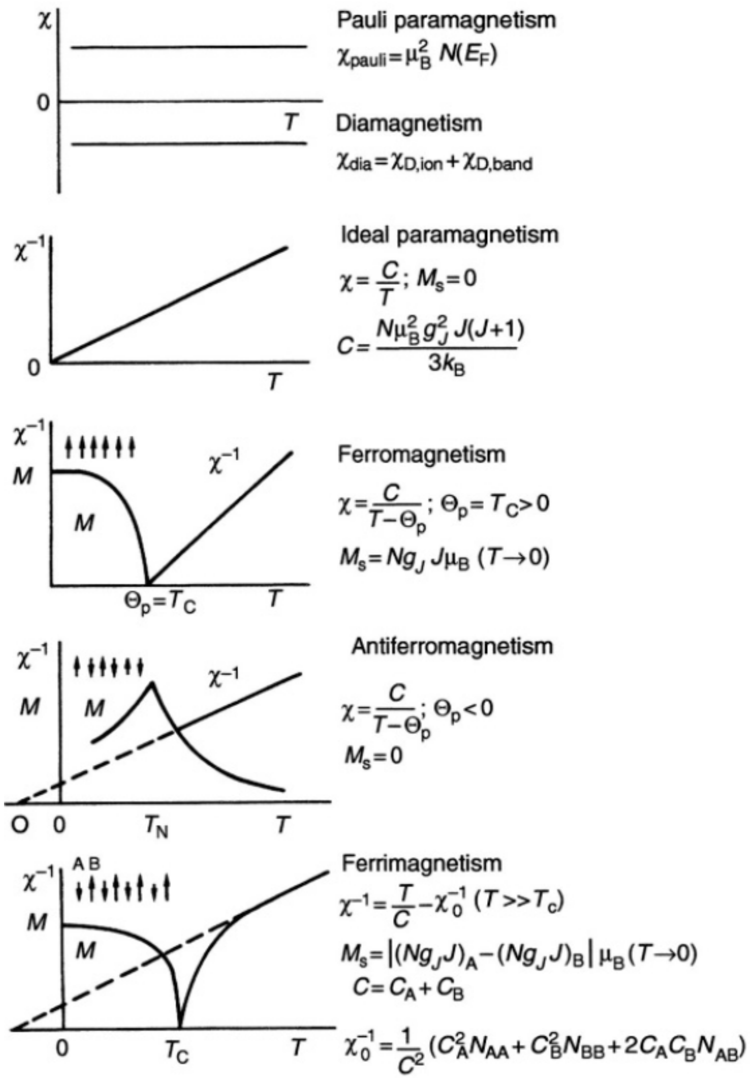
Minimal Stable Grain Diameter

$$D_P = \sqrt{\frac{60 \cdot k_B \cdot T}{K}}$$

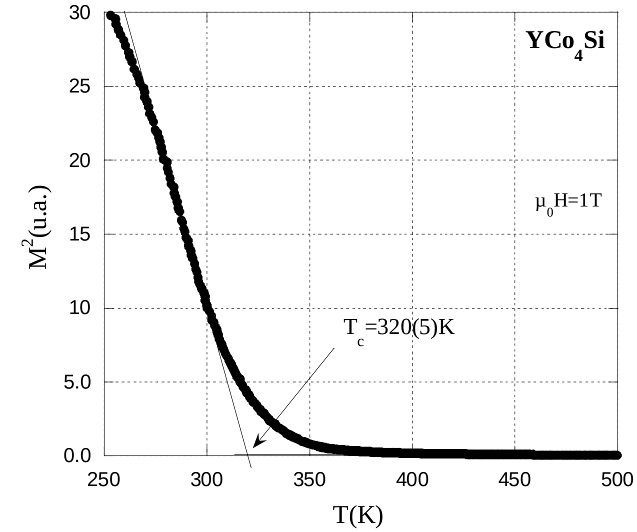
alloy system	material	K: anisotropy in 1e7 erg/cc	Ms: saturation magnetization in emu/cc	Hk: anisotropy field in kOe	Dp: minimal stable diameter in nm
	CoCrPtX	0.20	200-300	15-20	8-10
Co-alloys	Co	0.45	1400	6.4	8
	hex Co3Pt	2.0	1100	36	4.8
	FePd	1.8	1100	33	5.0
L10 phases	FePt	6.6-10	1140	116	2.8-3.3
	CoPt	4.9	800	123	3.6
	MnAl	1.7	560	69	5.1
RE-TM	Nd2Fe14B	4.6	1270	73	3.7
	Co5Sm	11-20	910	240-400	2.2-2.7

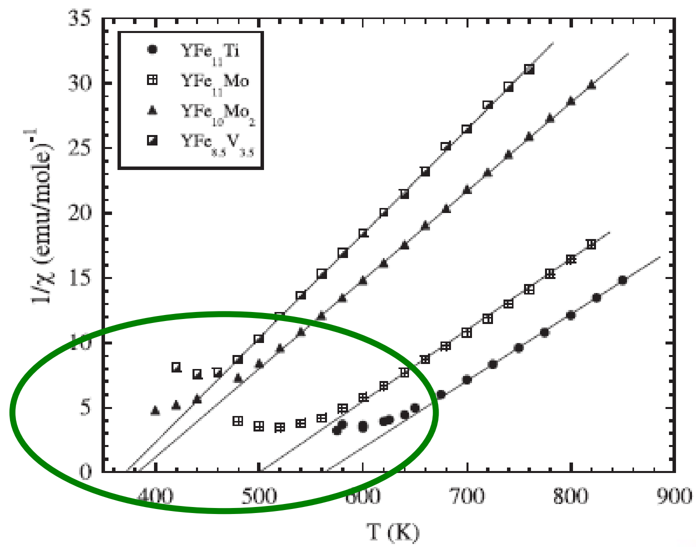
A few nm

Ideally



In practise





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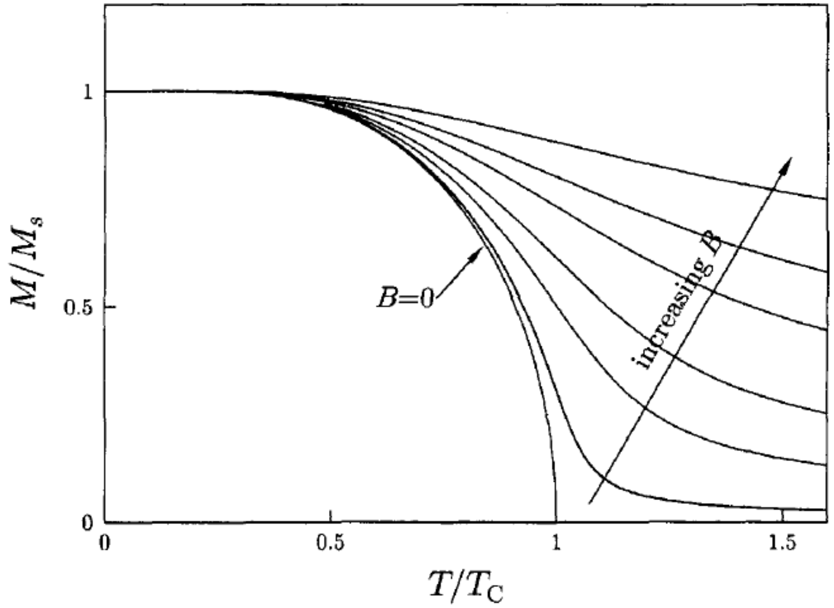

1
0.5
0
0
0.5
1
1.5
M/M_s
T/T_C
B=0
increasing B

Origin of this behavior ?
Short range ordering = correlation between neighbouring spins even just above Tc

Existence of a typical correlation length which is infinite in the ordered state
Tends to zero at high temperature
Typical scale where there is correlation between the magnetic moments
⇒No longer independent => not strictly paramagnetic
⇒Reminiscent of magnetic order for a certain T range

How to observe it experimentally
Neutron scattering
since short range order => diffuse neutron scattering
Small angle scattering depending upon coherence length