What Magnetic Measurements tell us about magnetism?

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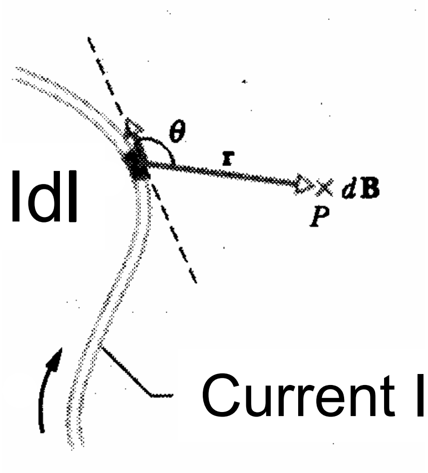
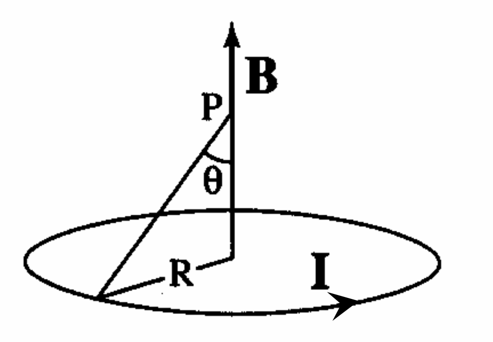
Magnetic moment

An electrical current, I, is the source of a magnetic field B

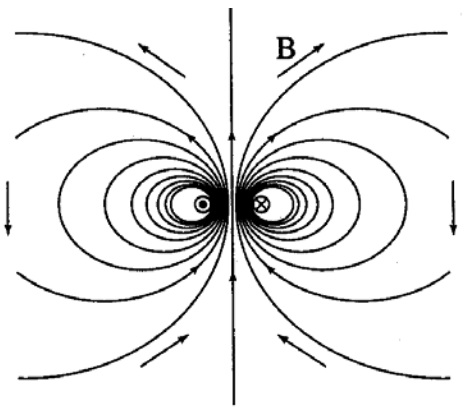


$$\mathbf{B} = \frac{\mu_0}{4\pi}\int_C \frac{I d\mathbf{l}}{r^2} \times \frac{\mathbf{r}}{r}$$

Magnetic field generated by a single-turn coil



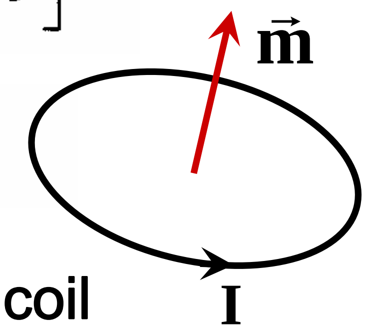
$$B = \frac{\mu_0 I}{2R}\sin^3\theta$$



far from the origin:

$$\mathbf{B} = \frac{\mu_0}{4\pi}\left[3\frac{(\mathbf{m}.\mathbf{r})\mathbf{r}}{r^5} - \frac{\mathbf{m}}{r^3}\right]$$

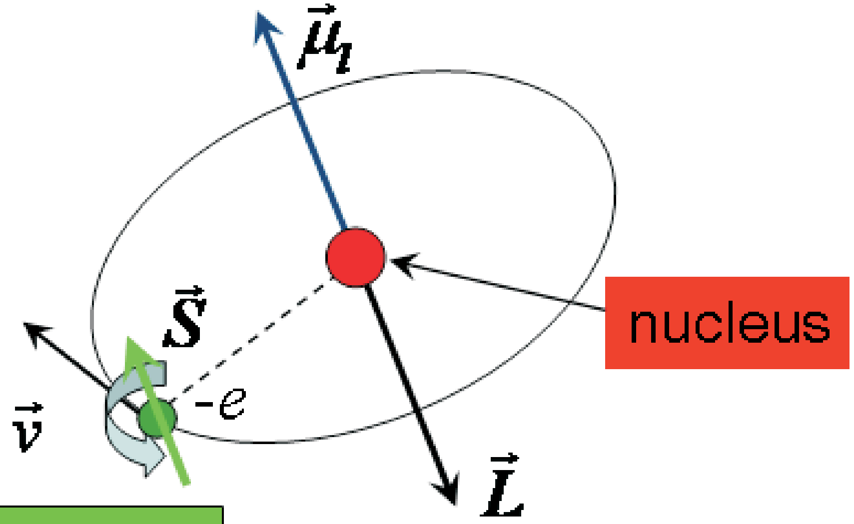
with $\mathbf{m} = I S \hat{\mathbf{n}}$



$\vec{m}$ is by definition the magnetic moment of the single-turn coil

Kinetic moments of the electron in the atoms:

- **Orbital kinetic moment** $\vec{L}$
- **Spin kinetic moment** $\vec{S}$



Kinetic moment of a charge

Magnetic moment: $\vec{m} = g\mu_B\vec{J}$

$\mu_B \equiv$ spin magnetic momentul of free electron

$$\mu_B = \frac{e\hbar}{2m_e} \qquad (SI) \qquad \mu_B = 9{,}2742 \cdot 10^{-24}\ A \cdot m^2$$

$$\mu_B = \frac{e\hbar}{2m_e c} \qquad (CGS)$$

$$g = 1 + \frac{J(J+1) + S(S+1) - L(L+1)}{2J(J+1)}$$

Landé factor

$$\begin{cases} \vec{m}_l = -g_l \dfrac{e}{2m_e}\vec{L}; \quad g_l = 1 \\ \vec{m}_s = -g_s \dfrac{e}{2m_e}\vec{S}; \quad g_s = 2 \end{cases}$$

magnetisation M

magnetic susceptibility χ

magnetic permeability μ

$$\vec{\mathbf{M}} = \frac{\sum \vec{\mathbf{m}}}{V}$$

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

$$\vec{\mathbf{B}} = \mu_0 \left(\vec{\mathbf{H}} + \vec{\mathbf{M}} \right)$$

$$\mu = \frac{B}{H}$$

$B = \mu_0(H + \chi H) = \mu_0(1 + \chi)H = \mu H$

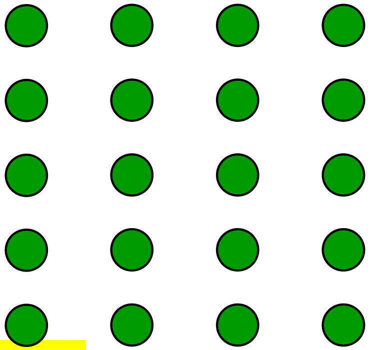
$$\mu = \mu_0 (1 + \chi)$$

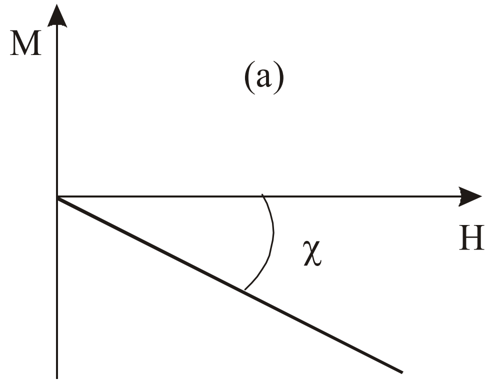
$\mu_0 = 4\pi \cdot 10^{-7}$ H/m

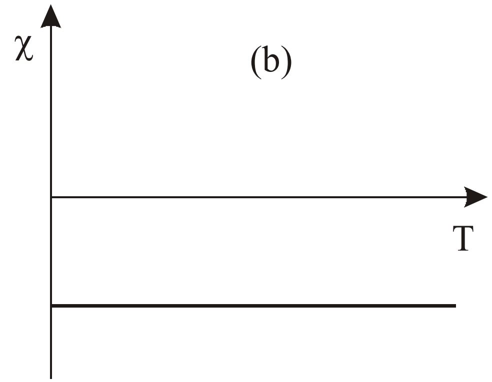
Diamagnetic

$$\vec{m} = 0$$

$$\chi < 0$$







C, Cu, Pb, H_2O, NaCl, SiO_2

Diamagnetic

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$\chi < 0$

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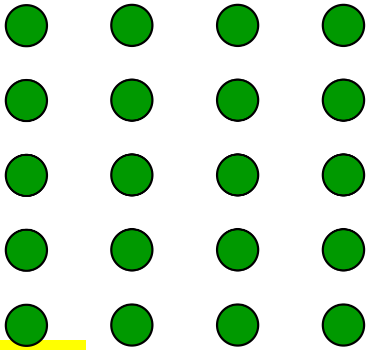
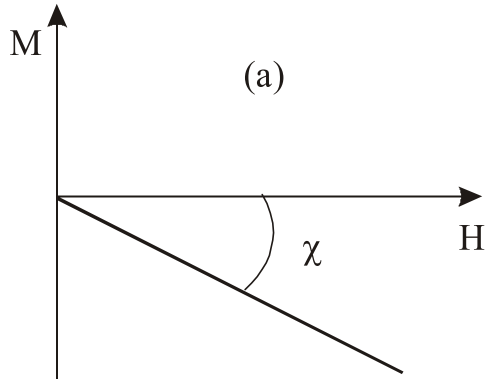
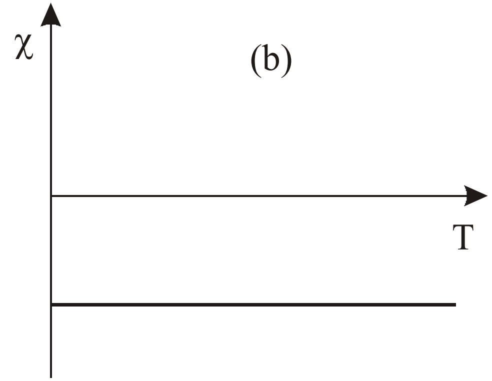






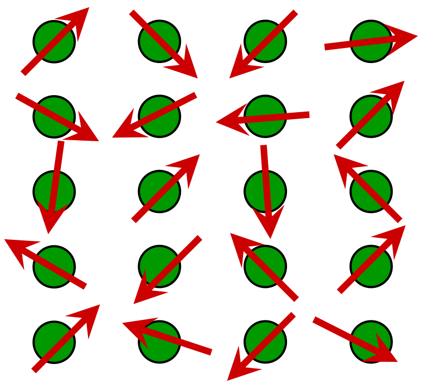
Paramagnetic

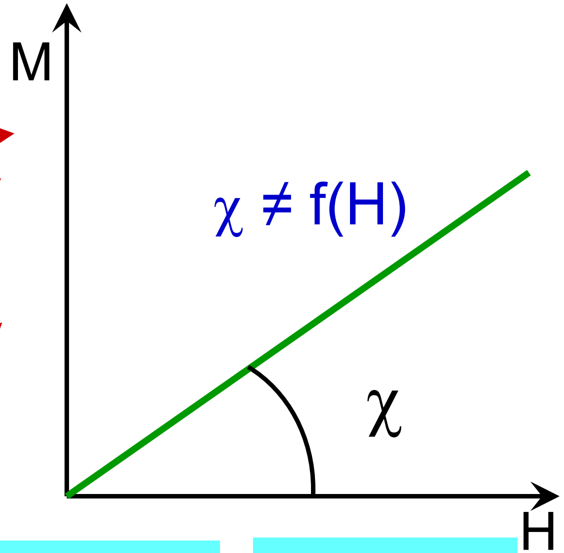
$\vec{m} \neq 0$

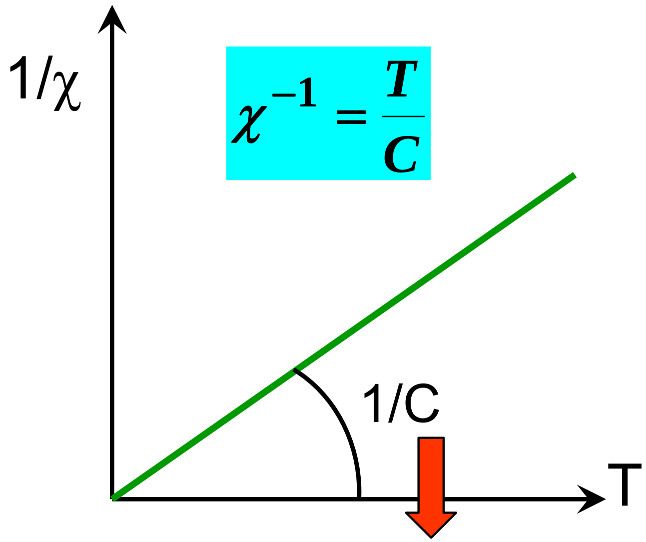
$J_{ij} = 0$

$\chi > 0$

Na, Al, $CuCl_2$







$$\chi^{-1} = \frac{T}{C}$$

$$\mu_{eff} = \sqrt{\frac{3k_B}{N \cdot \mu_0} C}$$

if $\chi(\mu_B/T \cdot f.u)$: $\mu_{eff}(\mu_B) = \sqrt{4{,}466 \cdot C}$

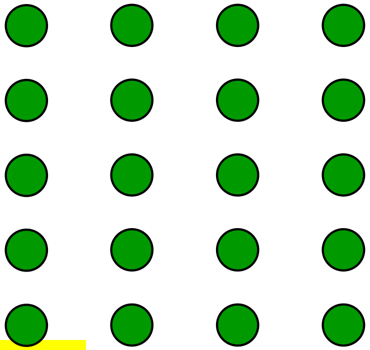
if χ(emu/mole): $\mu_{eff}(\mu_B) = \sqrt{8 \cdot C}$

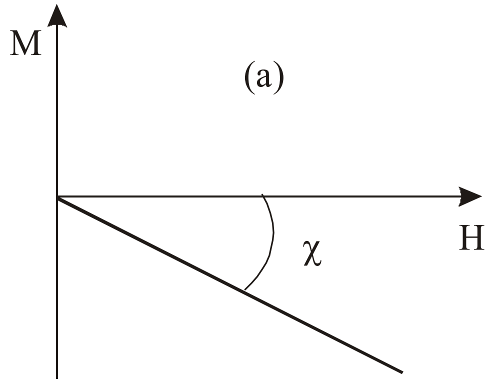
$$\mu_{eff} = g\mu_B\sqrt{J(J+1)}$$ → ***J***

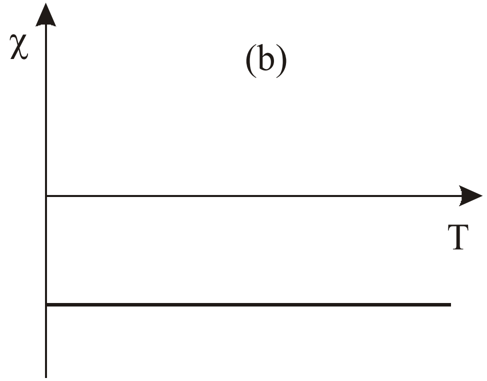
Diamagnetic

$\vec{m} = 0$

$\chi < 0$







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Paramagnetic

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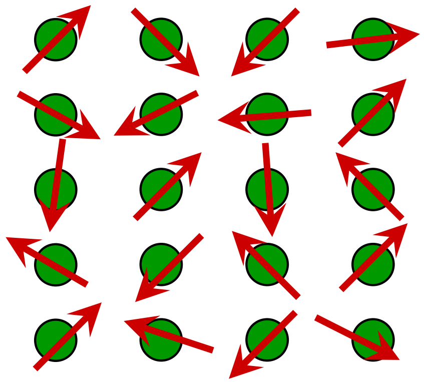
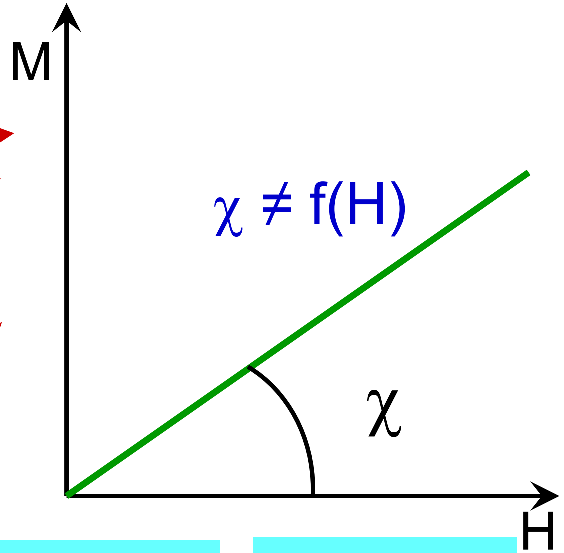
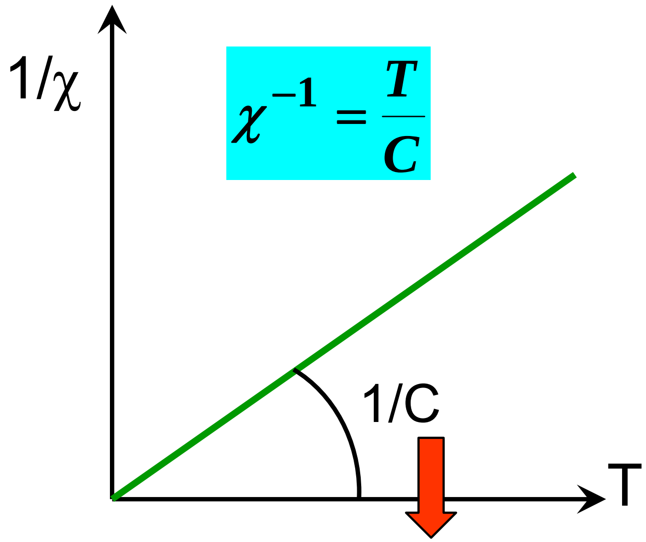
Na, Al, $CuCl_2$







$$\chi^{-1} = \frac{T}{C}$$

$$\mu_{eff} = \sqrt{\frac{3k_B}{N \cdot \mu_0} C}$$

if $\chi(\mu_B/T \cdot f.u)$

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if χ(emu/mole)

$$\mu_{eff}(\mu_B) = \sqrt{8 \cdot C}$$

J

$$\mu_{eff} = g\mu_B \sqrt{J(J+1)}$$

Magnetic ordered

$\vec{m} \neq 0$

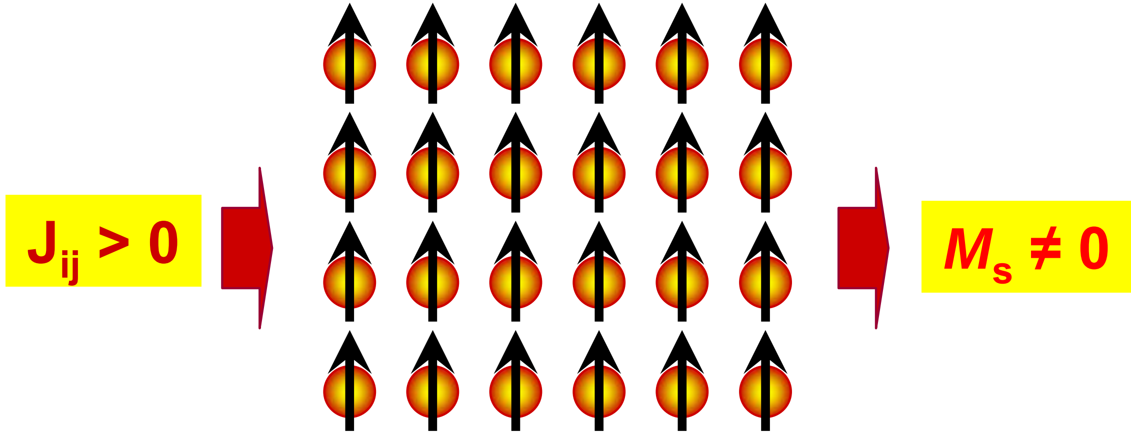
$J_{ij} \neq 0$

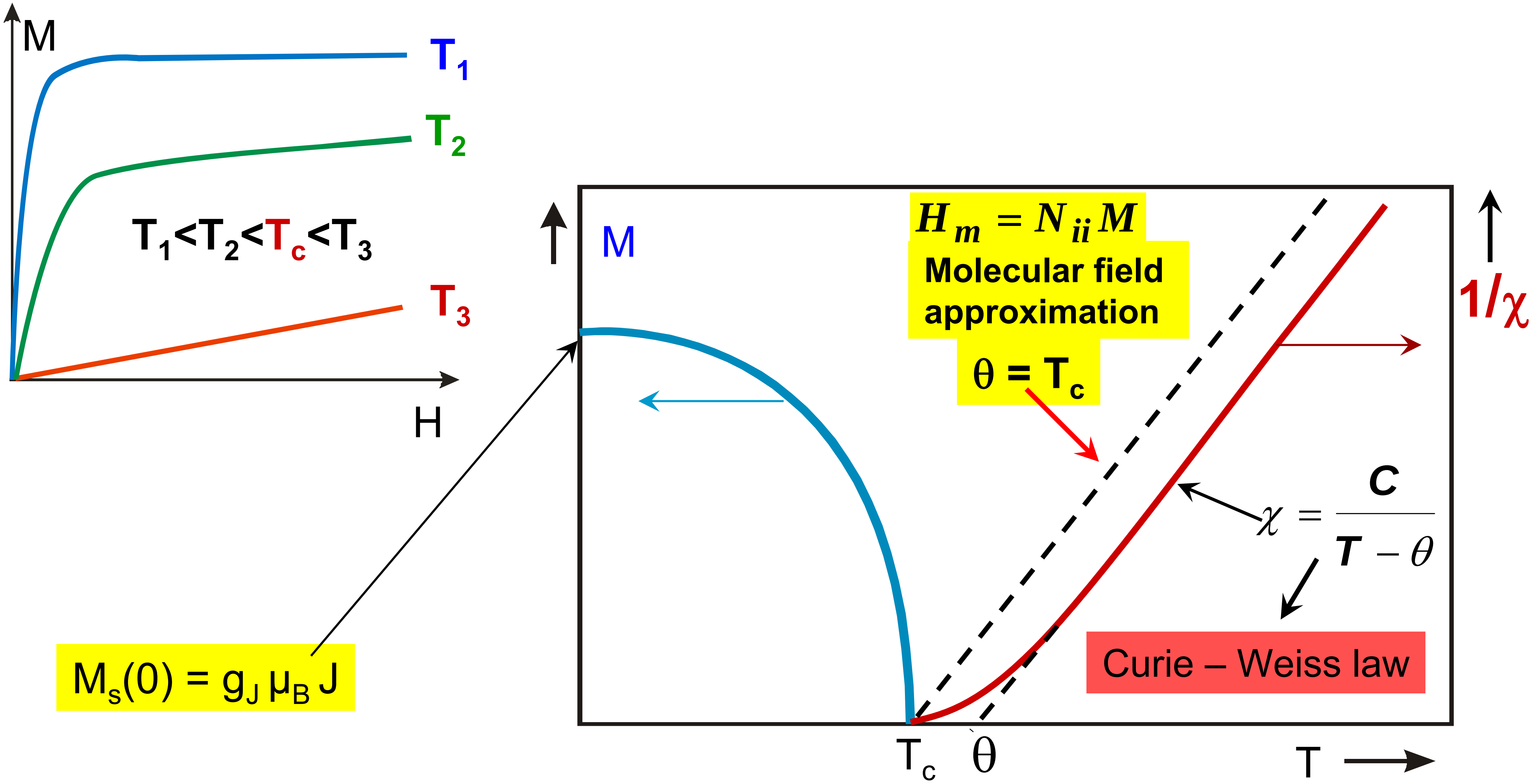
$\chi >> 0$

a) ferromagnetic

$$H = -2J_{ij}\ \vec{S}_i \cdot \vec{S}_j$$

Fe, Co, Ni, Gd…

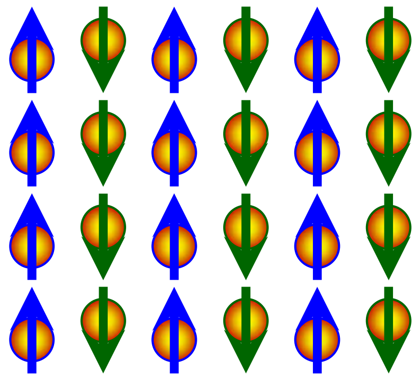




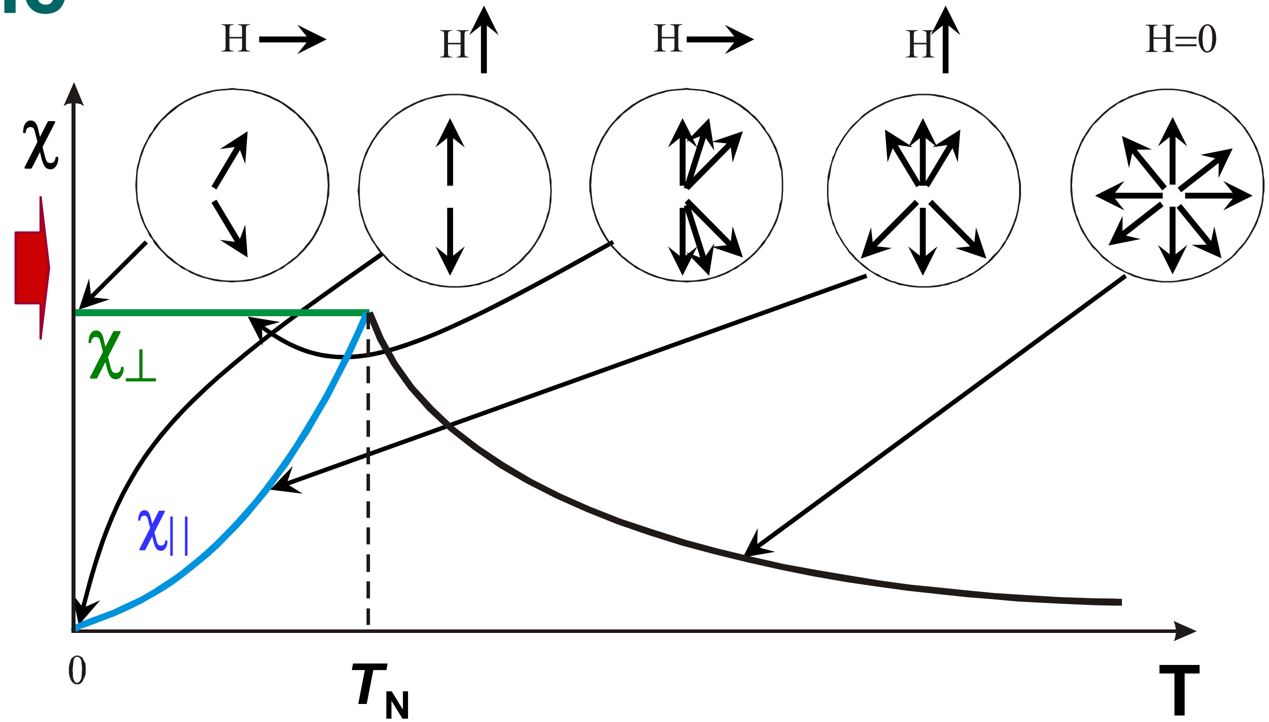
b) antiferromagnetic

$J_{ij} < 0$

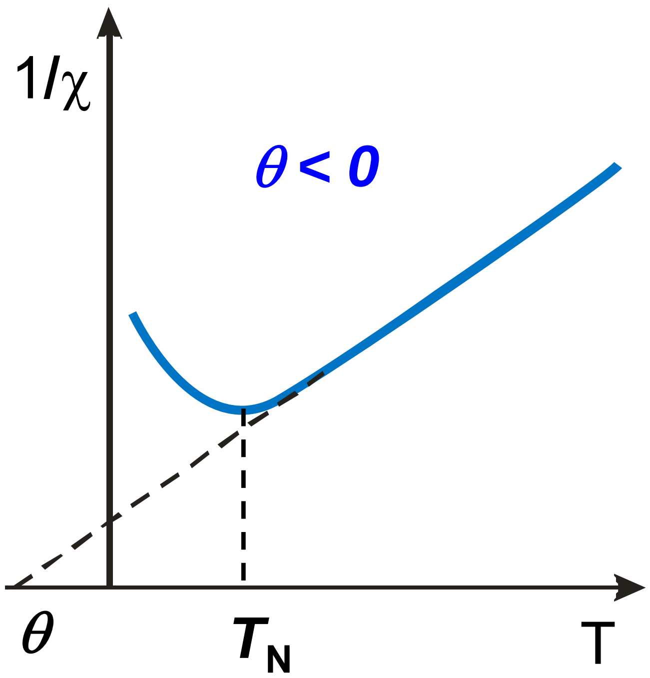
$|\vec{M}_A| = |\vec{M}_B|$



$M_s = 0$



MnO, Mn, Cr…

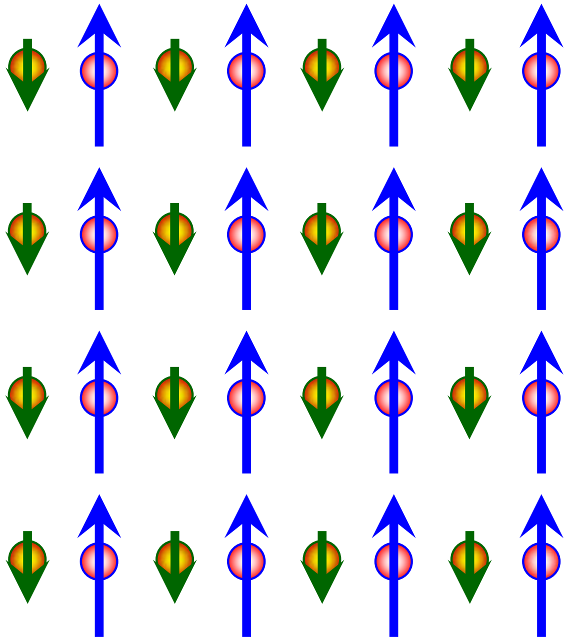


$$\chi = \frac{M_A + M_B}{H} = \frac{C}{T + \theta}$$

c) ferrimagnetism

$J_{ij} < 0$

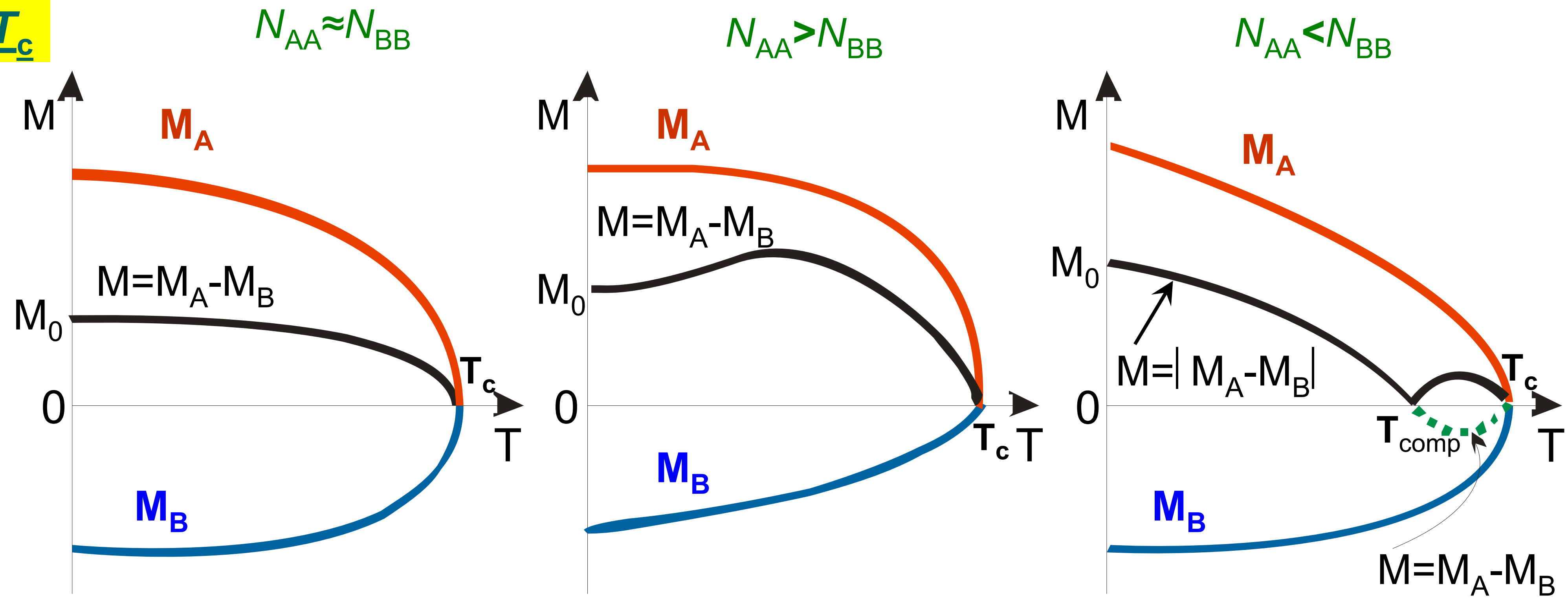
$|\vec{M}_A| \neq |\vec{M}_B|$



$M_s \neq 0$

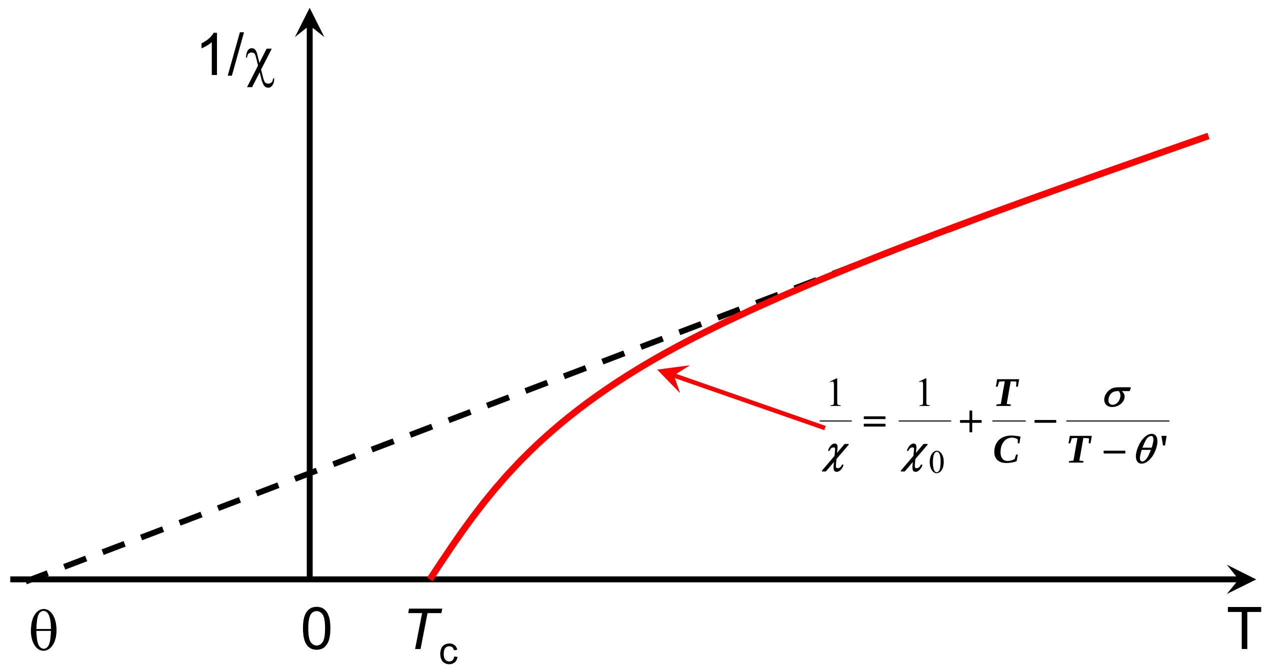
Fe_3O_4, ferrites, $GdCo_5$,…

$T<T_c$

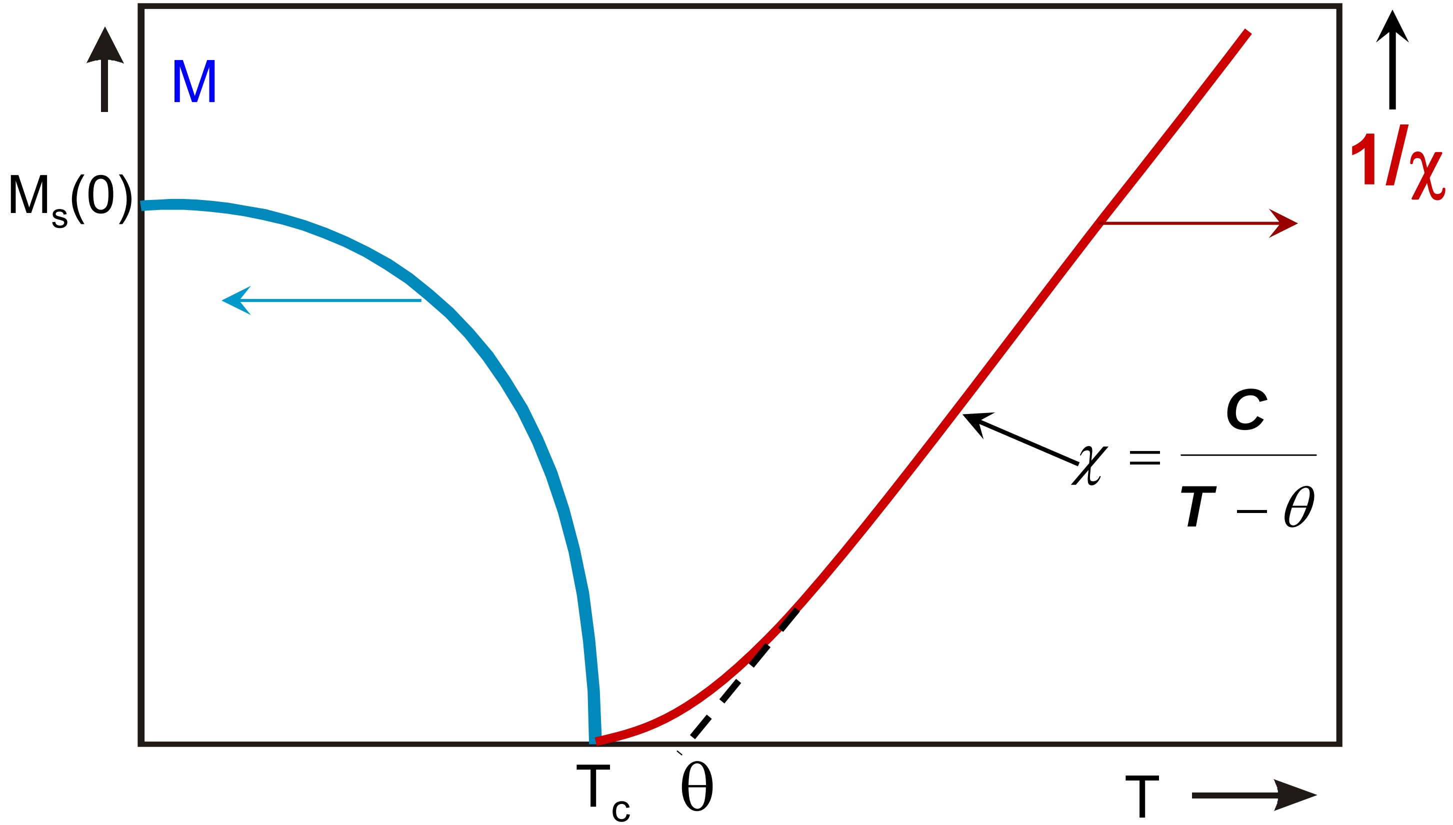


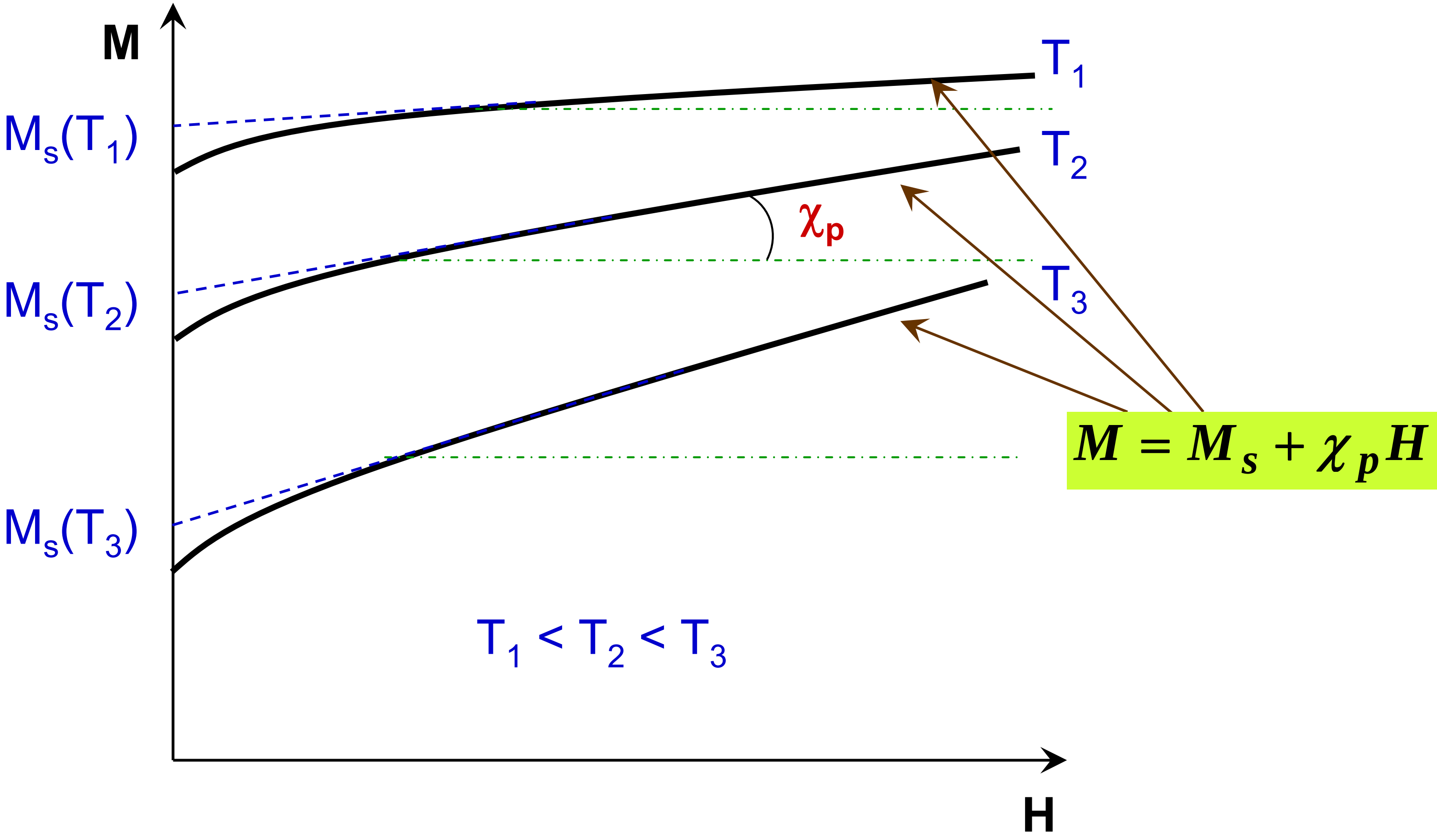
N_AA≈N_BB
N_AA>N_BB
N_AA<N_BB
M
M_A
M=M_A-M_B
M_0
0
T_c
T
M_B
M=| M_A-M_B|
T_comp

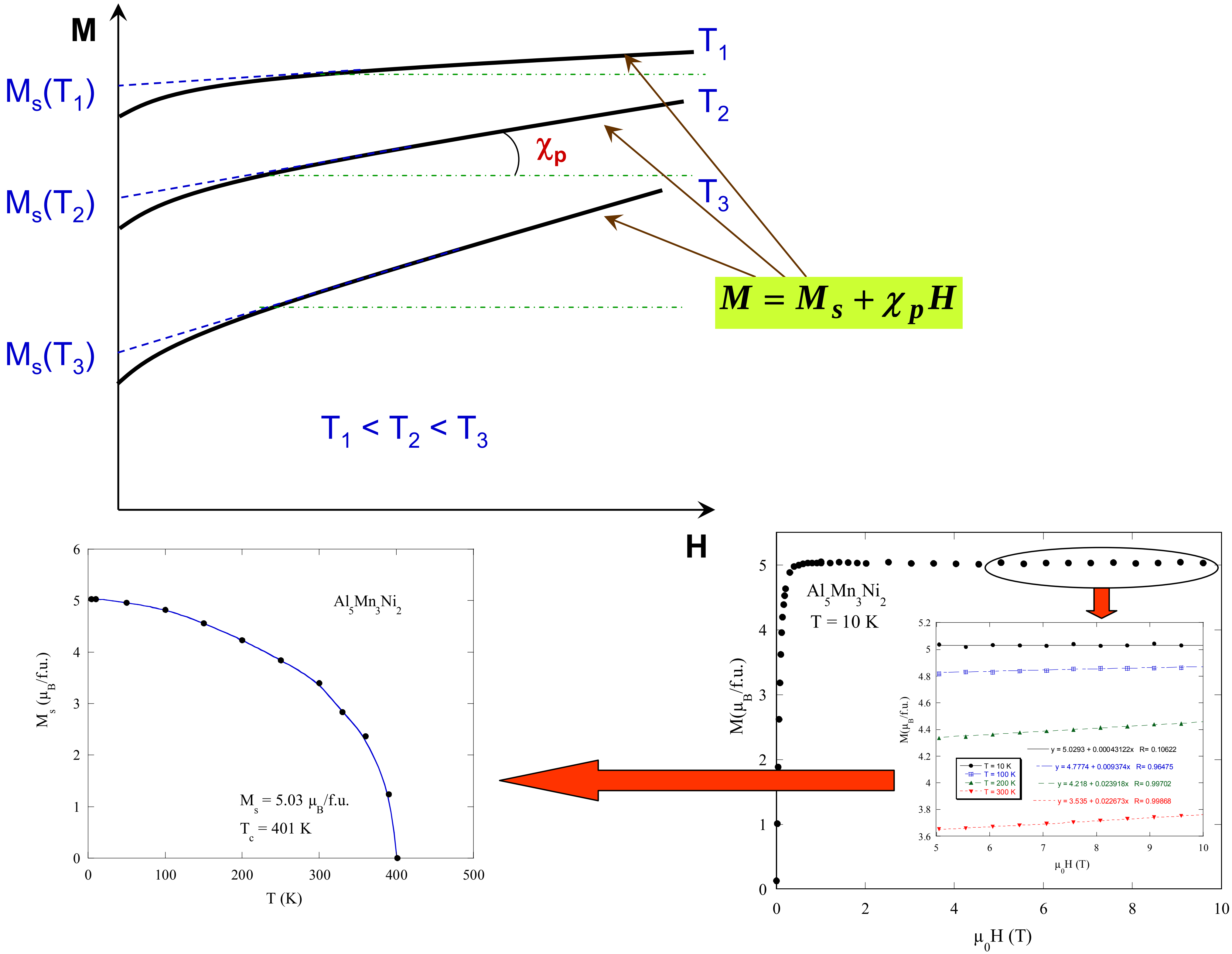
$T>T_c$



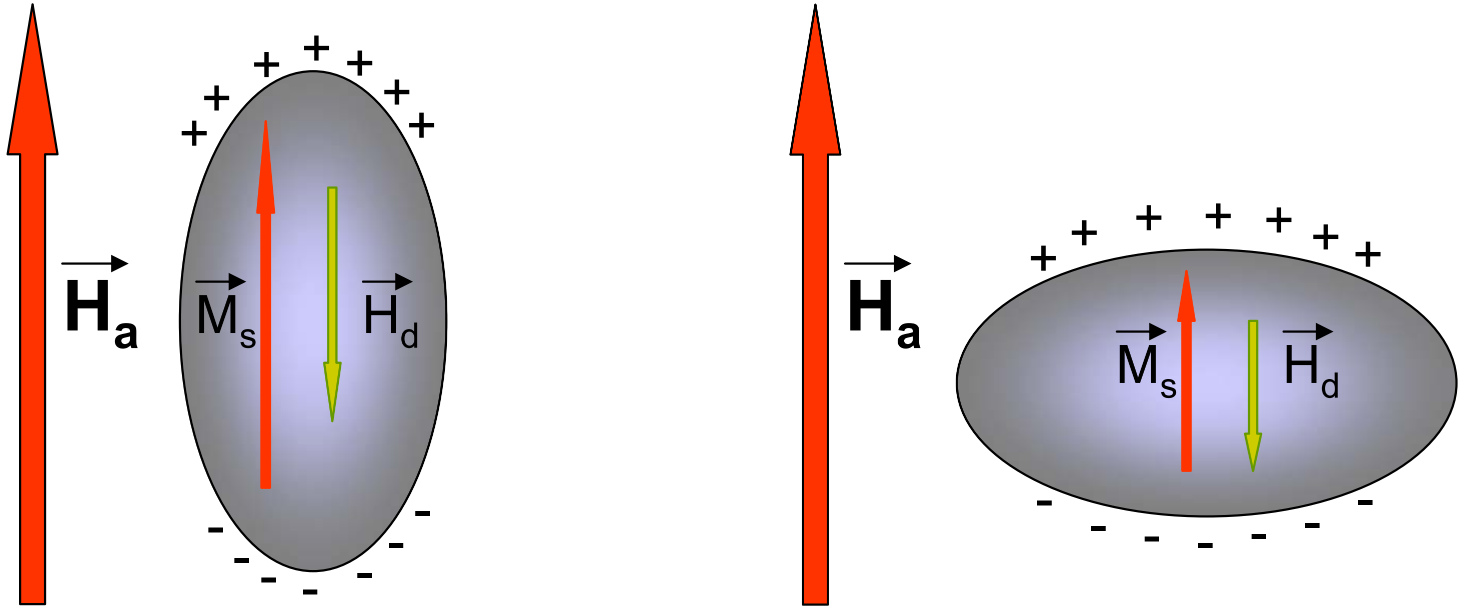
1/χ
$$\frac{1}{\chi} = \frac{1}{\chi_0} + \frac{T}{C} - \frac{\sigma}{T-\theta'}$$
θ
0
T_c
T


M
$M_s(0)$
$1/\chi$
$\chi = \frac{C}{T - \theta}$
T_c
θ
T


M
H
T1
T2
T3
Ms(T1)
Ms(T2)
Ms(T3)
χp
T1 < T2 < T3
M = Ms + χpH



M
H
$M_s(T_1)$
$M_s(T_2)$
$M_s(T_3)$
T_1
T_2
T_3
χ_p
$M = M_s + \chi_p H$
$T_1 < T_2 < T_3$
$Al_5Mn_3Ni_2$
$M_s = 5.03\ \mu_B$/f.u.
$T_c = 401$ K
M_s (μ_B/f.u.)
T (K)
$Al_5Mn_3Ni_2$
T = 10 K
M(μ_B/f.u.)
μ_0H (T)
T = 10 K
T = 100 K
T = 200 K
T = 300 K
y = 5.0293 + 0.00043122x R= 0.10622
y = 4.7774 + 0.009374x R= 0.96475
y = 4.218 + 0.023918x R= 0.99702
y = 3.535 + 0.022673x R= 0.99868



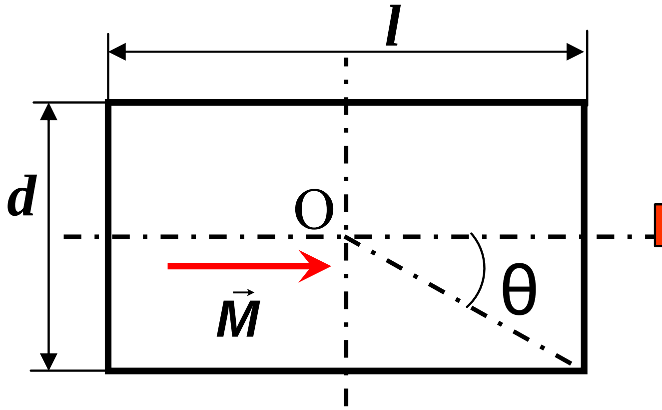
$$H_d = N_{||} M_s \Leftarrow \vec{H}_d = -N_d \vec{M} \Rightarrow H_d = N_{\perp} M_s$$

The influence of the demagnetising field on the magnetisation curves

$$\vec{H}_d = -N_d \vec{M} \Rightarrow \vec{H} = \vec{H}_i = \vec{H}_a + \vec{H}_d$$

H_a = applied field

sphere $\Rightarrow$ $N_{dx} = N_{dy} = N_{dz} = 1/3.$



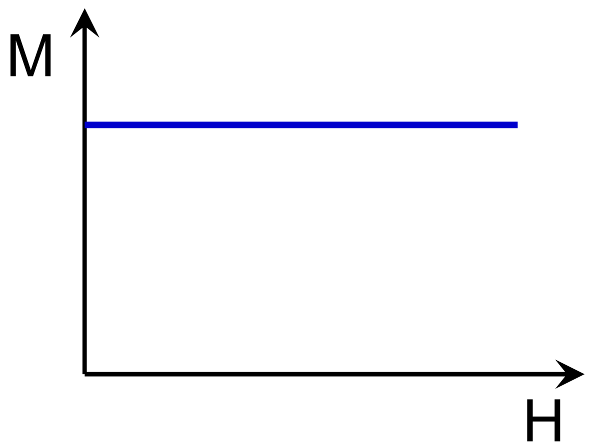
$$\vec{H}_d = -(1-\cos\theta)\cdot\vec{M}$$

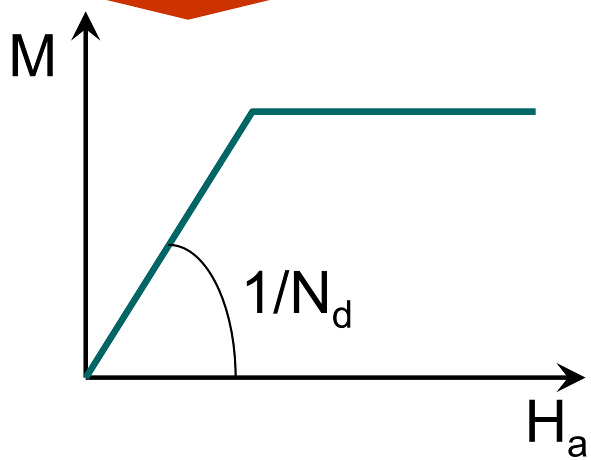
$d << l \Rightarrow N_d = 0$

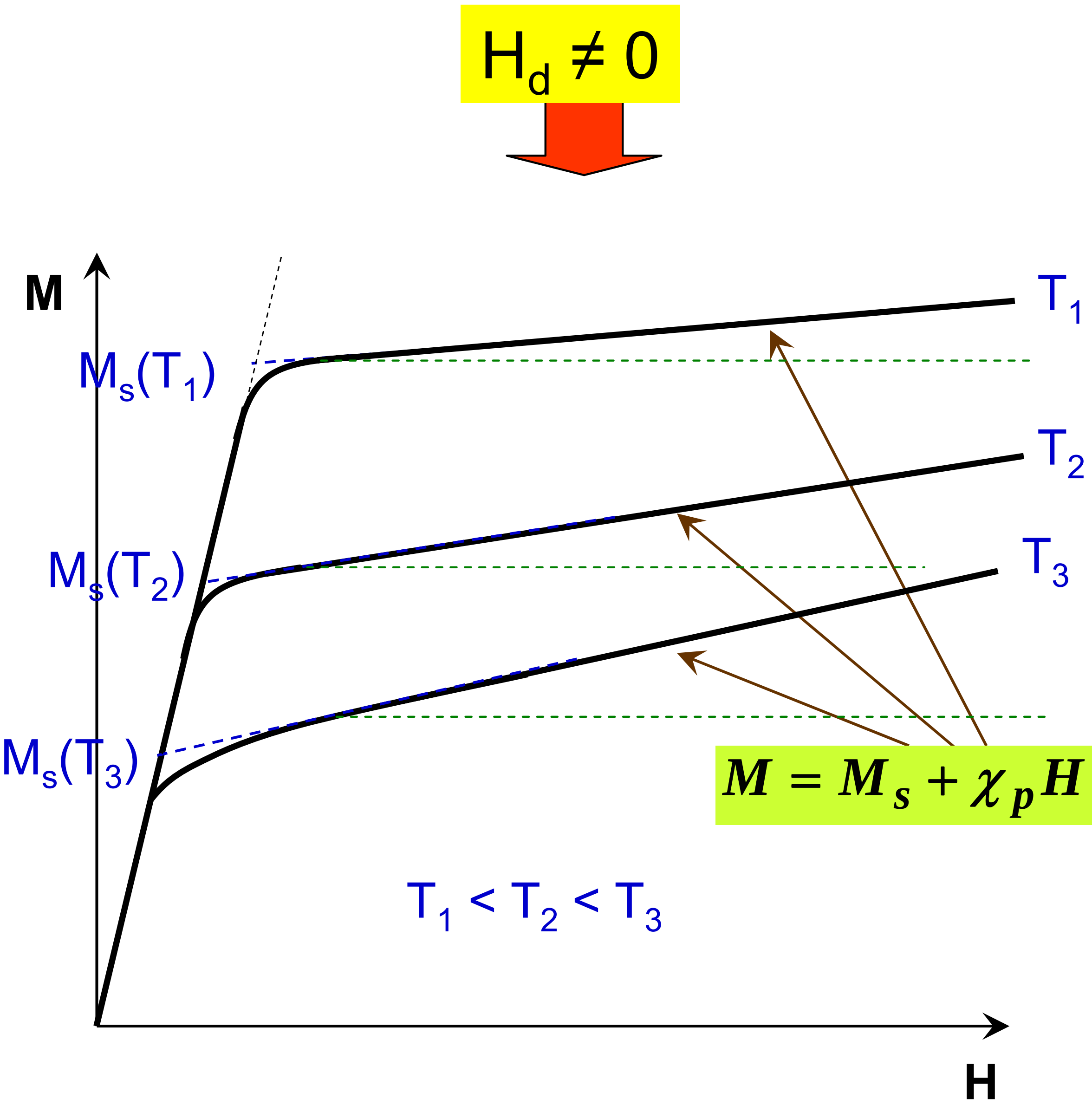
$d >> l \Rightarrow N_d = -1$

$$M = \chi H = \chi(H_a + H_d) = \chi(H_a - N_d M)$$

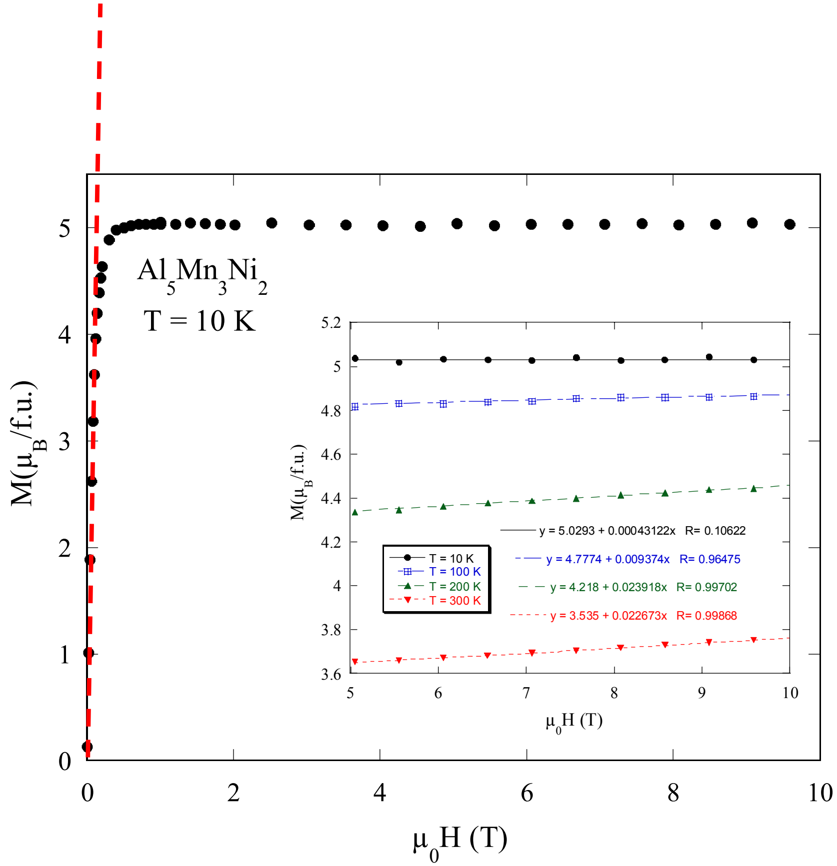
$$M = \frac{\chi}{1 + N_d \chi} H_a$$







H_d ≠ 0
M
M_s(T_1)
M_s(T_2)
M_s(T_3)
T_1
T_2
T_3
M = M_s + χ_p H
T_1 < T_2 < T_3
H



Al_5Mn_3Ni_2
T = 10 K
M(μ_B/f.u.)
μ_0H (T)
T = 10 K
T = 100 K
T = 200 K
T = 300 K
y = 5.0293 + 0.00043122x R= 0.10622
y = 4.7774 + 0.009374x R= 0.96475
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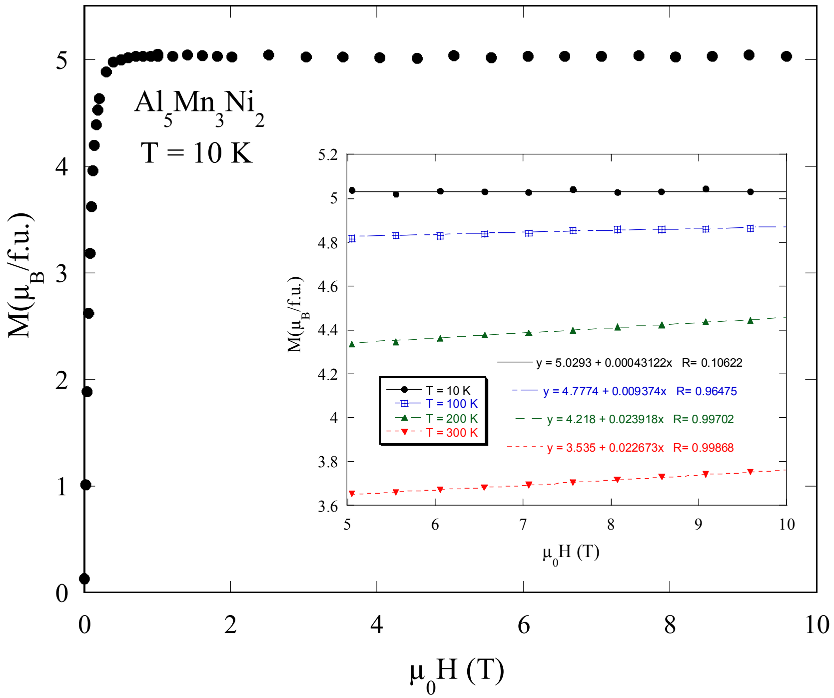
Al5Mn3Ni2
T = 10 K
M(μB/f.u.)
μ0H (T)
T = 10 K
T = 100 K
T = 200 K
T = 300 K
y = 5.0293 + 0.00043122x R= 0.10622
y = 4.7774 + 0.009374x R= 0.96475
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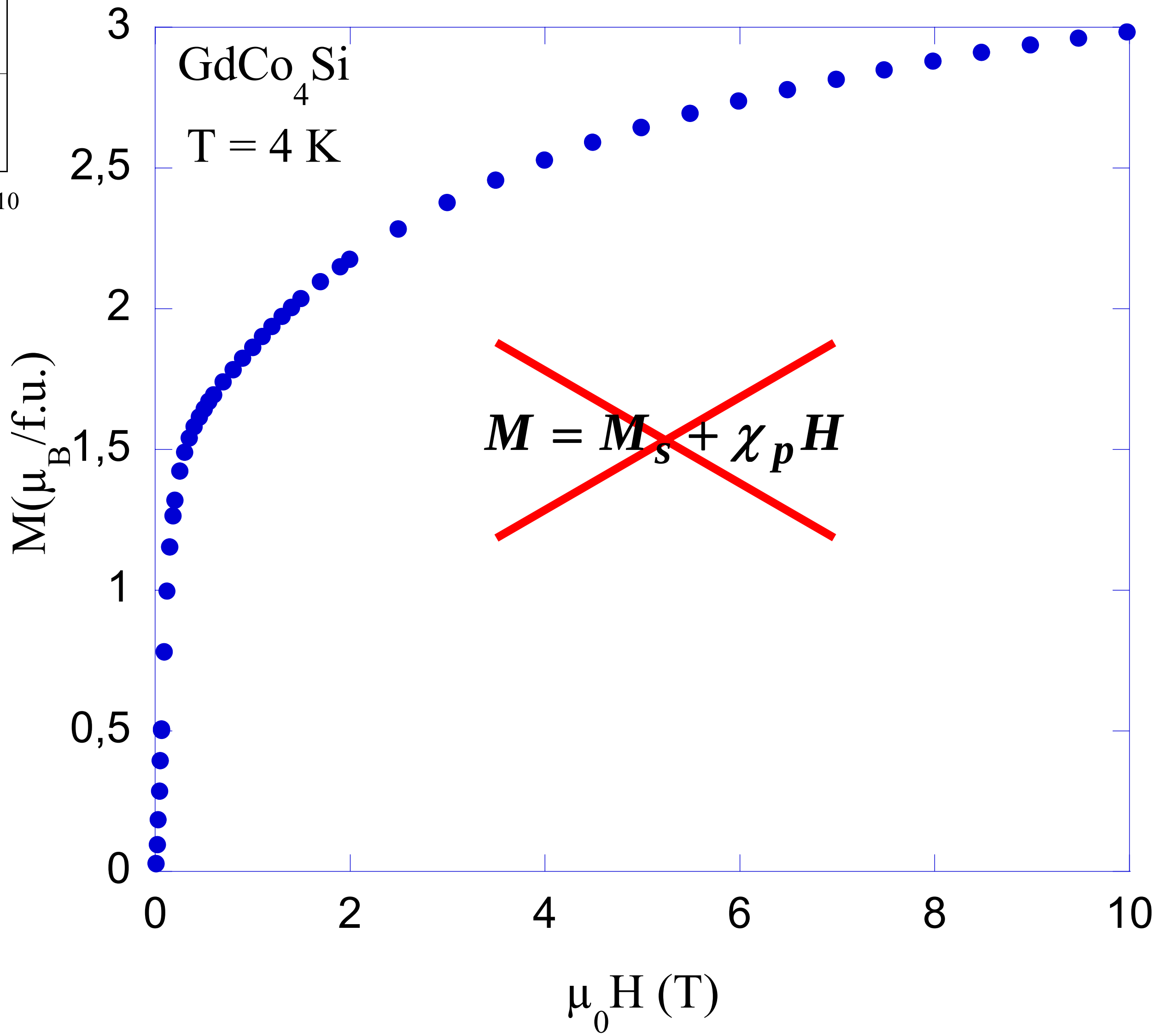
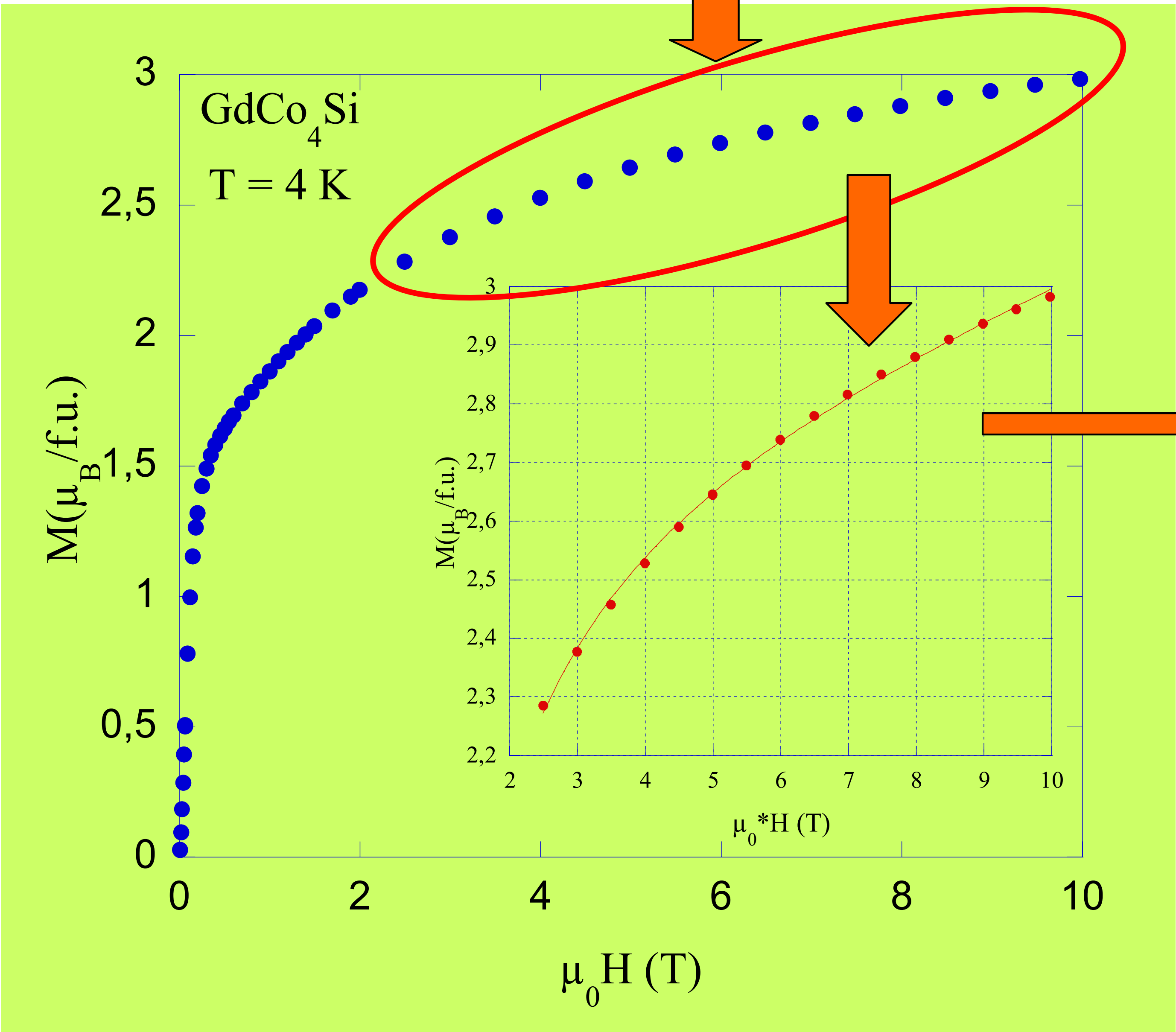

GdCo4Si
T = 4 K
M(μB/f.u.)
μ0H (T)
$M = M_s + \chi_p H$

$$M = M_s\left(1 - \frac{a}{H}\right) + \chi_p H$$

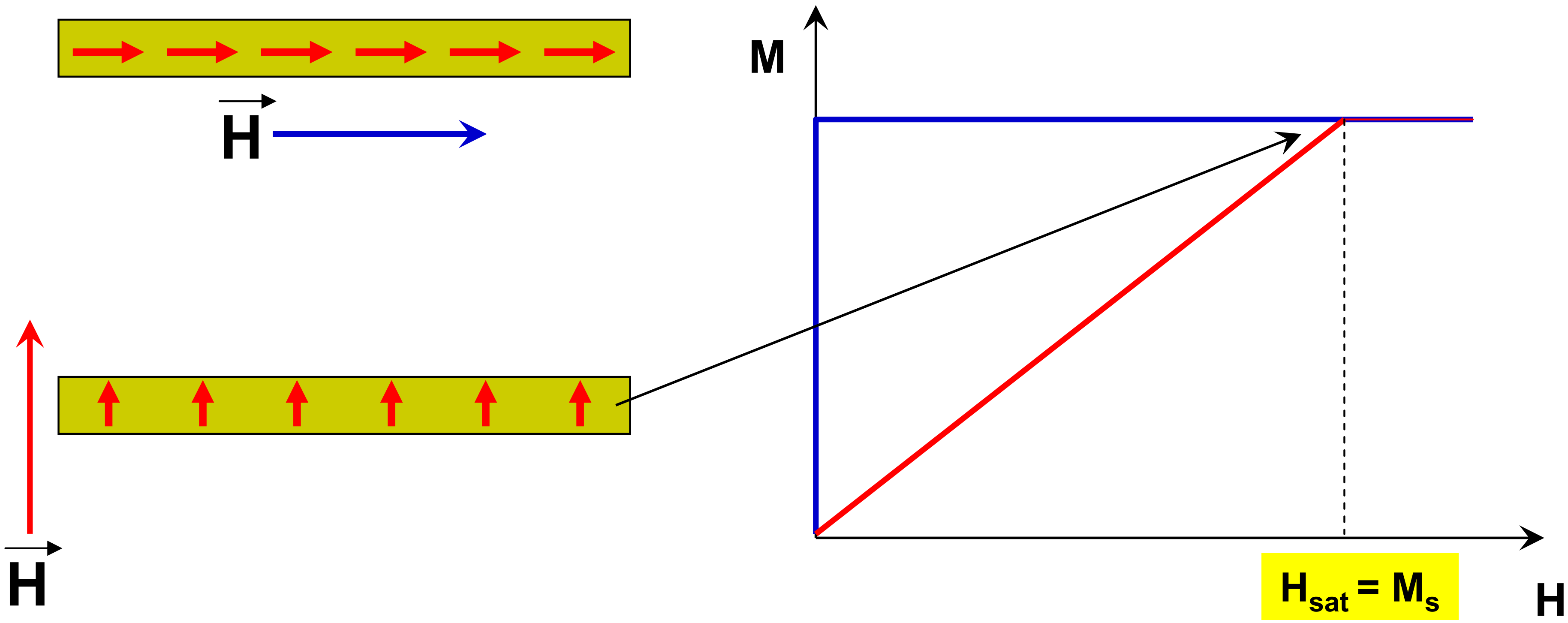


$M_s(T)$

Case study:

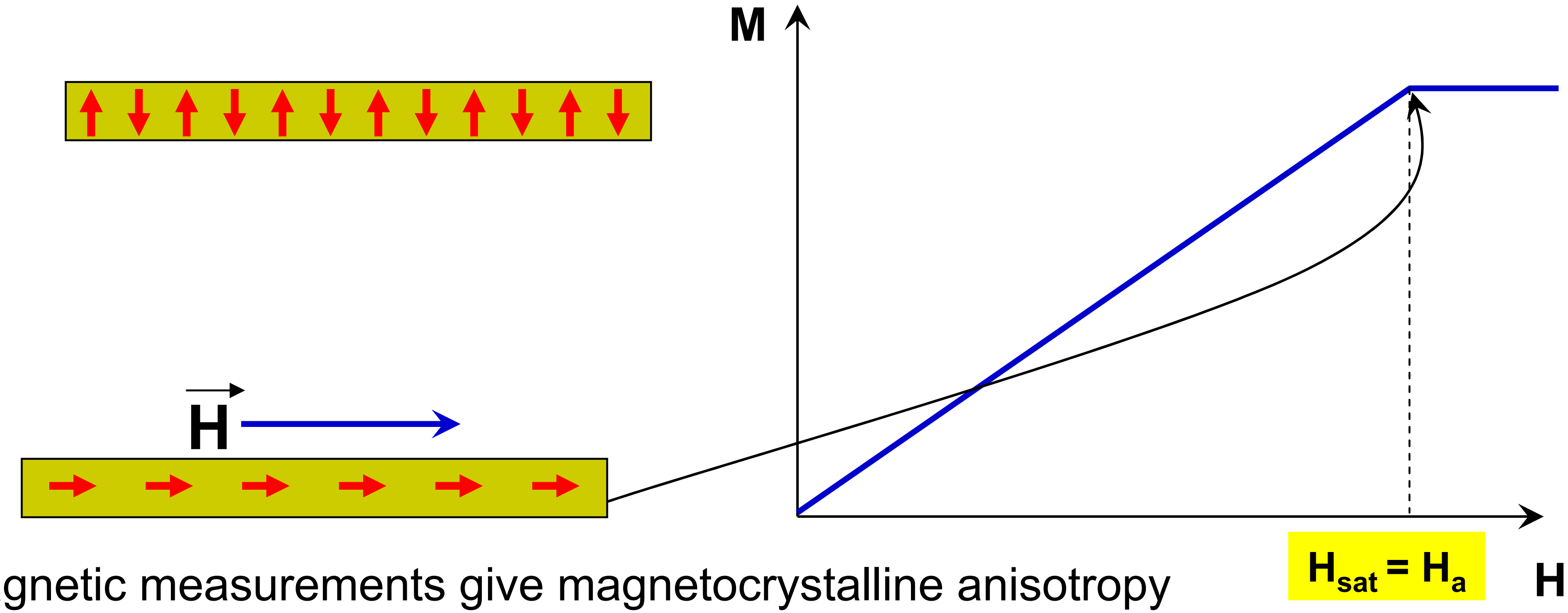
magnetic measurements on ***plate shape samples***

NO MAGNETOCRYSTALLINE ANISOTROPY

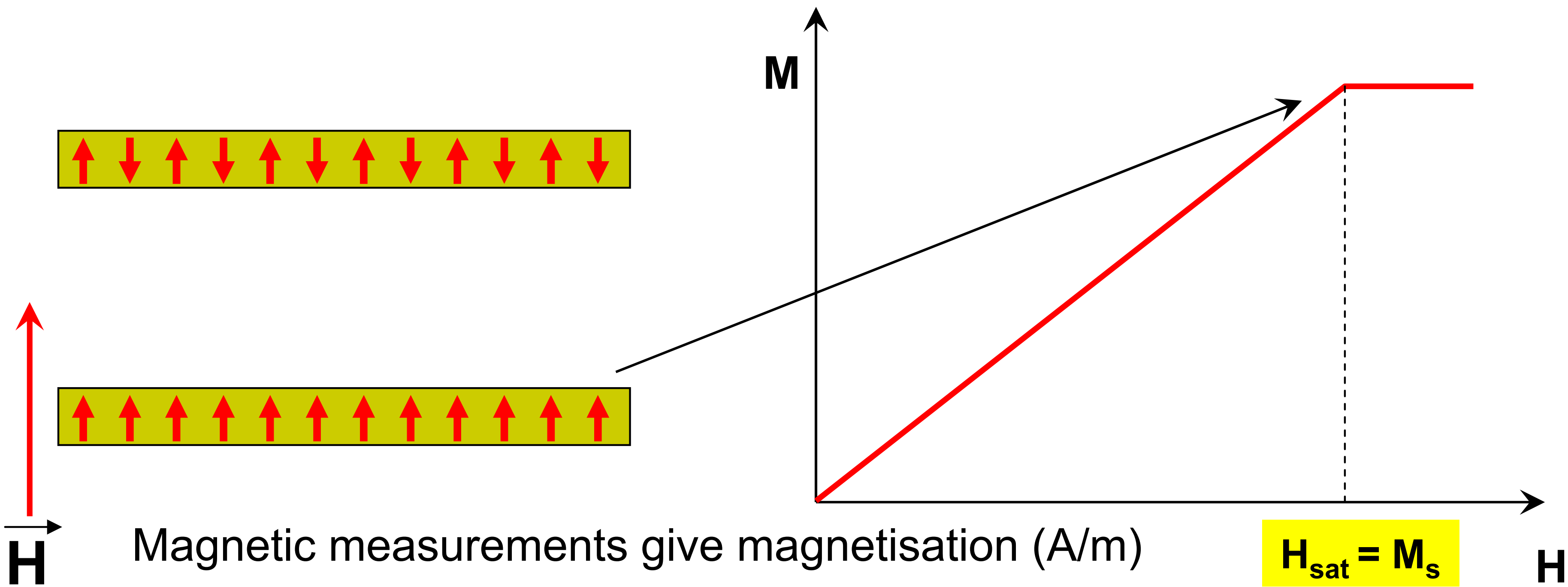


Magnetic measurements give magnetisation (A/m)

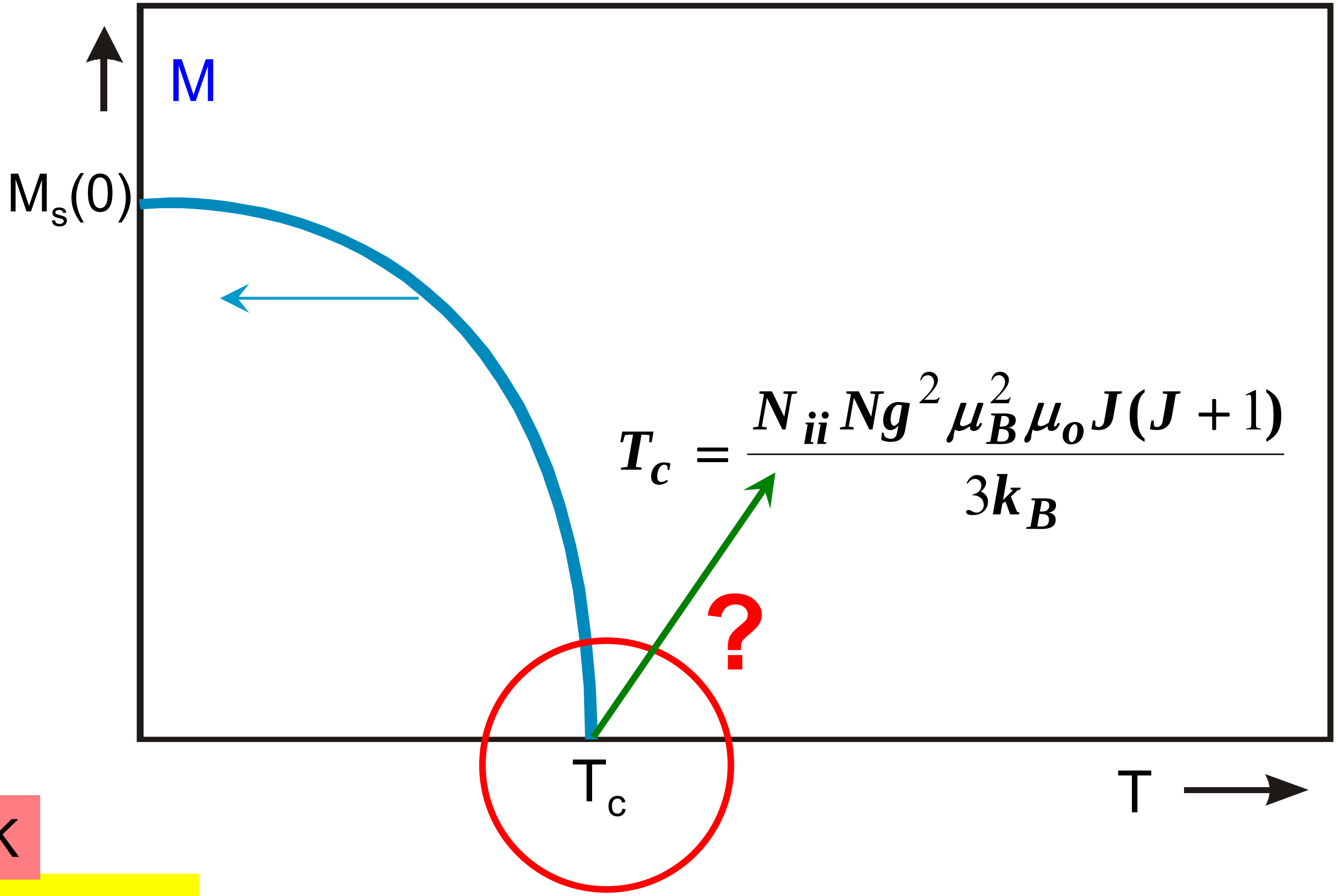
PERPENDICULAR ANISOTROPY



Magnetic measurements give magnetocrystalline anisotropy



Magnetic measurements give magnetisation (A/m)



$T \rightarrow 0K$

$M_s(0) = g_J \mu_B J_0$

For the rare earth (Gd for example): $J_0 = J_p$

For **3d transition metals** (Fe, Co, Ni…), the orbital moment is blocked by crystalline field:

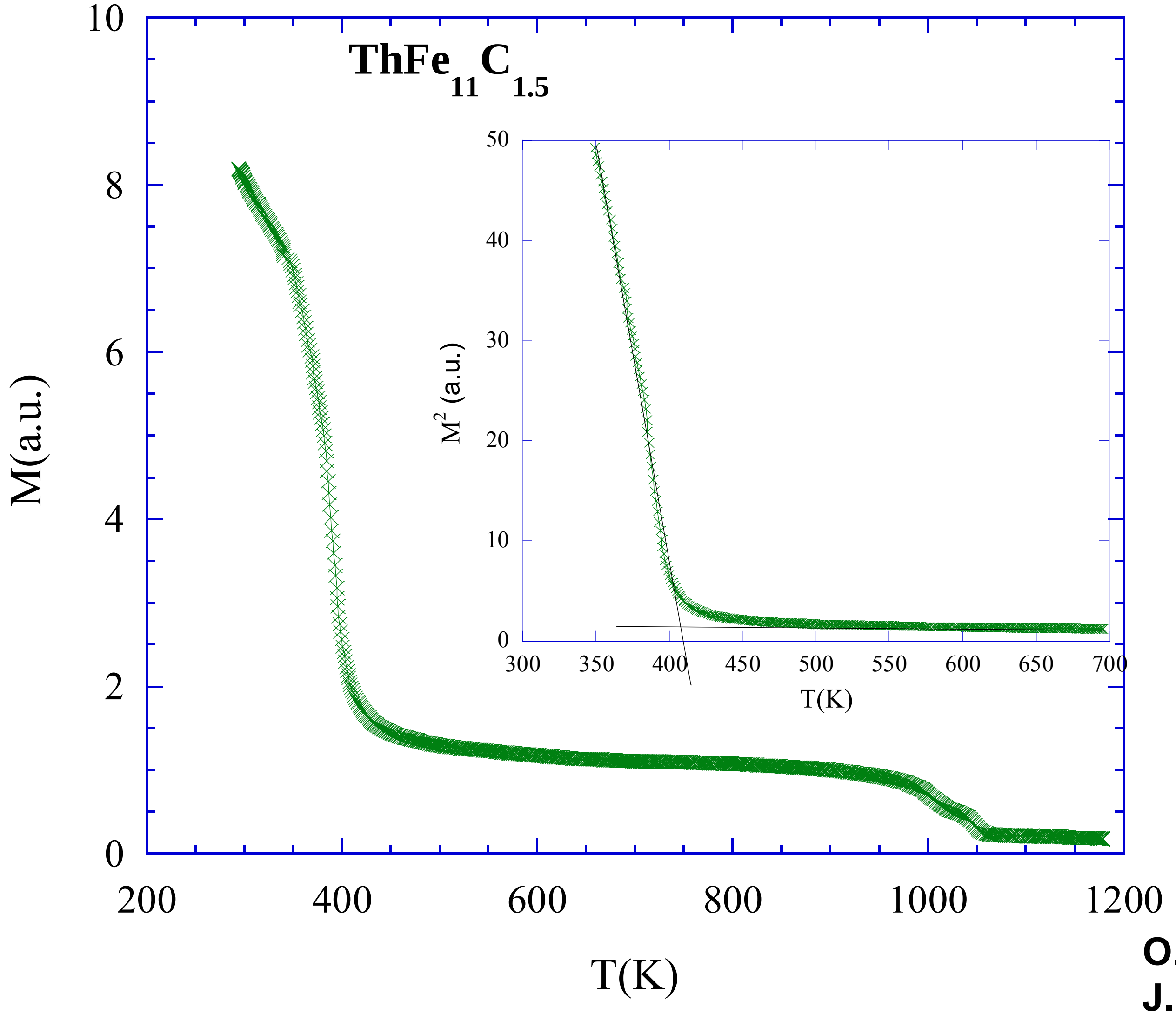
$T \rightarrow 0K$

$M_s(0) = g_J \mu_B S_0$

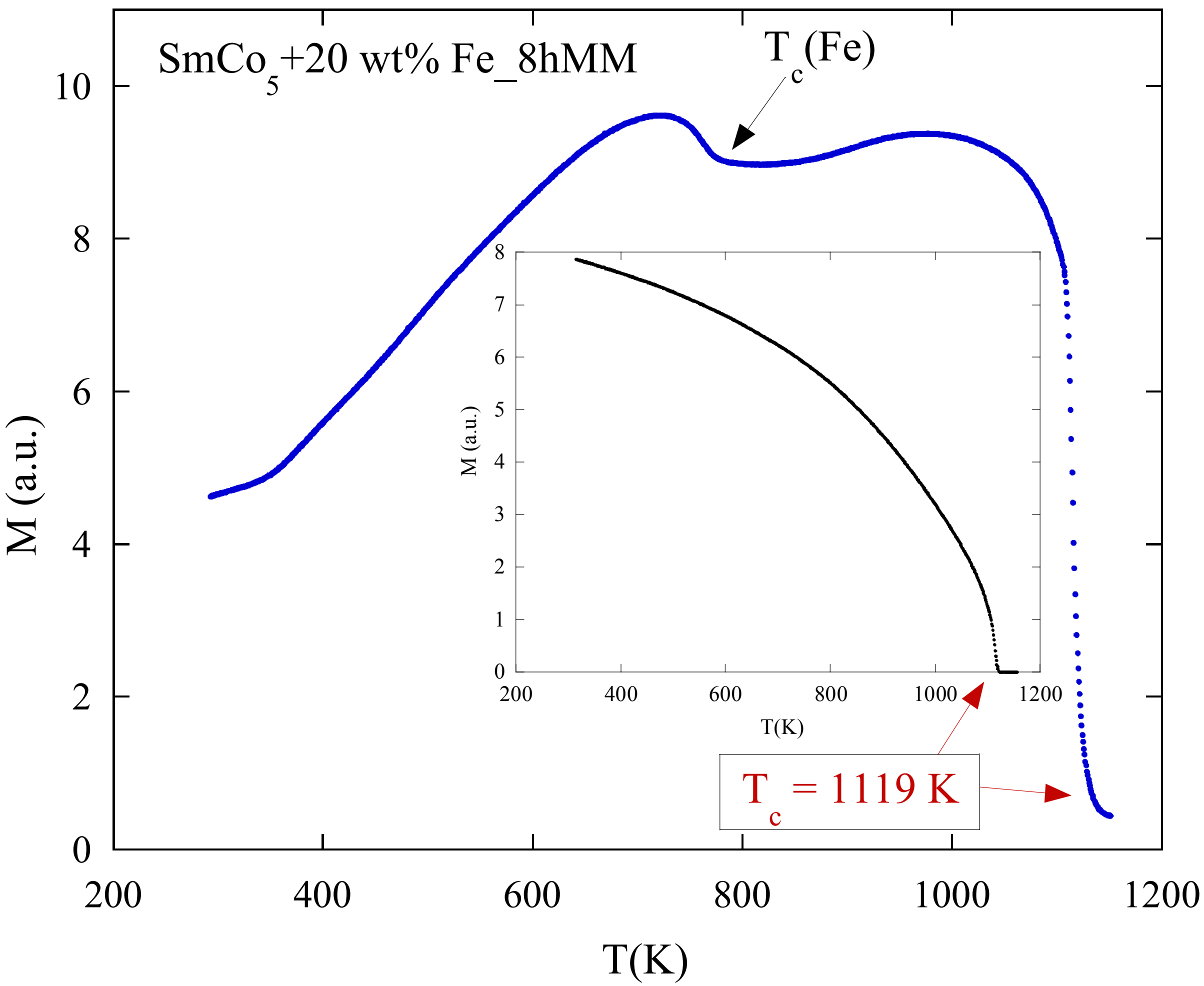
Curie temperature evaluation

$T \rightarrow T_c$; $T < Tc$

$$\left[\frac{M(T)}{M(0)}\right]^2 = \frac{10}{3} \cdot \frac{(J+1)^2}{J^2 + (J+1)^2}\left(1 - \frac{T}{T_c}\right)$$



O. Isnard, V. Pop, K.H.J. Buschow,
J. Magn. Magn. Mat. 256 (2003) 133


SmCo5+20 wt% Fe_8hMM
Tc(Fe)
Tc = 1119 K
M (a.u.)
T(K)
0
2
4
6
8
10
200
400
600
800
1000
1200
M (a.u.)
T(K)
0
1
2
3
4
5
6
7
8
200
400
600
800
1000
1200

In the low magnetisation region - for example $T \to Tc$; $T < Tc$

$$F_m(M) = a\frac{M^2}{2} + b\frac{M^4}{4} + \cdots - \mu_0 MH$$

$$\frac{dF_m}{dM} = 0 \Rightarrow aM + bM^3 = \mu_0 H \quad \text{or} \quad M^2 = \frac{M}{H}\frac{\mu_0}{b} - \frac{a}{b}$$

molecular field approximations:

$$\frac{\mu_0 N_{ii}(T - T_c)}{T_c} M + \frac{\mu_0 3(2J^2 + 2J + 1)T}{10 M_0^2 (J+1)^2 C} M^3 = \mu_0 H$$

$H_m = N_{ii} M$

$N_{ii} = T_c / C$

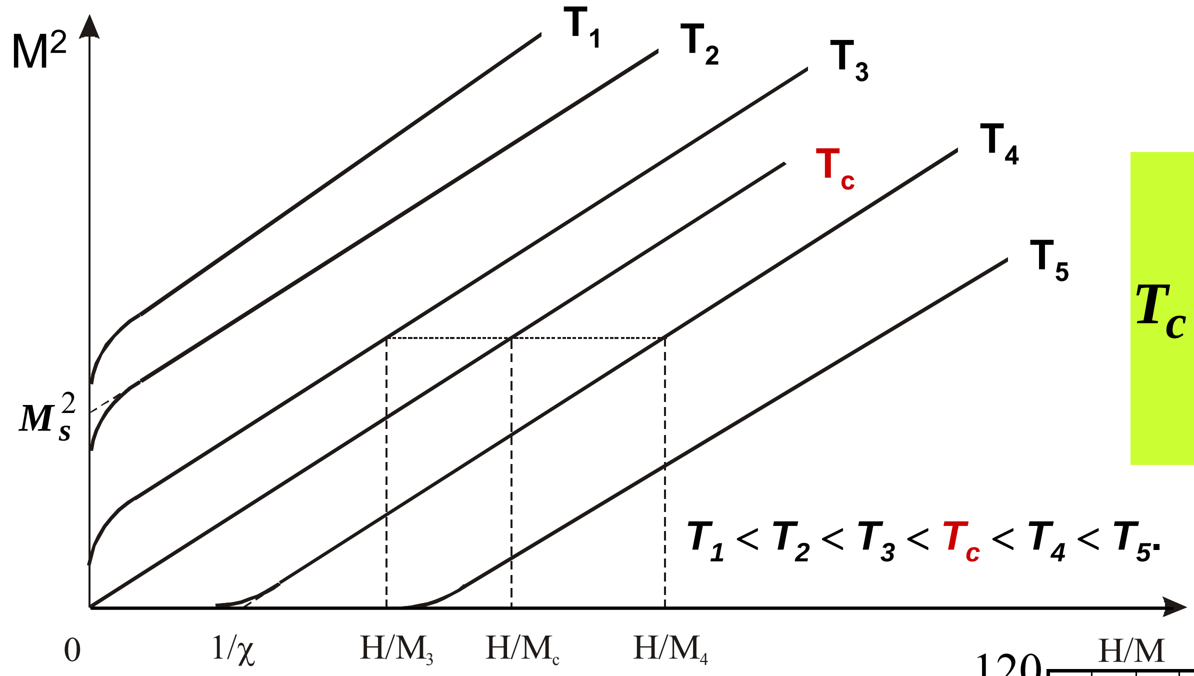
$$a = \frac{\mu_0 N_{ii}(T - T_c)}{T_c}$$

$T < Tc \rightarrow a < 0$

$T = Tc \rightarrow a = 0$

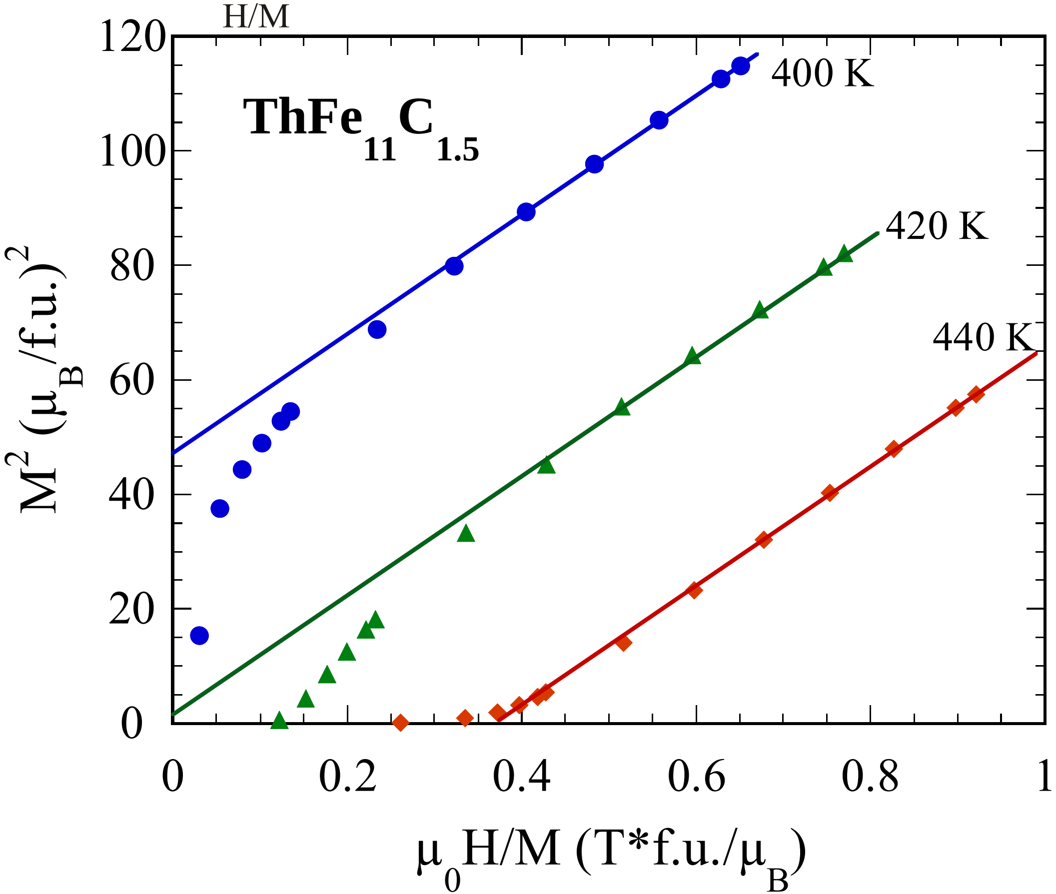
$T > Tc. \rightarrow a > 0$

$$b = \frac{\mu_0 3(2J^2 + 2J + 1)T}{10 M_0^2 (J+1)^2 C}$$

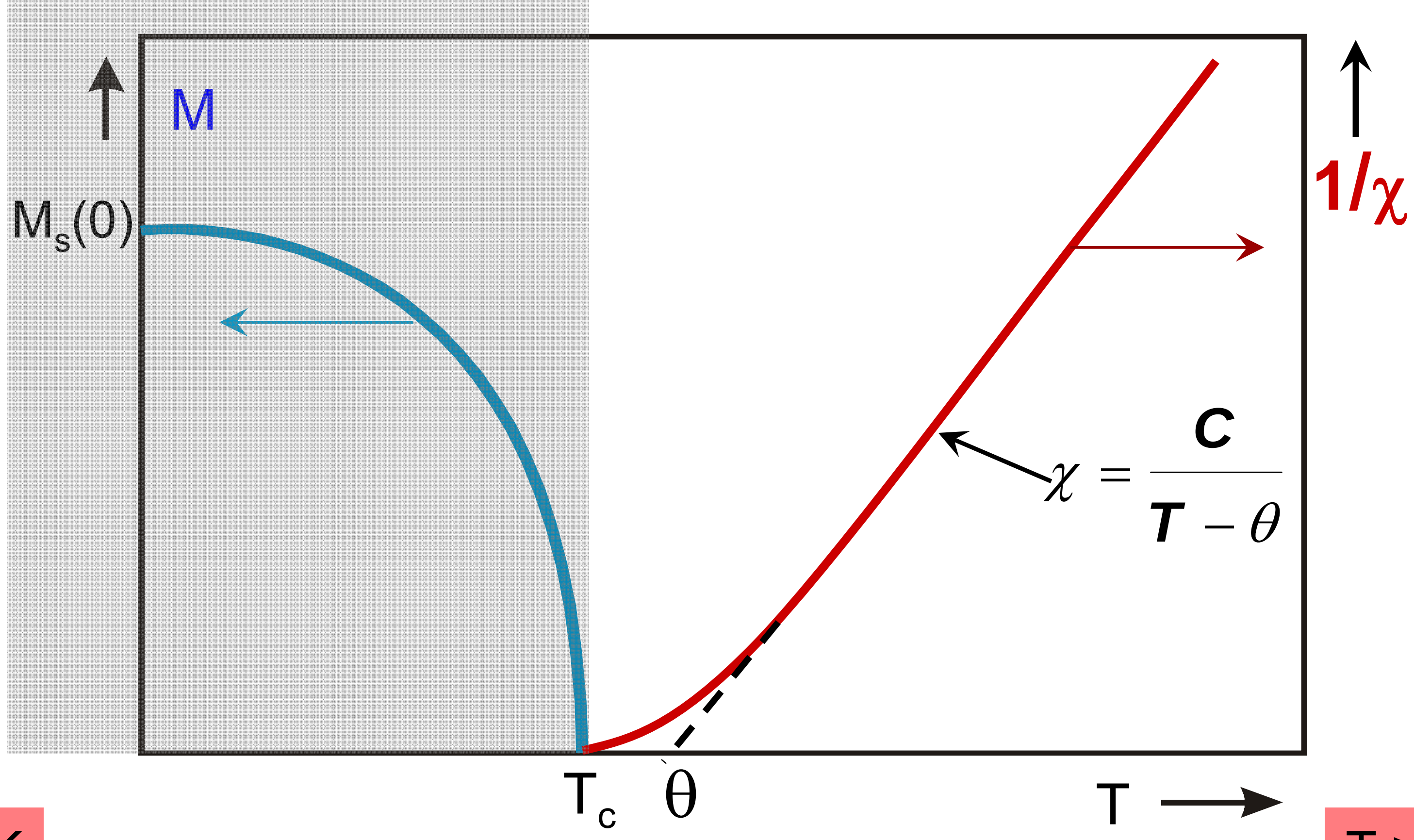


$$T_c = \frac{T_4\left(\frac{H}{M_c} - \frac{H}{M_3}\right) + T_3\left(\frac{H}{M_4} - \frac{H}{M_c}\right)}{\left(\frac{H}{M_4} - \frac{H}{M_3}\right)}$$

Arrott plot



O. Isnard, V. Pop, K.H.J. Buschow, J. Magn. Magn. Mat. 256 (2003) 133



T→0K

$M_s(0) = g_J\,\mu_B\,J_0$

T > T_c

$$\mu_{eff} = g\mu_B\sqrt{J_p(J_p+1)}$$

For the rare earth (Gd for example): **$J_0 = J_p$**

For 3d transition metals (Fe, Co, Ni…), the orbital moment is blocked by crystalline field:

T→0K

$M_s(0) = g_J\,\mu_B\,S_0$

$$r = \frac{S_p}{S_0} > 1$$

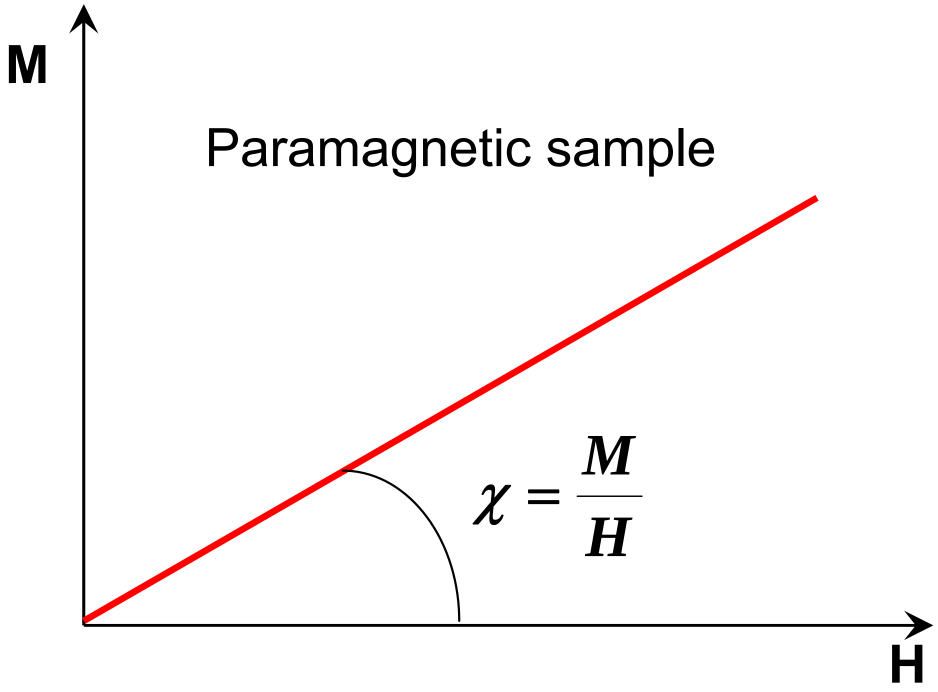
T > T_c

$$\mu_{eff} = g\mu_B\sqrt{S_p(S_p+1)}$$

r = 1 local moment limit
$r \rightarrow \infty$ total delocalisation limit

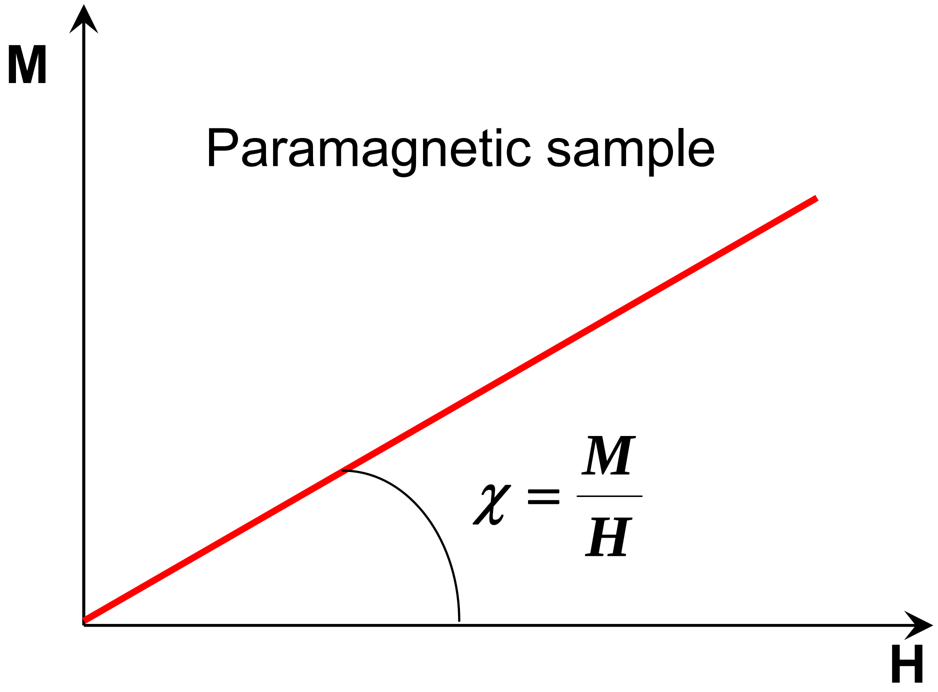
	Gd[1]	Fe[1]	Co[1]	$ThFe_{11}C_{1.5}$[2]	Fe_3C[3]	$HoCo_4Si$[4]	YCo_3B_2[5]
r	**1.00**	**1.01**	**1.32**	**1.5**	**1.69**	**2.03**	$\rightarrow\infty$

[1] P.R. Rhodes, E.P. Wolfarth, Proc. R. Soc. 273 (1963) 347.
[2] O. Isnard, V. Pop, K.H.J. Buschow, J. Magn. Magn. Mat. 256 (2003) 133
[3] D. Bonnenberg, K.A. Hempel, H.P.J. Wijn, Landolt-B.orsntein new series, Vol. III, 19a, Springer, Berlin, 1986, p. 142.
[4] O. Isnard, N. Coroian, V. Pop (unpublished)
[5] R. Ballou, E . Burzo, and V. Pop, J. Magn. Magn. Mat. 140-144 (1995) 945.



If there are some ferromagnetic impurity

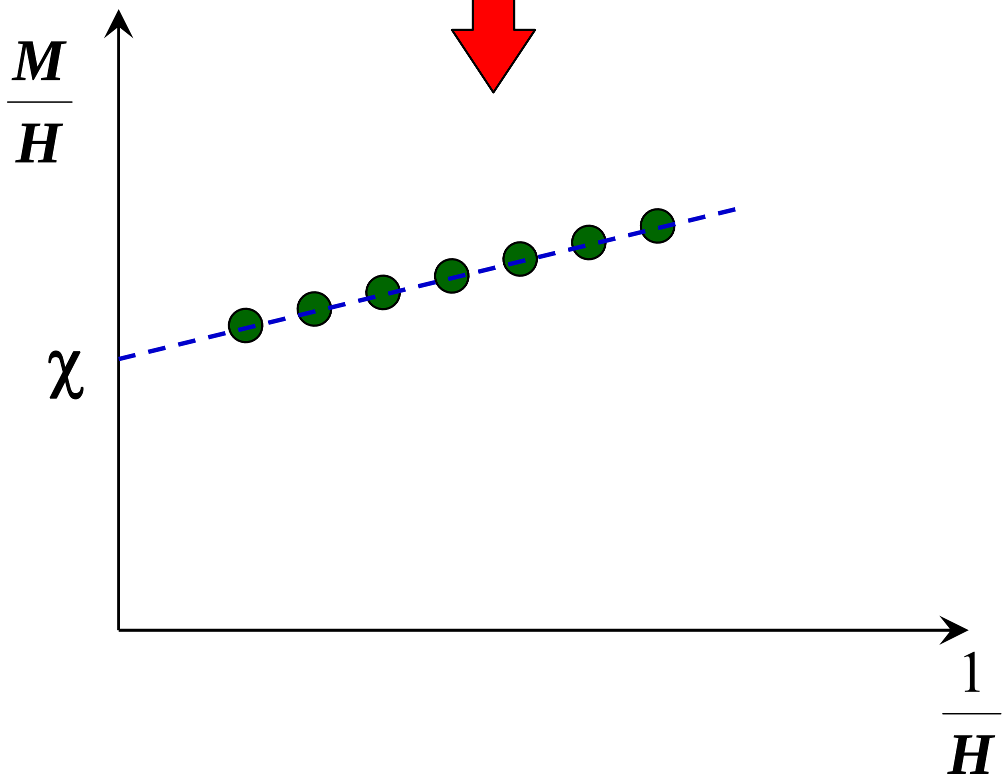
$$M = \chi H + cM_s$$

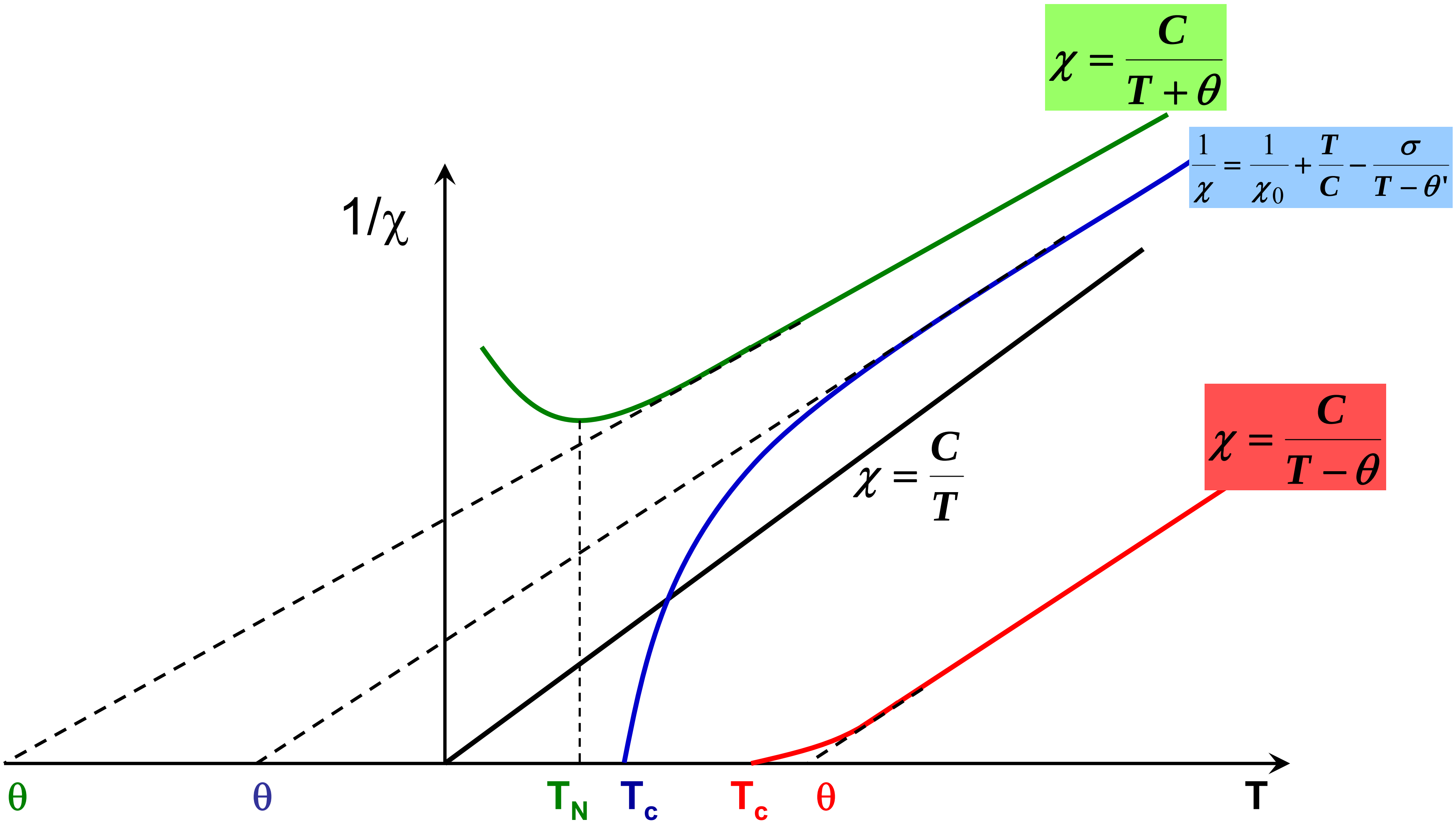


If there are some ferromagnetic impurity

$$M = \chi H + cM_s$$

$$\frac{M}{H} = \chi + c\frac{M_s}{H}$$



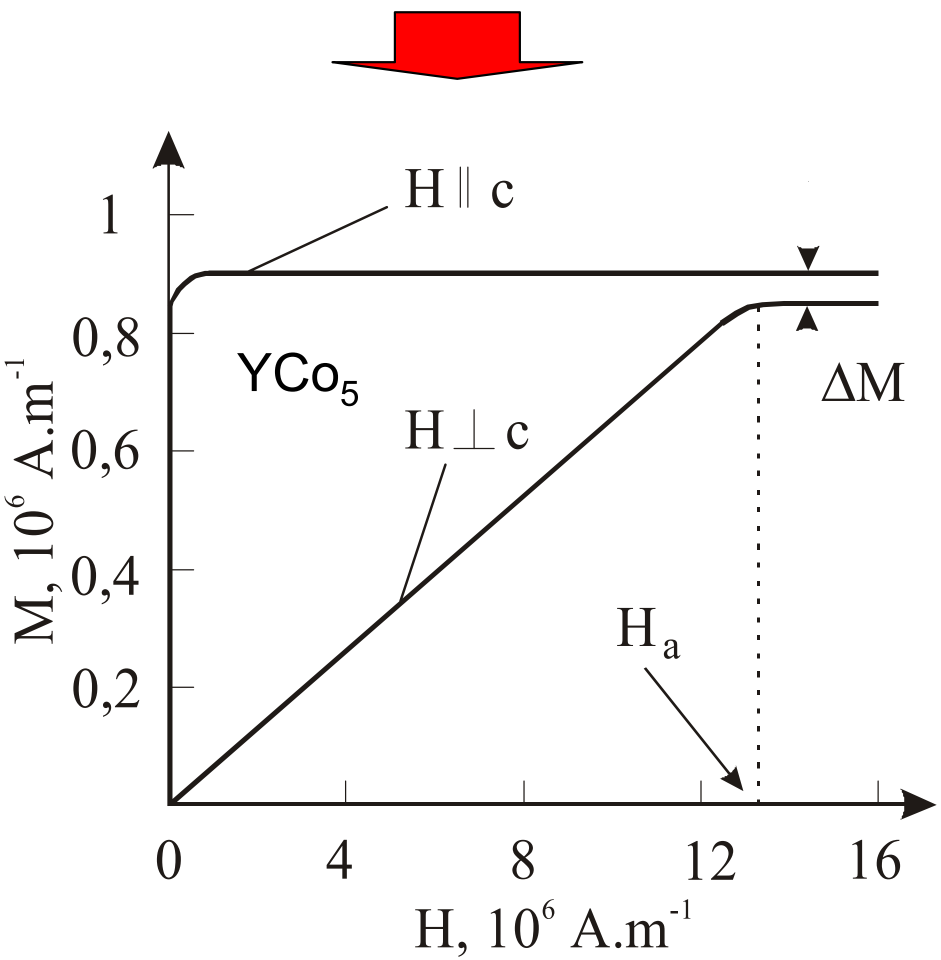


$\chi = \frac{C}{T+\theta}$
$\frac{1}{\chi} = \frac{1}{\chi_0} + \frac{T}{C} - \frac{\sigma}{T-\theta'}$
1/χ
$\chi = \frac{C}{T}$
$\chi = \frac{C}{T-\theta}$
θ
θ
T_N
T_c
T_c
θ
T

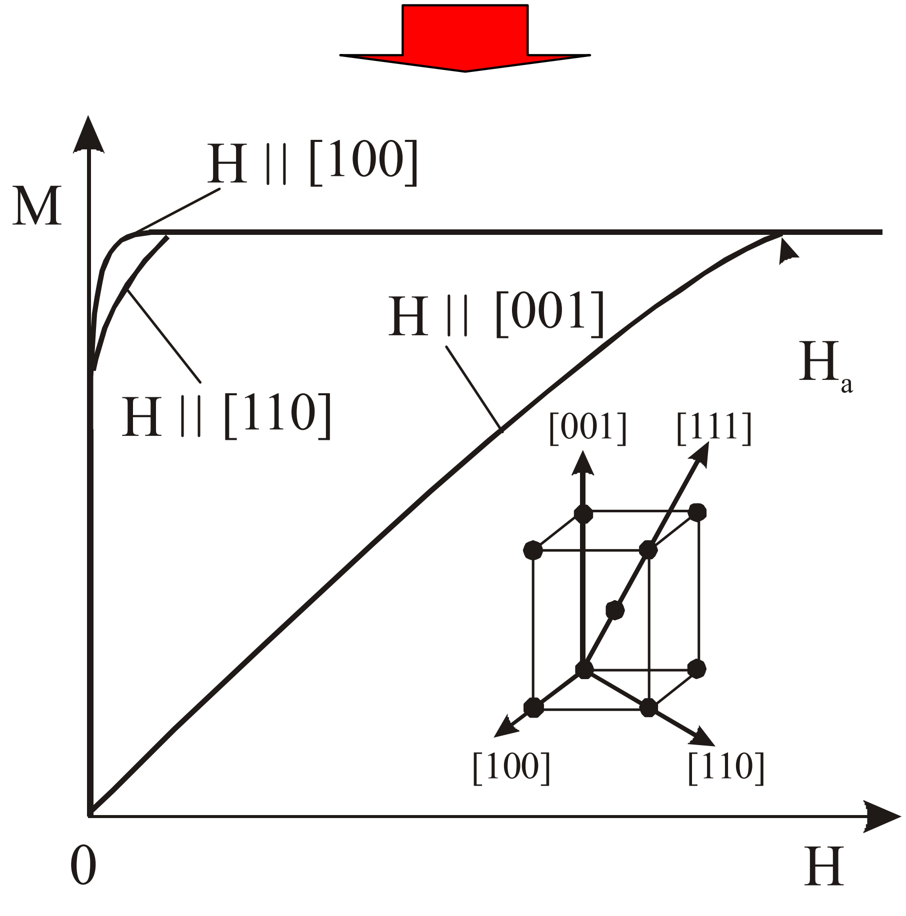
axial symmetry:

$$E_a \approx K_1 \sin^2 \theta$$

$K_1 > 0$



$K1 < 0$



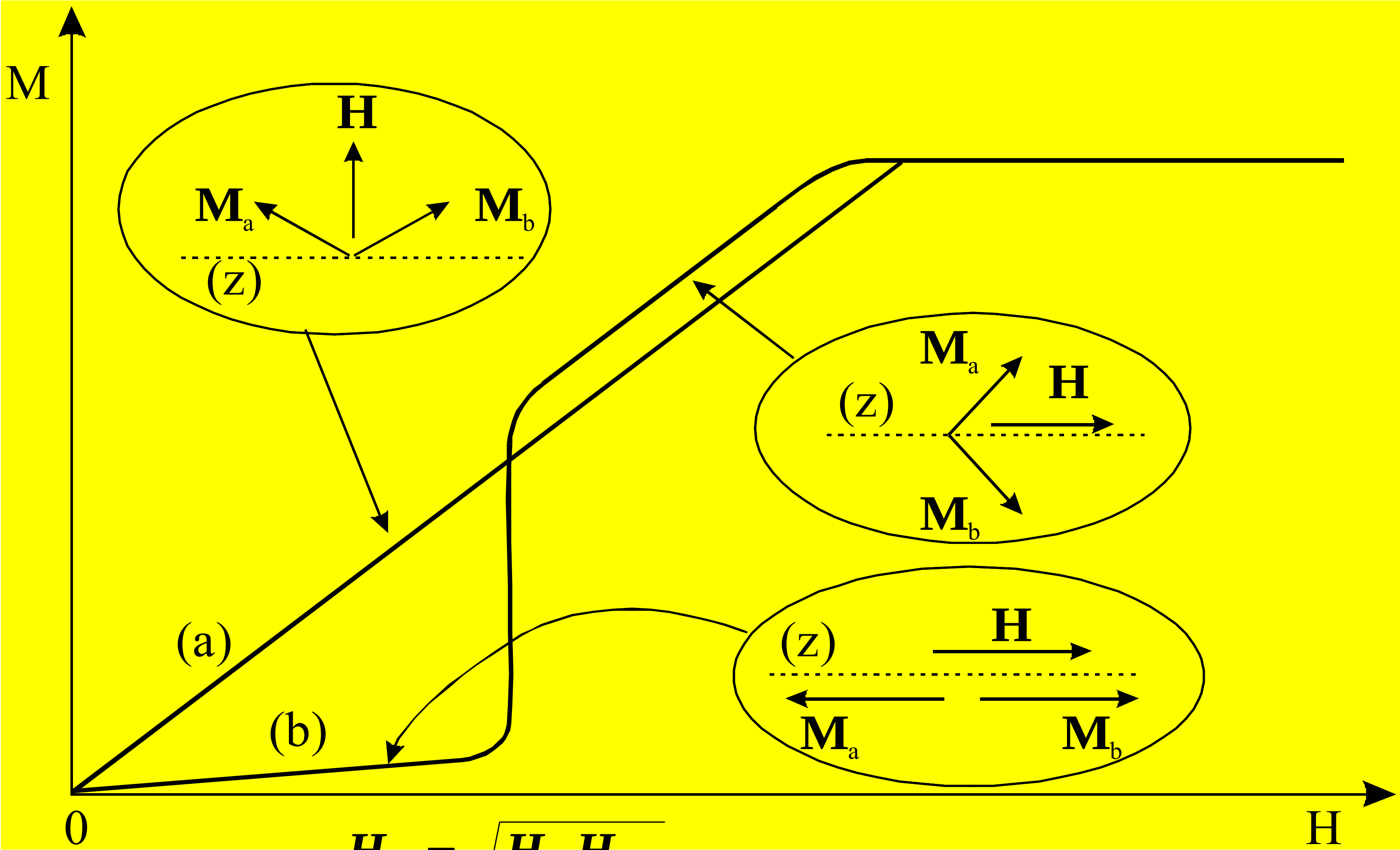
T < T_N, antiferromagnetic materials, $\chi_\perp > \chi_{||}$

Density of energy in magnetic field **H**,

$$E = -\chi\mu_0 H^2/2$$

low anisotropy energy

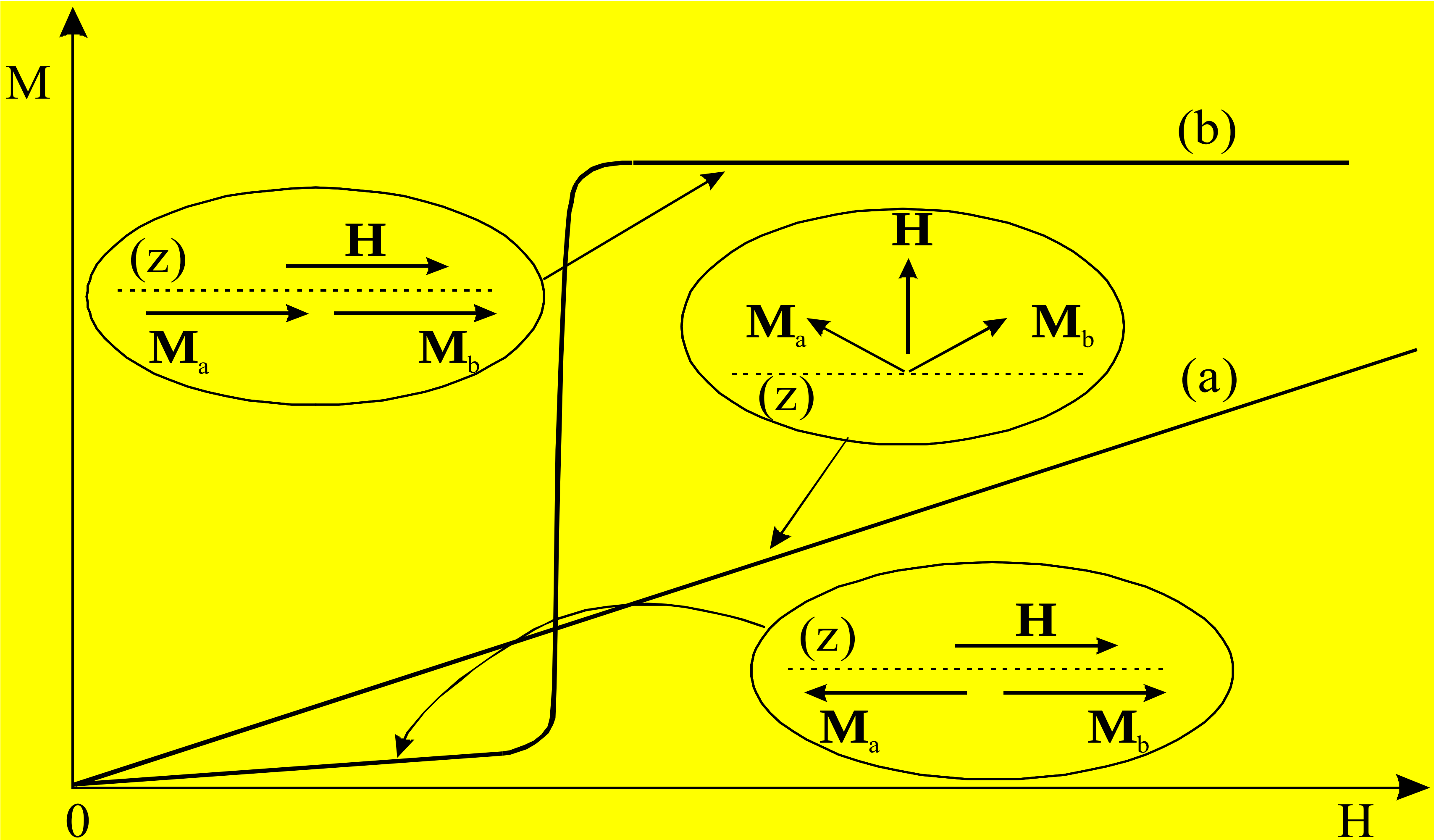
spin – flop **transition**



$$H_c = \sqrt{H_a H_{ex}}$$

E. Du Trémolet de Lacheisserie (editor),
Magnetisme, Presses Universitaires de Grenoble, 1999

High anisotropy energy
spin – flip transition

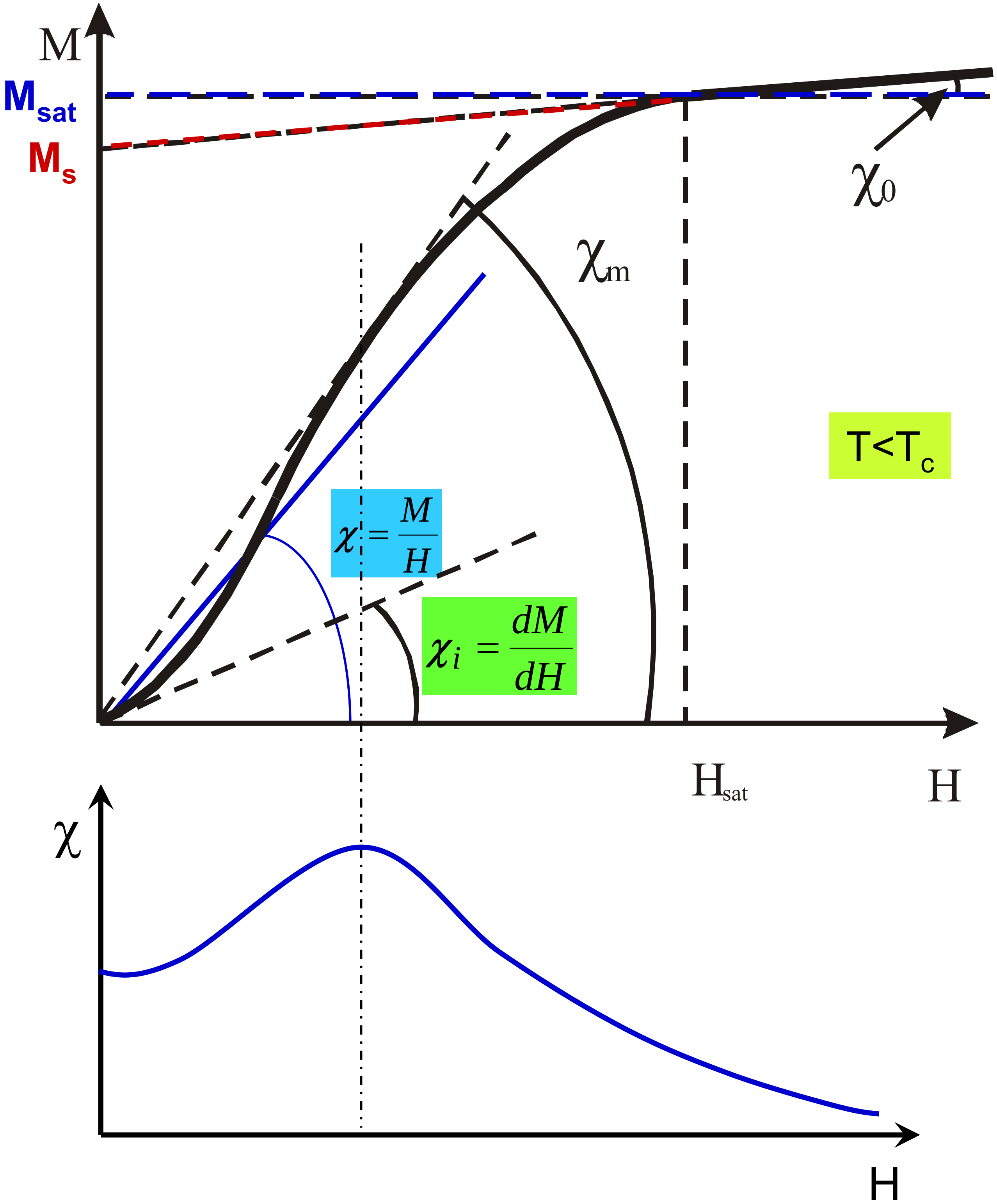


$$H_c \approx H_{ex}$$

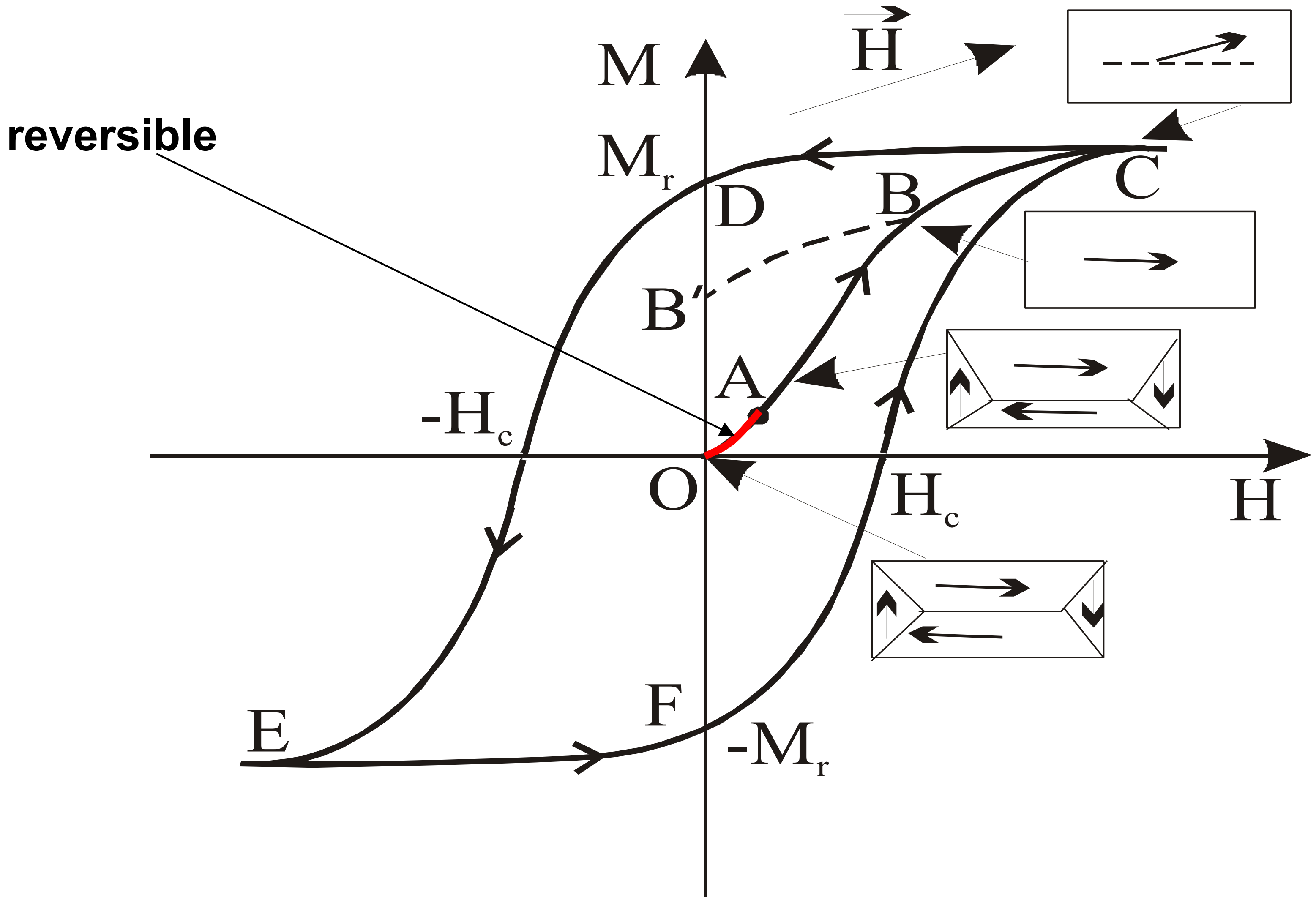
spin–flip
and
spin–flop

} metamagnetic transition

also in ferrimagnetic materials



M
M_{sat}
M_s
χ_0
χ_m
T<T$_c$
$\chi = \frac{M}{H}$
$\chi_i = \frac{dM}{dH}$
H_{sat}
H
χ
H

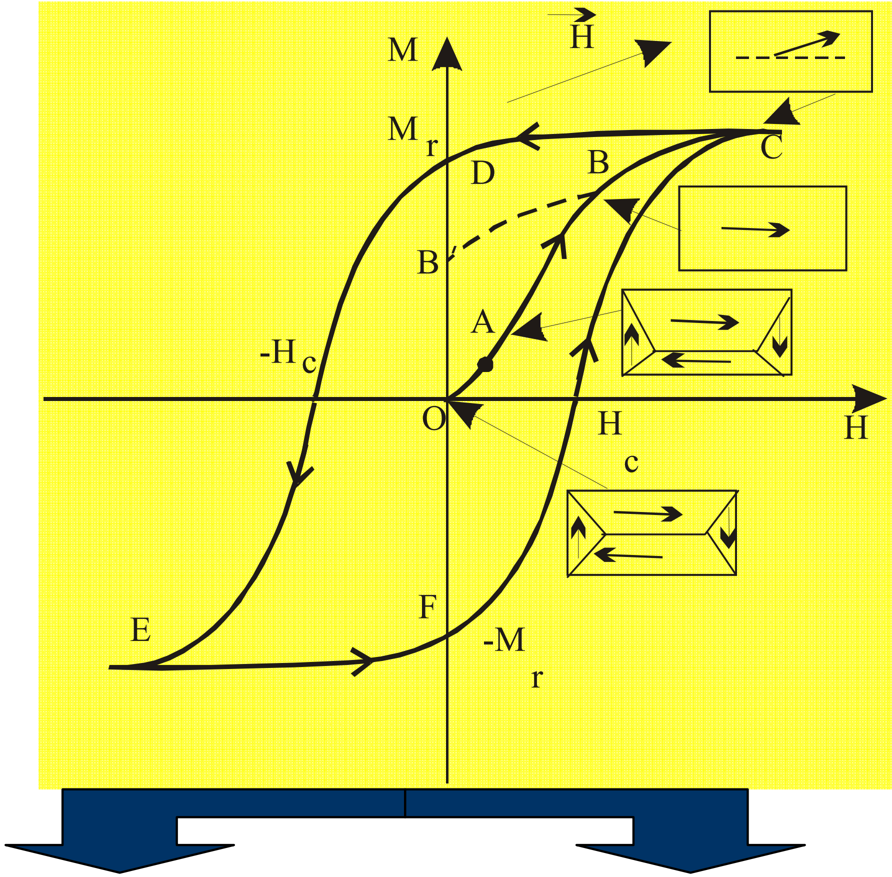


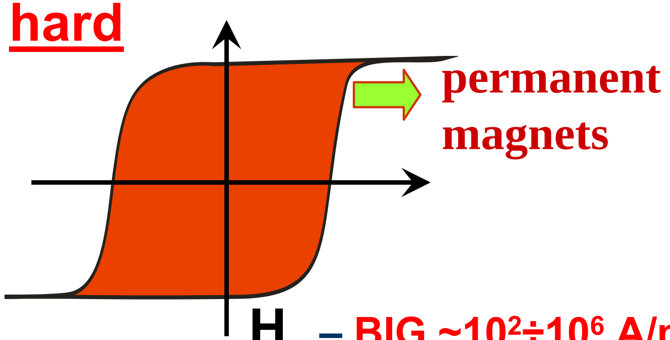
reversible
M
M_r
D
B
C
B′
A
$\vec{H}$
$-H_c$
O
H_c
H
E
F
$-M_r$

$$\vec{B} = \mu_0\left(\vec{H} + \vec{M}\right)$$

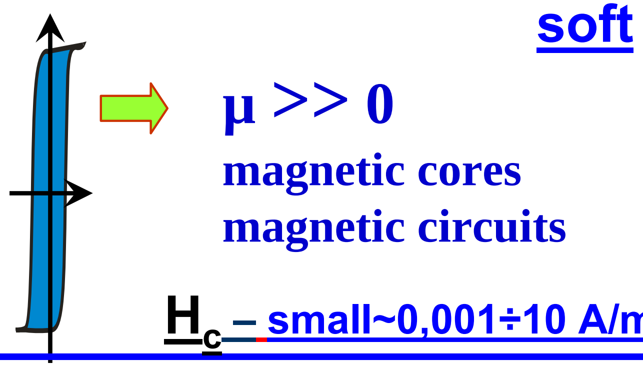
Fundamental research ➡ **M**

Application research ➡ **B**





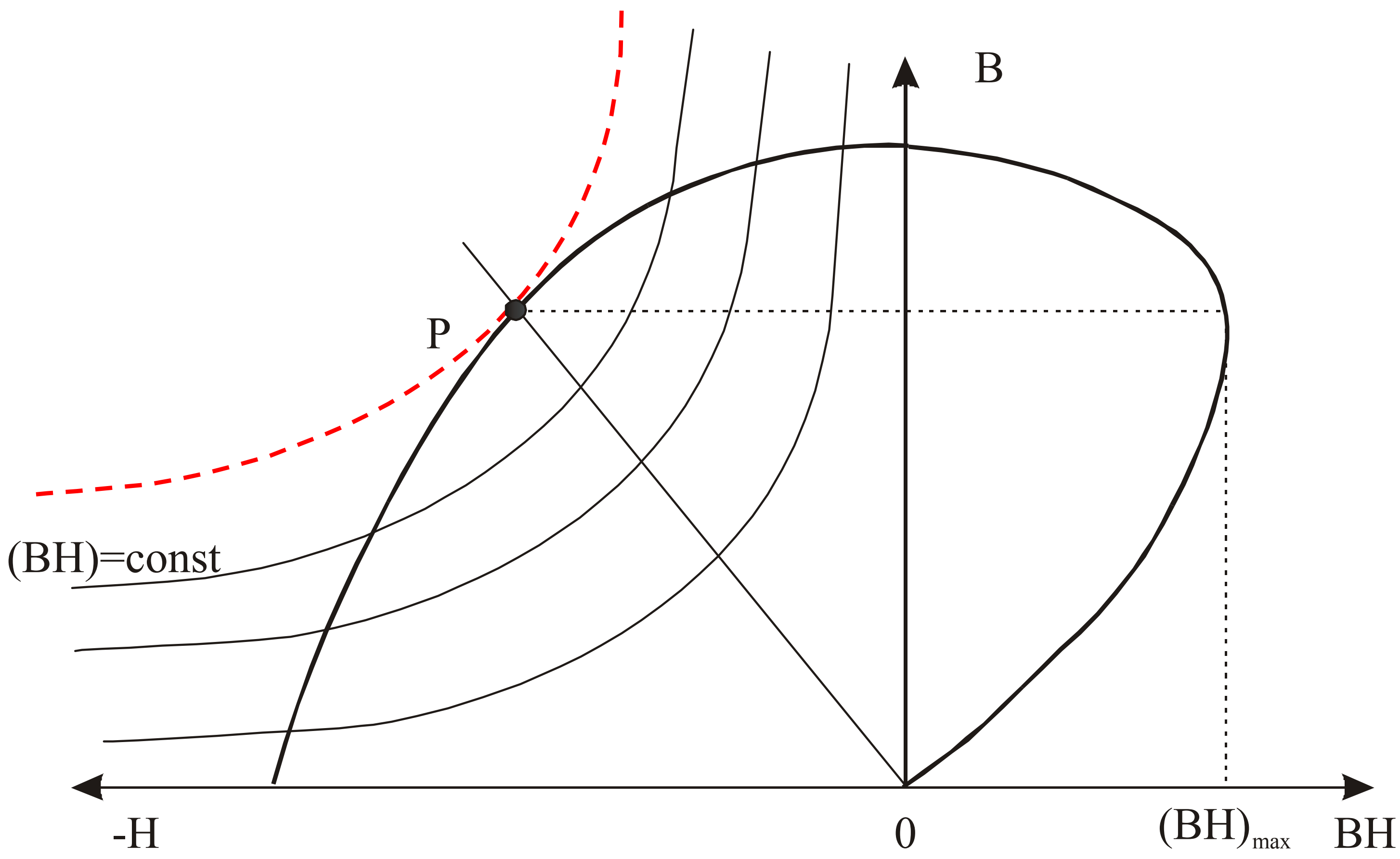
H_c – BIG ~$10^2 \div 10^6$ A/m



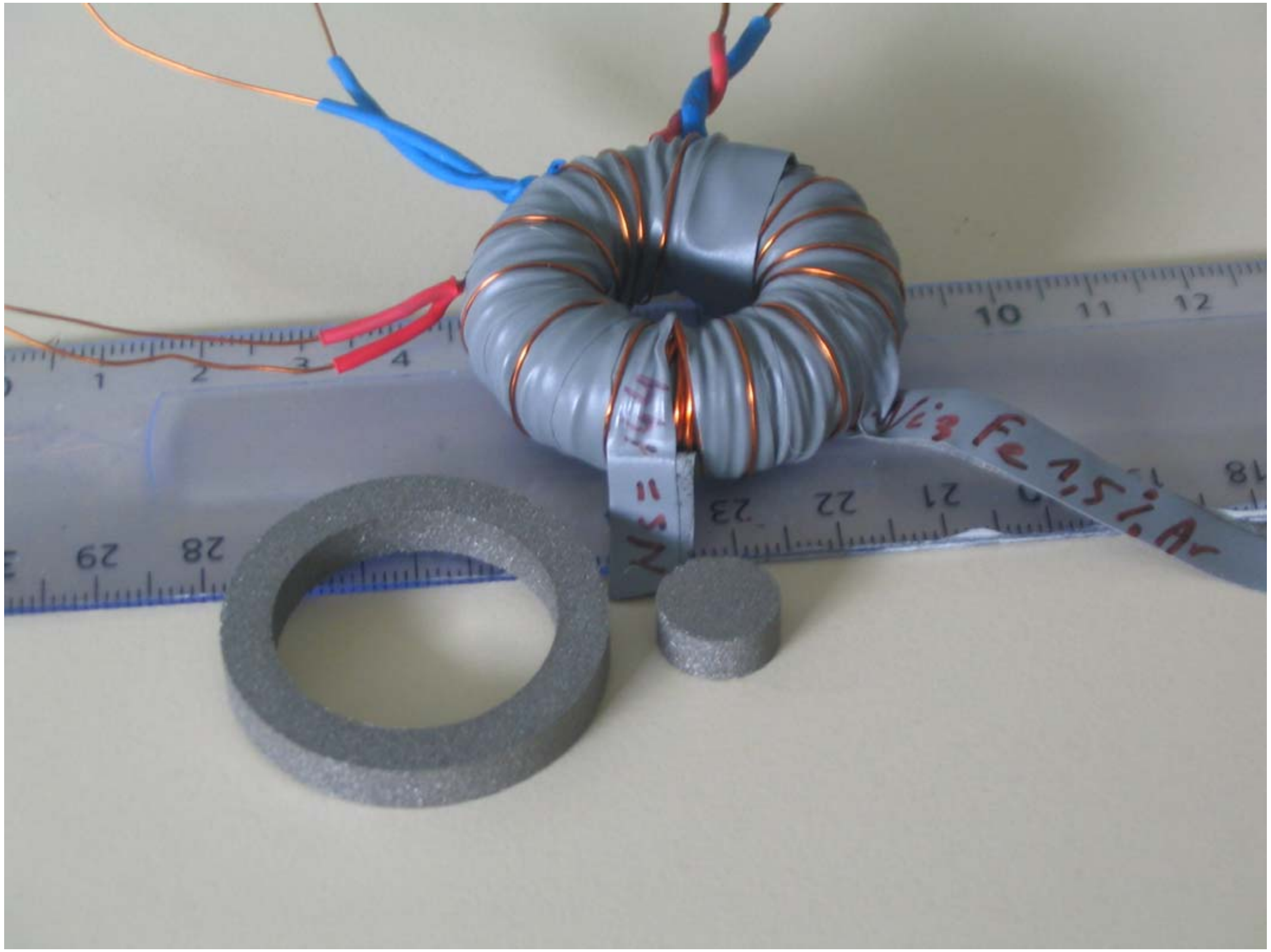
H_c – small~0,001÷10 A/m

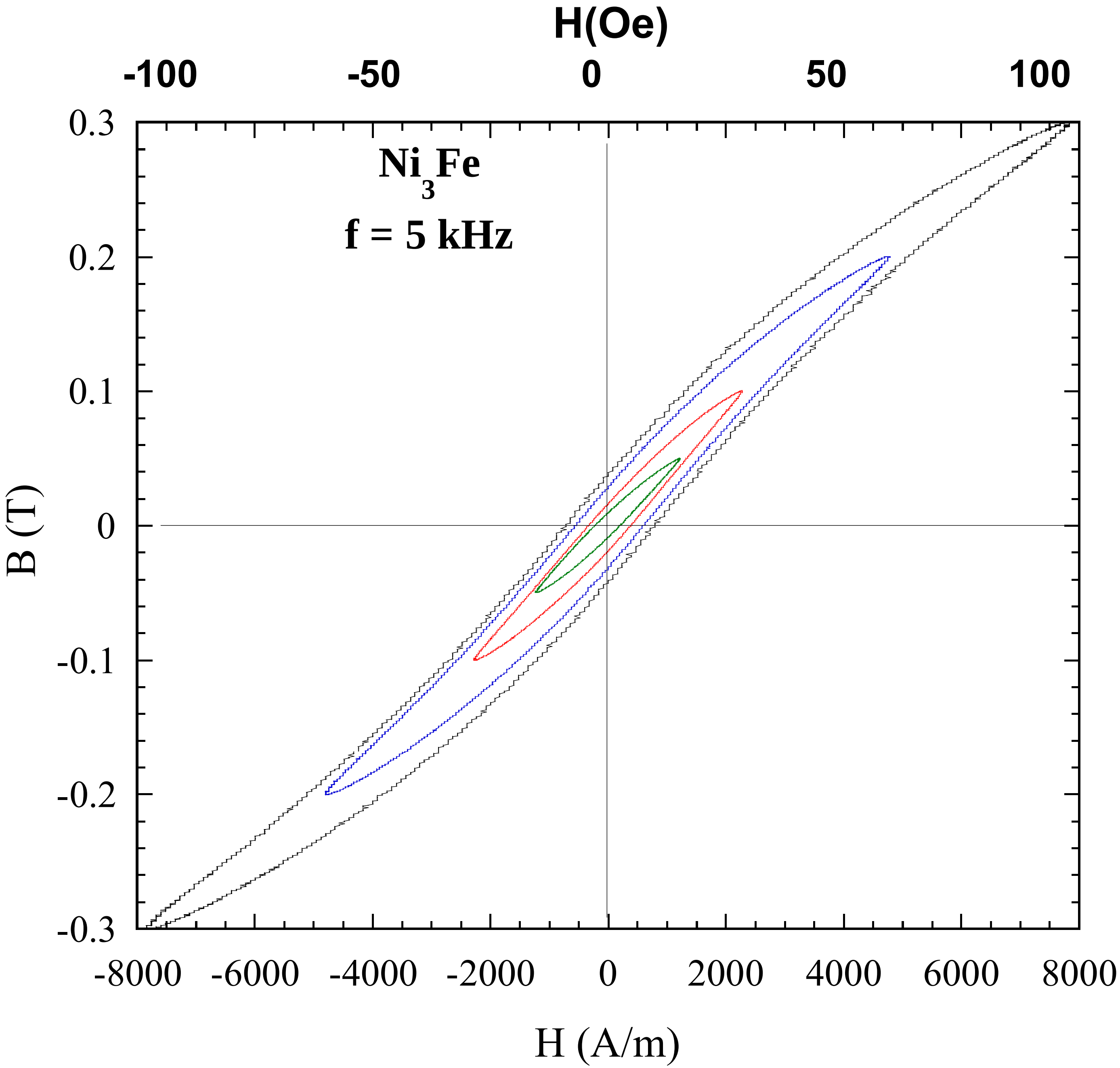
Curie temperature, T_c

Hard magnetic materials

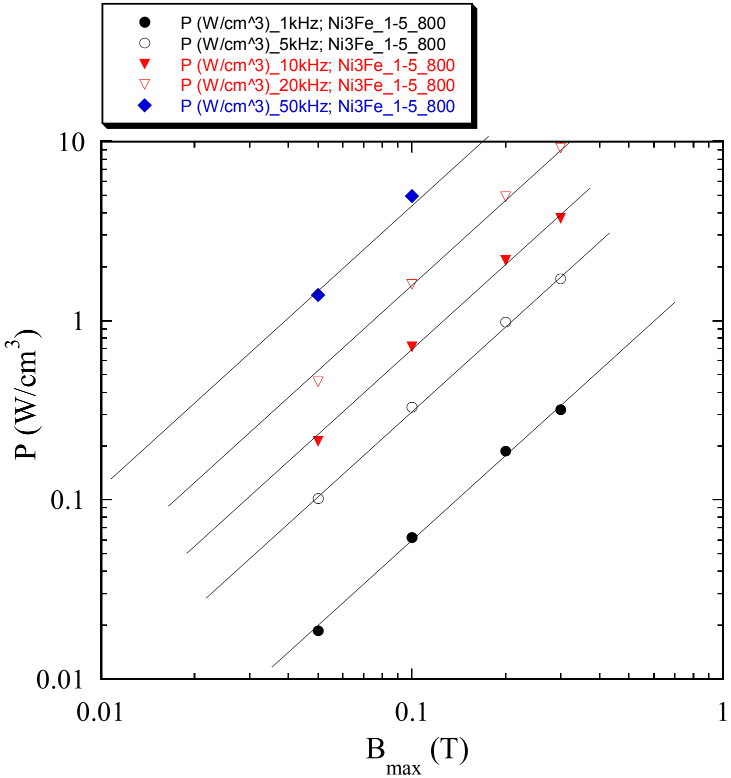


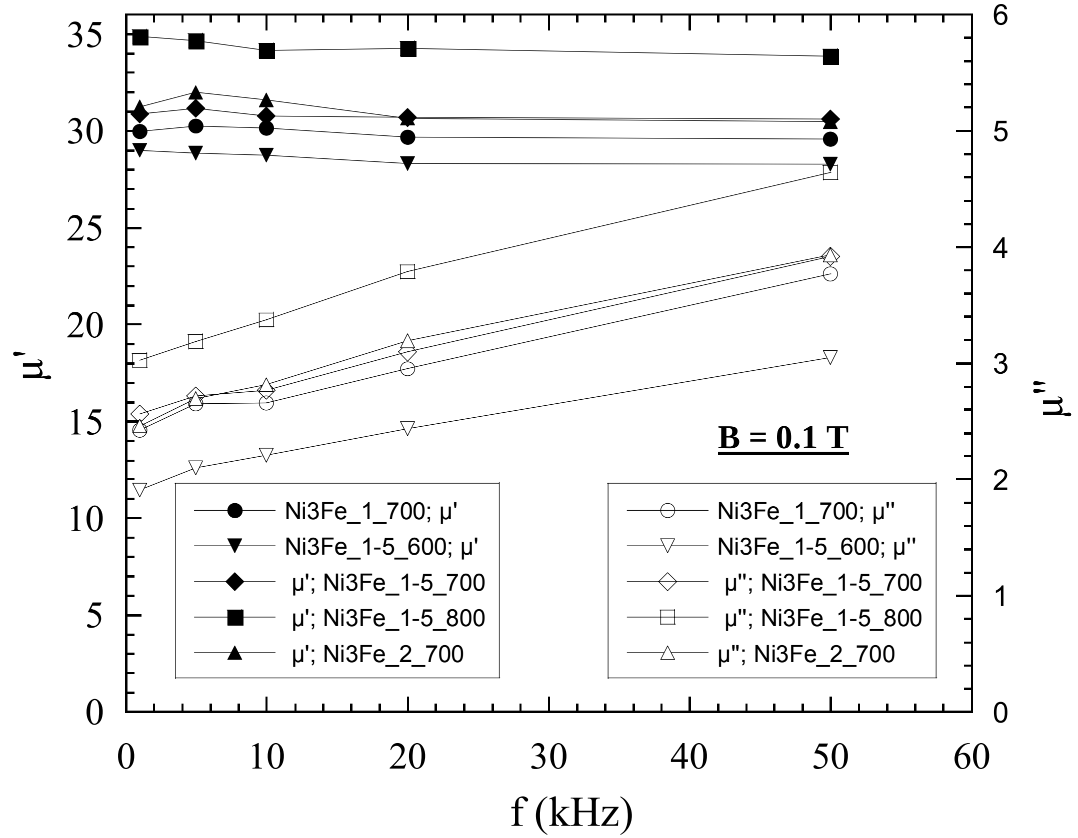
Hysteresis measurements in soft magnetic materials

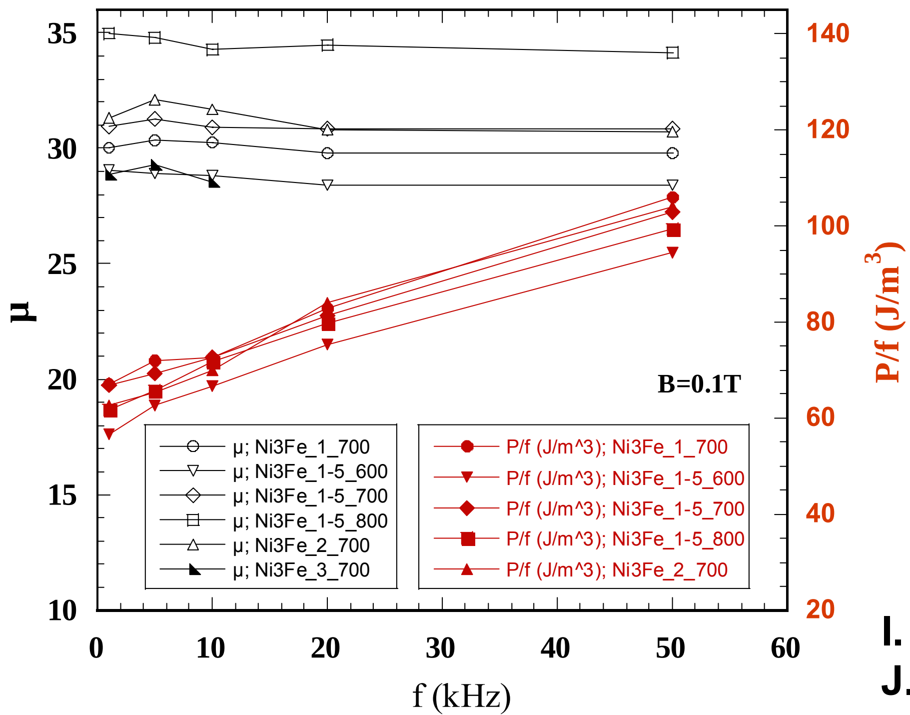




$H_{SI} = 10^3/4\pi \cdot H_{CGS} \approx 80\ H_{CGS}$

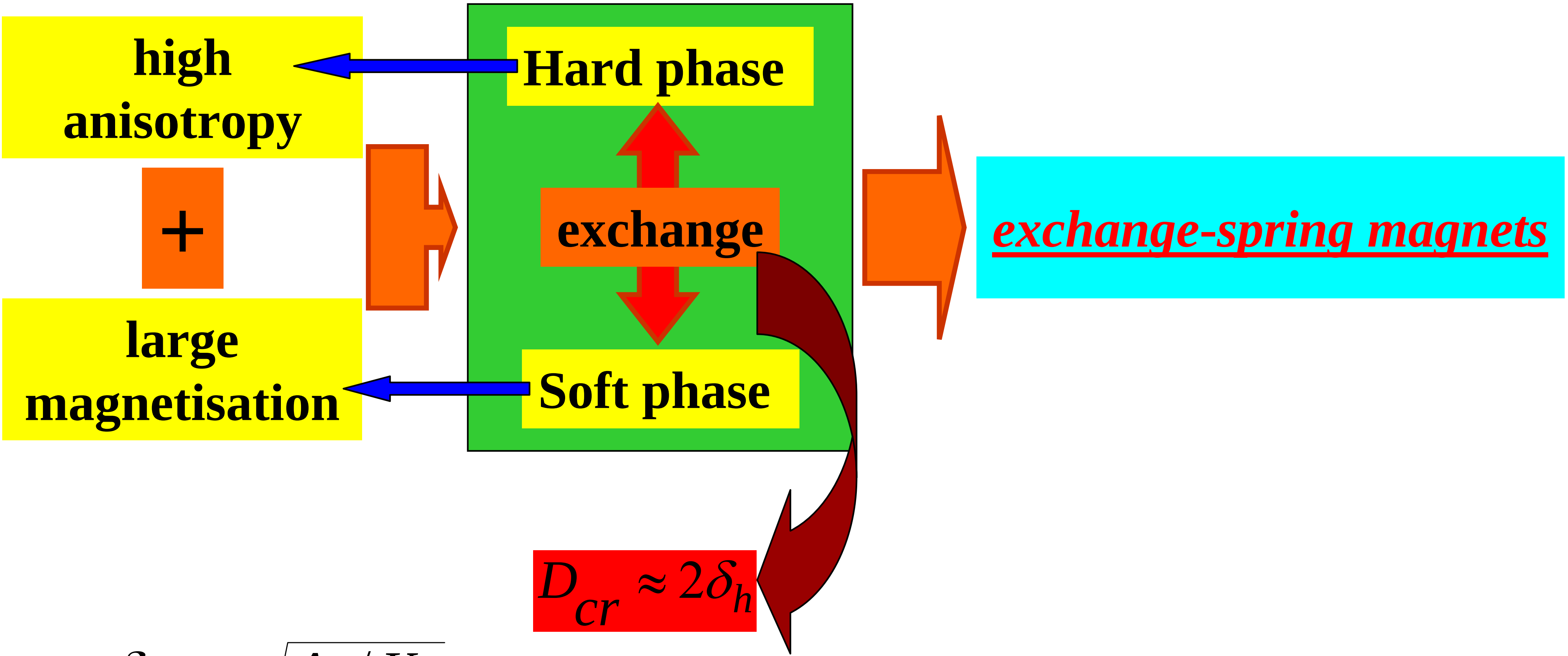






I. Chicinas, O. Geoffroy, O. Isnard, V. Pop
J. Magn. Magn. Mat. 290-291 (2005) 1531

Hard Magnetic Nanocrystalline Materials



$$\delta_h = \pi\sqrt{A_h / K_h}$$

$\boldsymbol{D}_{\mathbf{cr}}$ = soft phase critical dimension

$\boldsymbol{\delta}_{\mathbf{h}}$ = width of domain wall in the hard phase

$\boldsymbol{A}_{\mathbf{h}}$ and $\boldsymbol{K}_{\mathbf{h}}$ are the exchange and anisotropy constants

Hard Magnetic Nanocrystalline Materials

Large reversible demagnetization curve

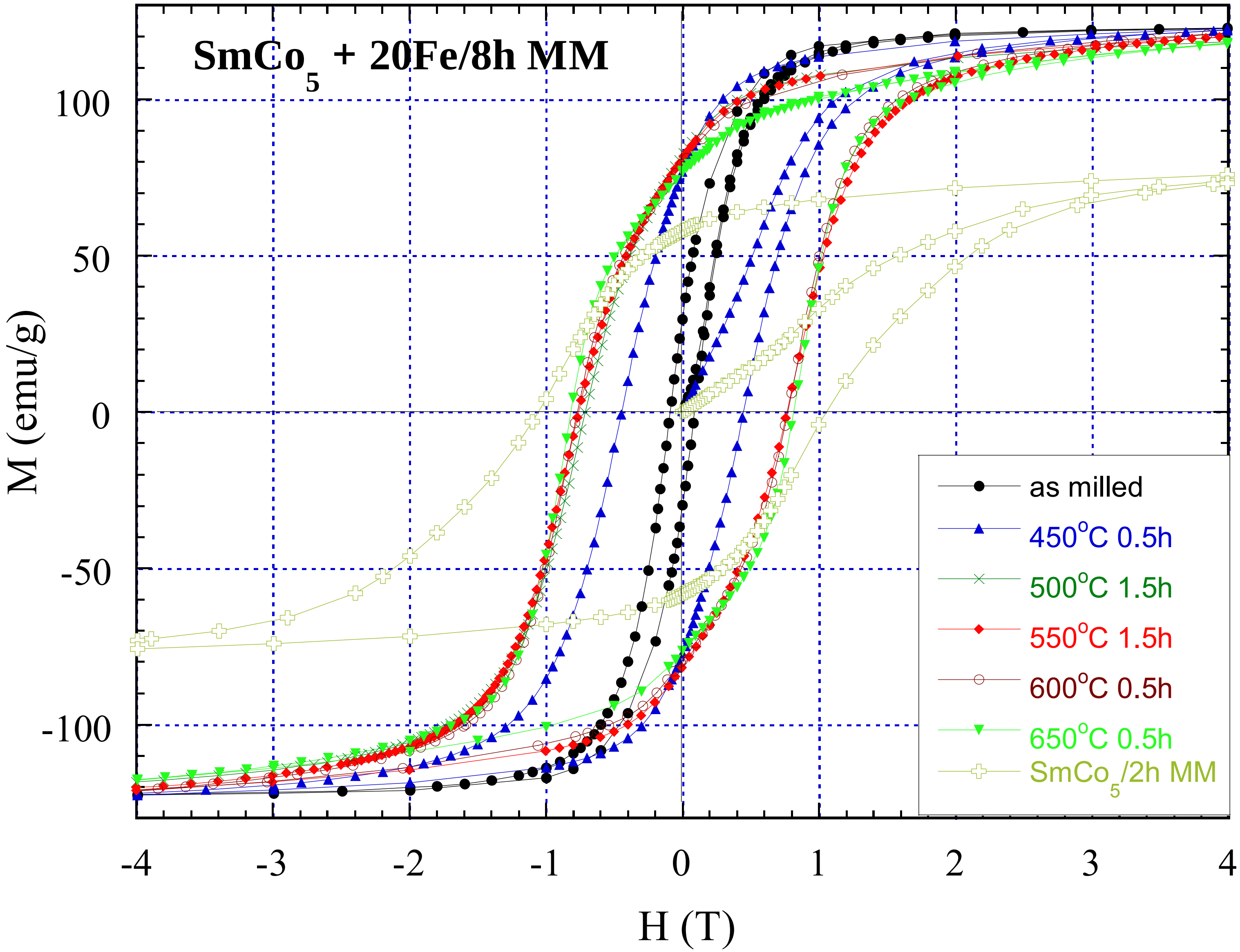
+

Enhanced remanence
$m_r > 0.5$ ($m_r = M_r/M_s$)

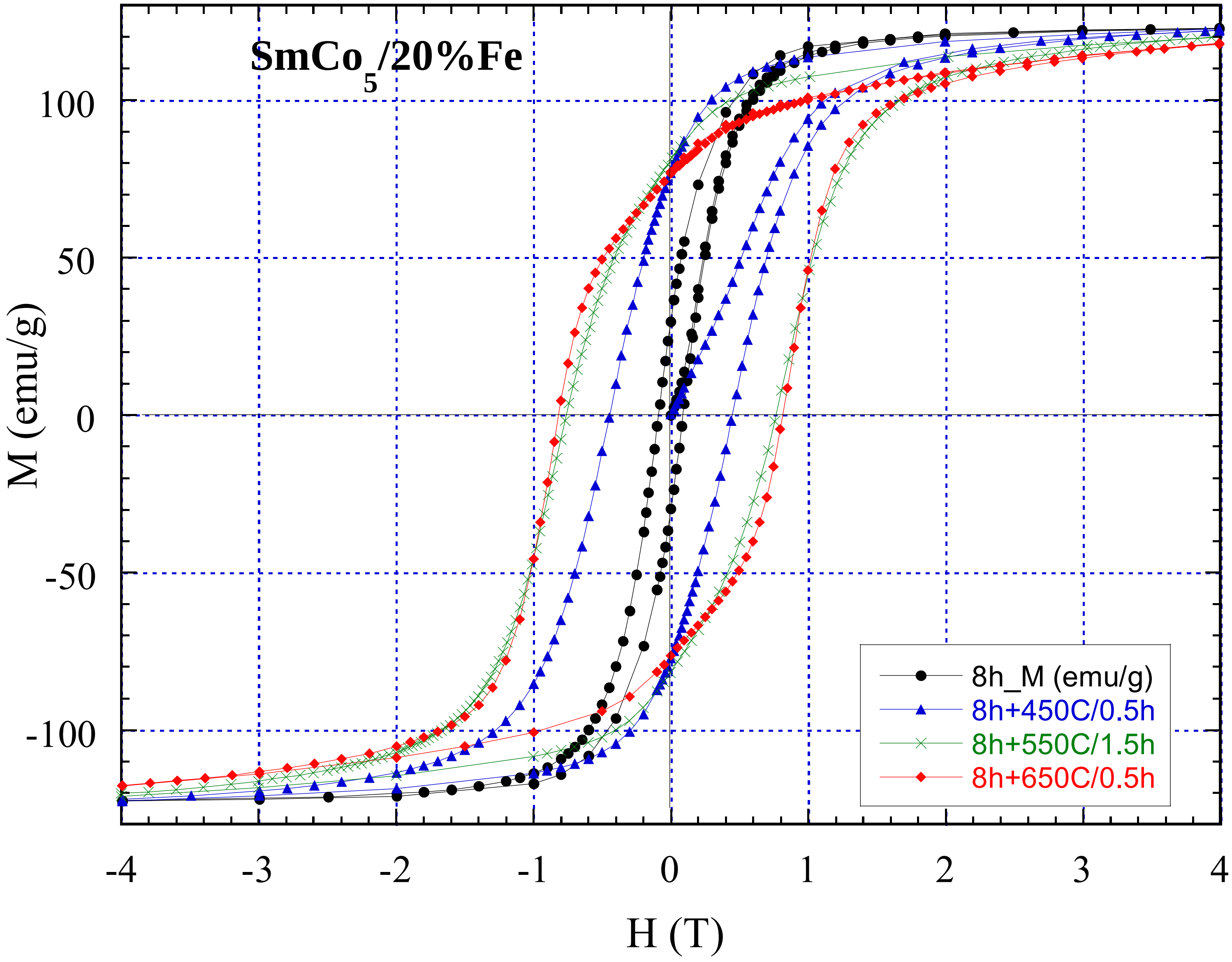
EXPERIMENTAL

criteria for the presence of the

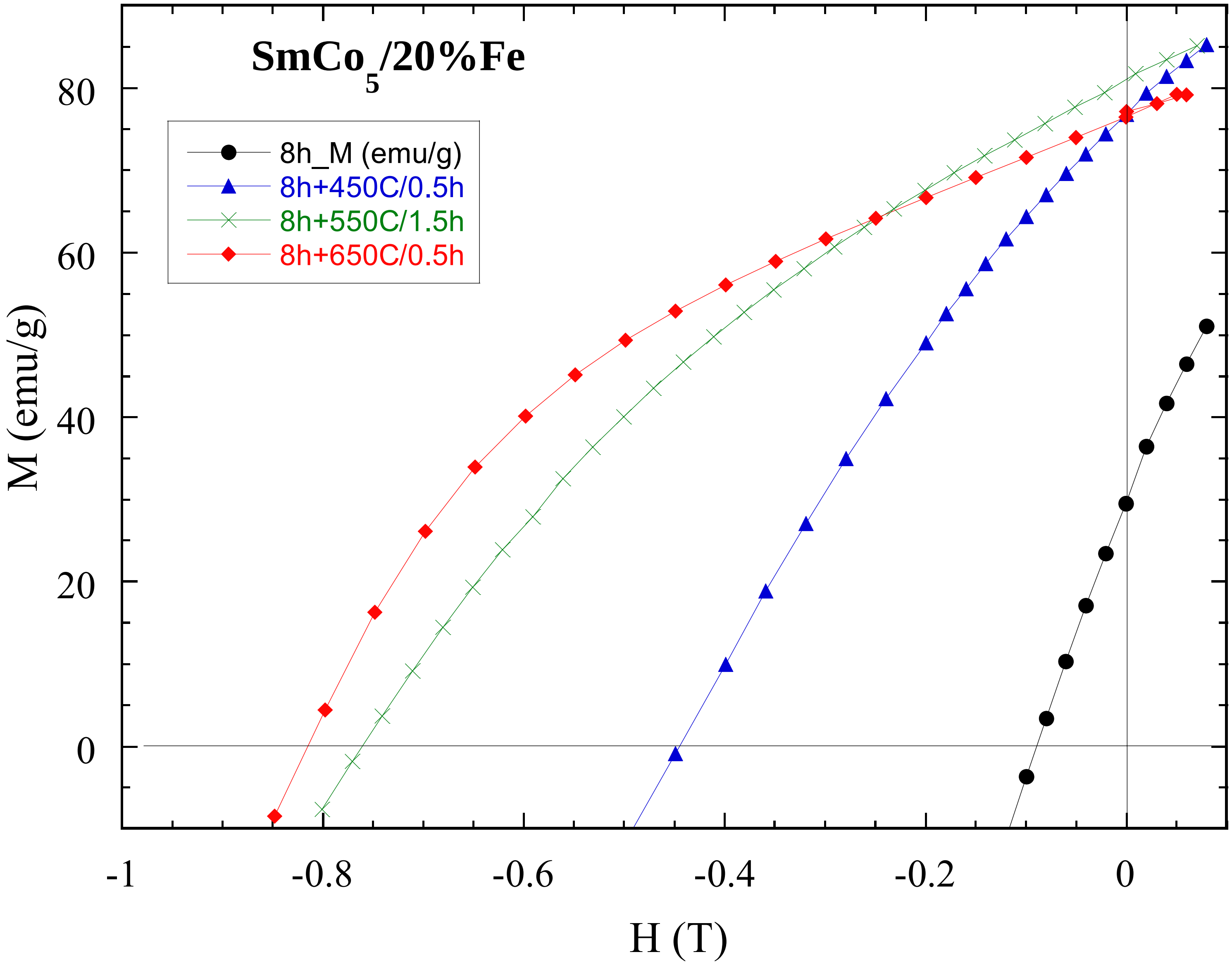
exchange spring mechanism



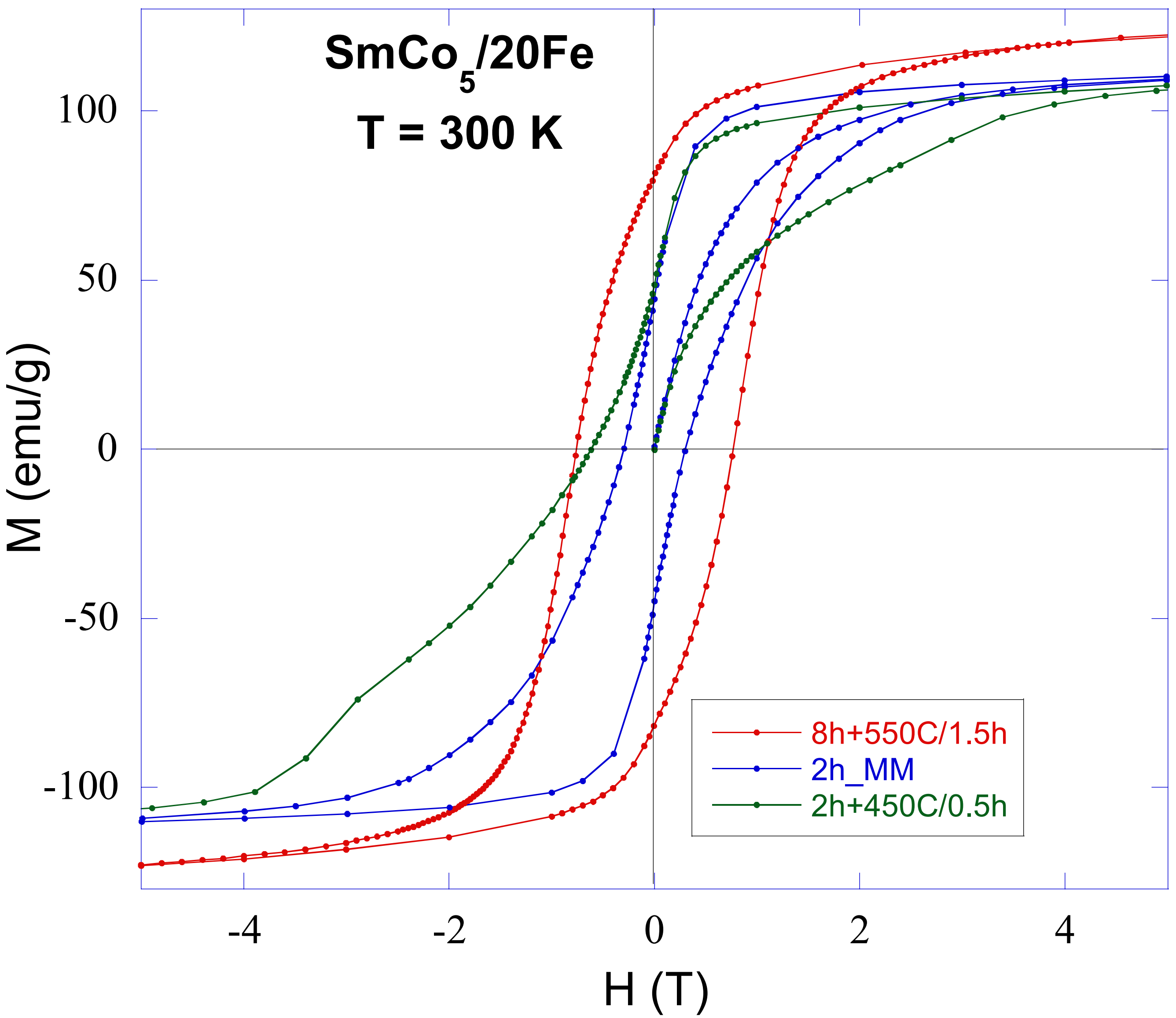
V. Pop, O. Isnard, I. Chicinas, D. Givord, Proceedings of Euro PM2005, Prague



SmCo5/20%Fe
M (emu/g)
H (T)
100
50
0
-50
-100
-4
-3
-2
-1
0
1
2
3
4
8h_M (emu/g)
8h+450C/0.5h
8h+550C/1.5h
8h+650C/0.5h



SmCo5/20%Fe
8h_M (emu/g)
8h+450C/0.5h
8h+550C/1.5h
8h+650C/0.5h
M (emu/g)
H (T)
80
60
40
20
0
-1
-0.8
-0.6
-0.4
-0.2
0


SmCo5/20Fe
T = 300 K
M (emu/g)
H (T)
100
50
0
-50
-100
-4
-2
0
2
4
8h+550C/1.5h
2h_MM
2h+450C/0.5h

N.H. Hai, N.M. Dempsey, D. Givord, JMMM262 (2003) 353

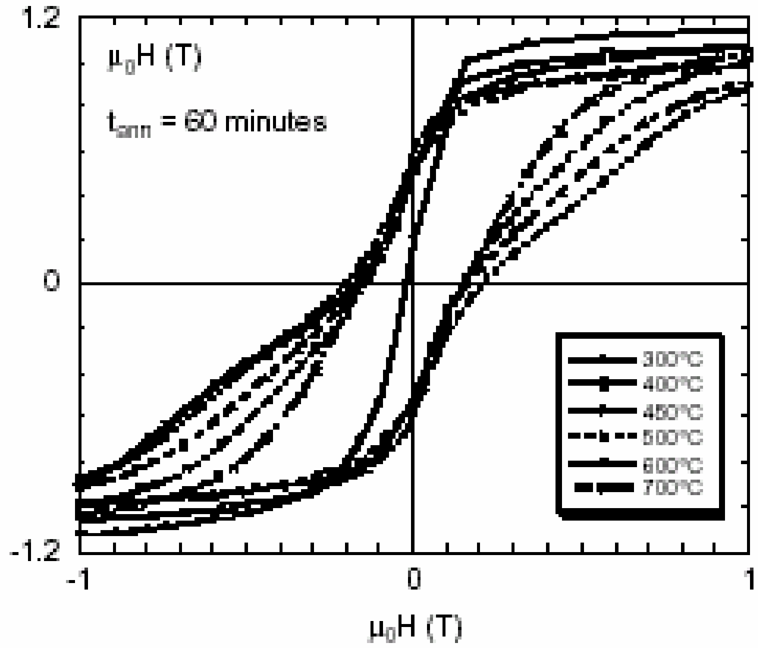


Fig. 6. Room temperature magnetisation loops of Fe-rich FePt foils heat treated in the temperature range 300–700°C (t_{anneal} = 60 min).

Exchange bias

E. Girgis et al, J. Appl. Phys. 97 (2005) 103911

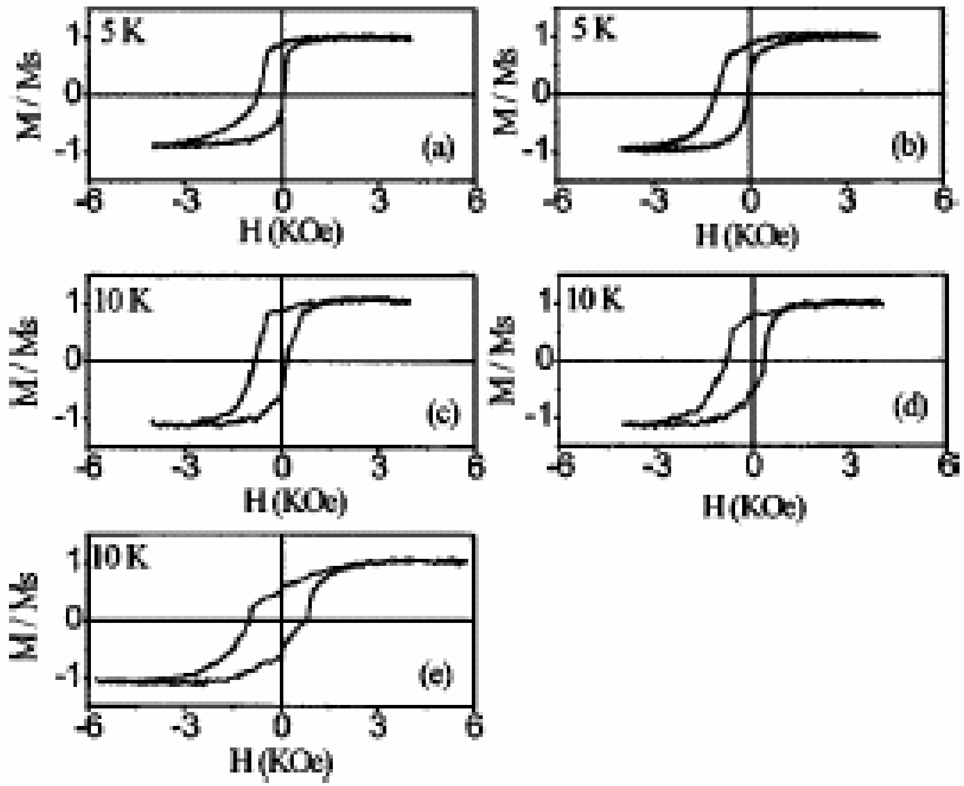
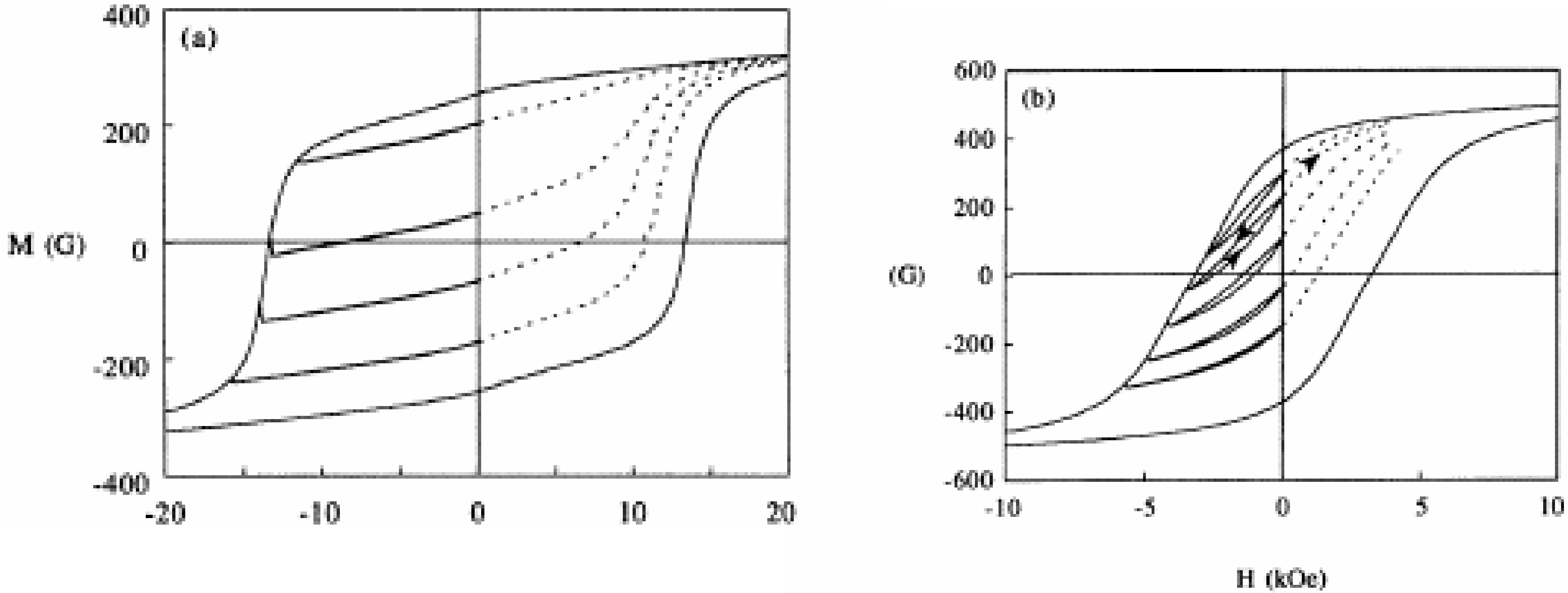


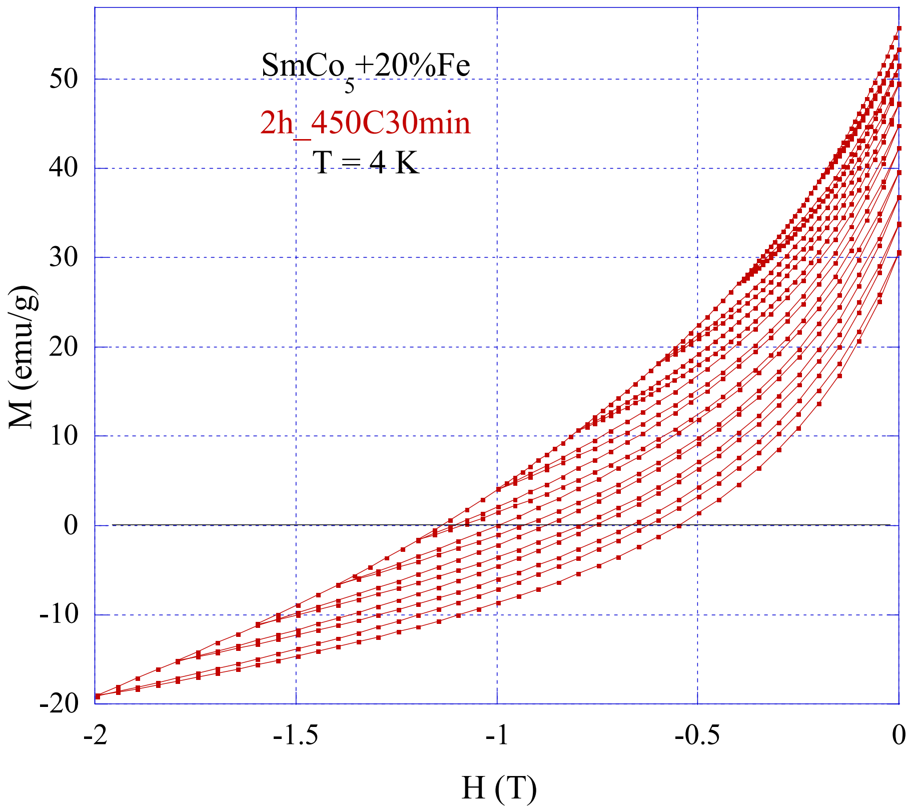
FIG. 2. Hysteresis loops of NiFe/CoO bilayer for (a) continuous film, a patterned nanodots with dimensions of (b) 900×900, (c) 700×700, (500×500, and (e) 300×300 nm^2.

recoil loops

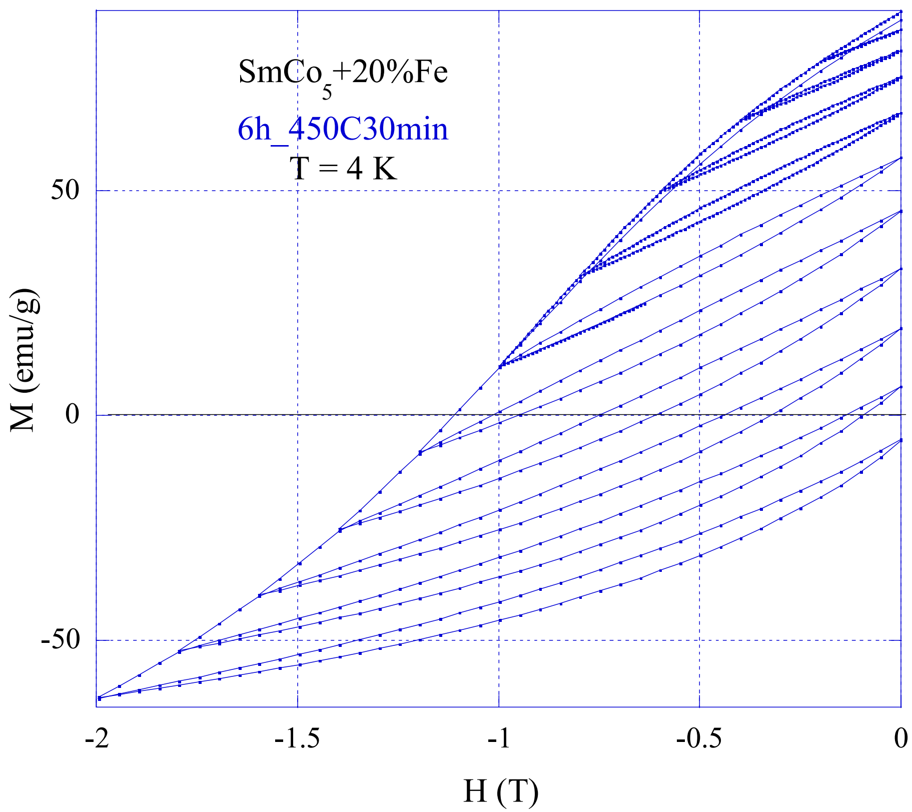


Major hysteresis loops with a selection of minor re-magnetization curves (broken lines) and recoil loops for (a) single-phase Sm2Fe14Ga3C2 and (b) two-phase $Sm_2Fe_{14}Ga_3C_2$/40vol% -Fe.

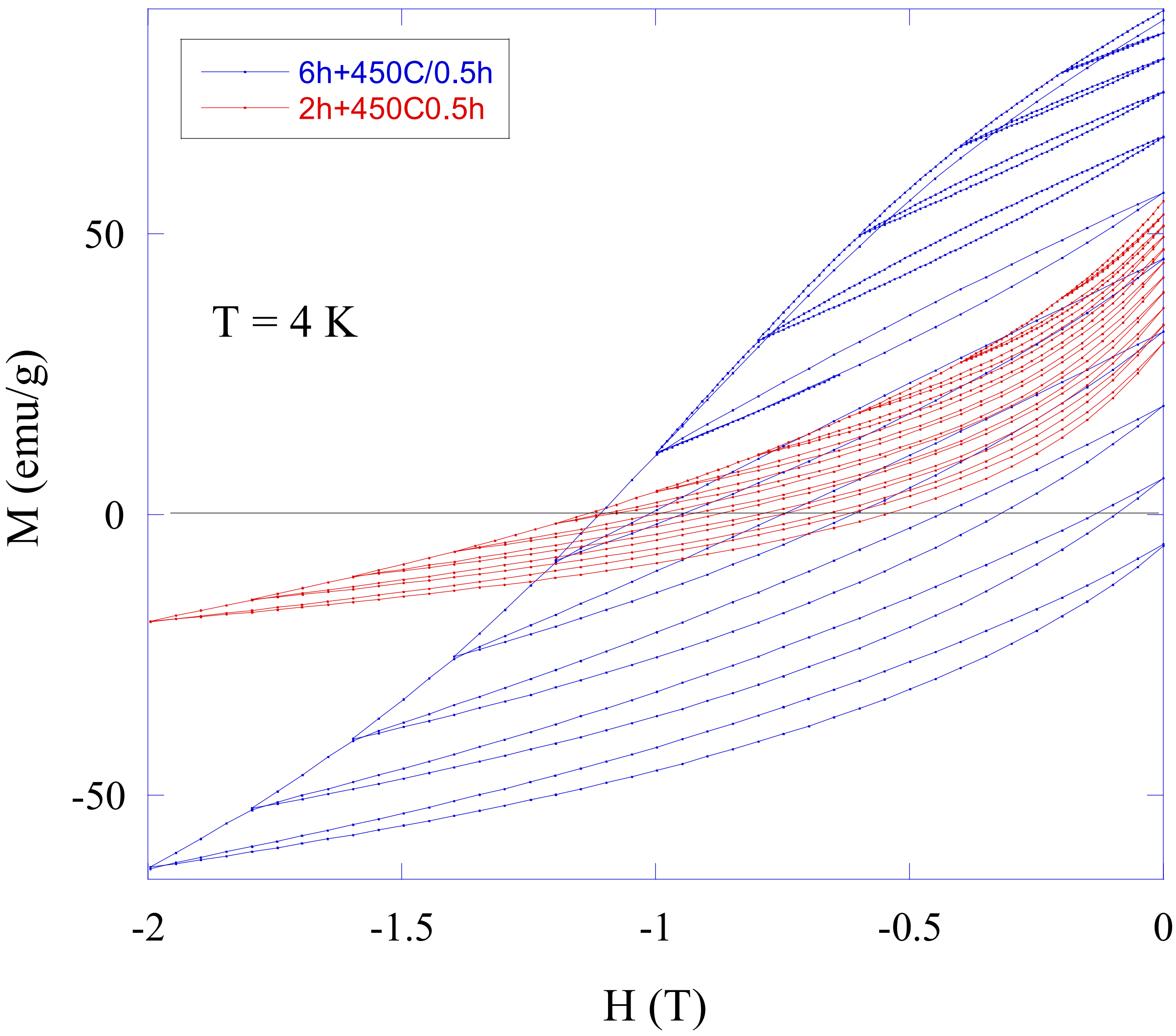
(Feutril et al, J. Phys.D: Appl. Phys. 29 (1996) 2320)



SmCo5+20%Fe
2h_450C30min
T = 4 K
M (emu/g)
H (T)



SmCo5+20%Fe
6h_450C30min
T = 4 K
M (emu/g)
H (T)



V. Pop, O. Isnard, I. Chicinas, D. Givord, (be published)

MECHANICAL ALLOYING soft magnetic materials