Brief Description of PREM 1.0

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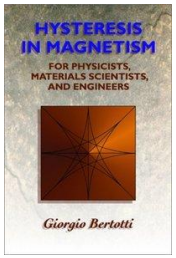
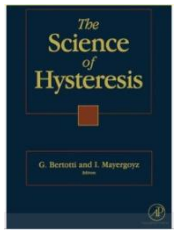
Classical Preisach Approach



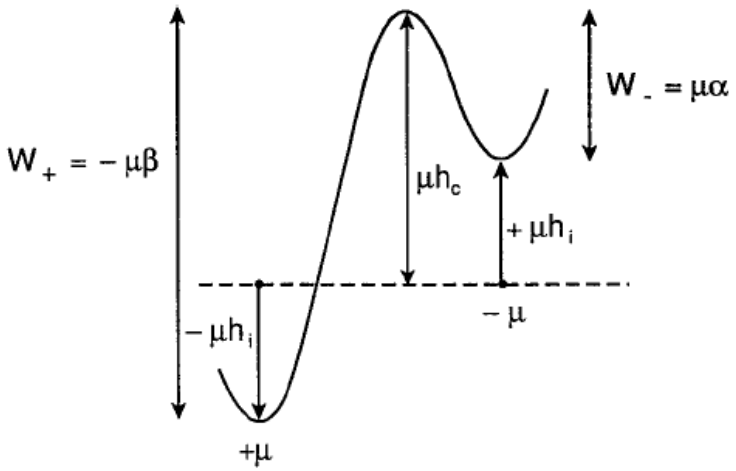
"The idea of describing a generic hysteretic system as the superposition of many bistable units is inevitably associated with the name of F. Preisach, who gave this idea an elegant and illuminating graphical representation."



"It was then gradually realized that the Preisach model contained a new general mathematical idea."…"In this way a new mathematical tool has evolved that can now be used for the mathematical description of hysteresis of various physical nature. At the same time this approach has strongly revealed the phenomenological nature of the Preisach model."

"The Preisach model of hysteresis generalizes hysteresis loops as the parallel connection of independent relay hysterons. It was first suggested in 1935 by P. Preisach in the German academic journal, "Zeitschrift für Physik". Since then, it has become a widely accepted model of hysteresis."

Energy profile



J. Phys.: Condens. Matter **13** (2001) 3443–3460

- A given magnetic material is identified by a particular distribution $f(W_+, W_-)$ of free energy barriers, or equivalently by a distribution of the characteristic fields $p(h_c, h_i)$.
- The barriers can be represented by a coercive field $h_c = (W_+ + W_-)/2\mu$ and an asymmetry field $h_i = (W_+ - W_-)/2\mu$.

$$p(h_c, h_i) = (2\pi\sigma_c^2)^{-1/2} \exp\left[-\frac{(h_c - \bar{h}_c)^2}{2\sigma_c^2}\right] (2\pi\sigma_i^2)^{-1/2} \exp\left[-\frac{(h_i - km)^2}{2\sigma_i^2}\right]$$

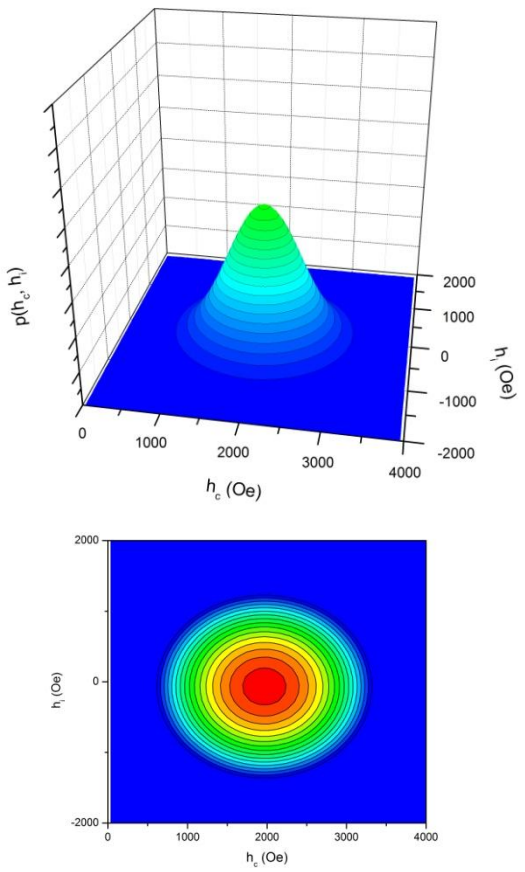
$$\bar{h}_c = \bar{h}_{c0}\left(1 - \frac{T}{T_C}\right)^{\Gamma_c}$$

$$\sigma_c = \sigma_{c0}\left(1 - \frac{T}{T_C}\right)^{\Gamma_c'}$$

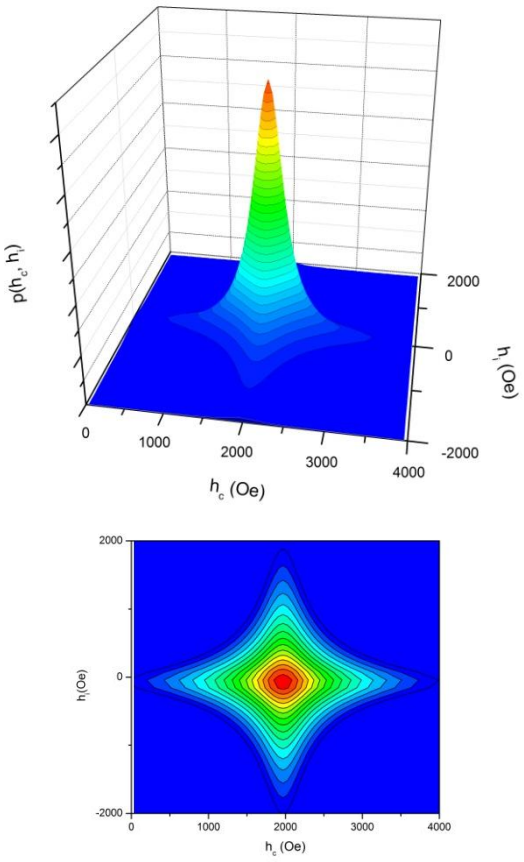
$$\sigma_i = \sigma_{i0}\left(1 - \frac{T}{T_C}\right)^{\Gamma_i}$$

Preisach Distribution Function

2D-Gauss



2D-Lorentz



h_{c0} = 2000 Oe
Γ_c = 0.3
σ_{c0} = 500 Oe
Γ'_c = 0.3
σ_{i0} =500 Oe
Γ_i= 0.3
km = 0 Oe

2D-integral of the PDF over the space is 1

Magnetic moment. Superparamagnetic response function.

Magnetic moment of the system at certain T and h_a is described by:

$$m = \int_0^{\infty} \mathrm{d}h_c \int_{-\infty}^{+\infty} \mathrm{d}h_i \; \varphi(h_c, h_i, h_a, T)\, p(h_c, h_i).$$

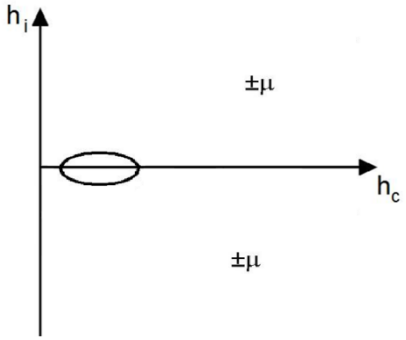
which includes PDF: $$p(h_c, h_i) = (2\pi\sigma_c^2)^{-1/2} \exp\left[-\frac{(h_c - \bar{h}_c)^2}{2\sigma_c^2} \right] (2\pi\sigma_i^2)^{-1/2} \exp\left[-\frac{(h_i - km)^2}{2\sigma_i^2} \right]$$

and superparamagnetic response function: $$\varphi_{sp} = \mu(T) \tanh[\mu(T)(h_a + h_i)/k_B T]$$

defined by the spontaneous magnetization at a certain temperature: $$\mu(T) = \mu_0 (1 - T/T_c)^{\Gamma}$$

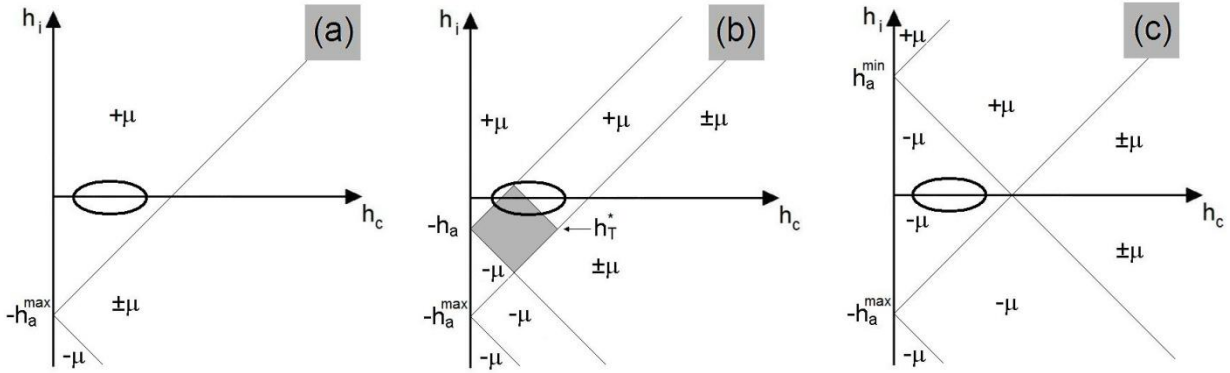
Integration of PDF in (h_c,h_i) space

Initial state of PDF (h_a=0, no magnetic history).



The total magnetic response m=0, since magnetic units are randomly magnetized .

Preisach diagram for M(H) measurement

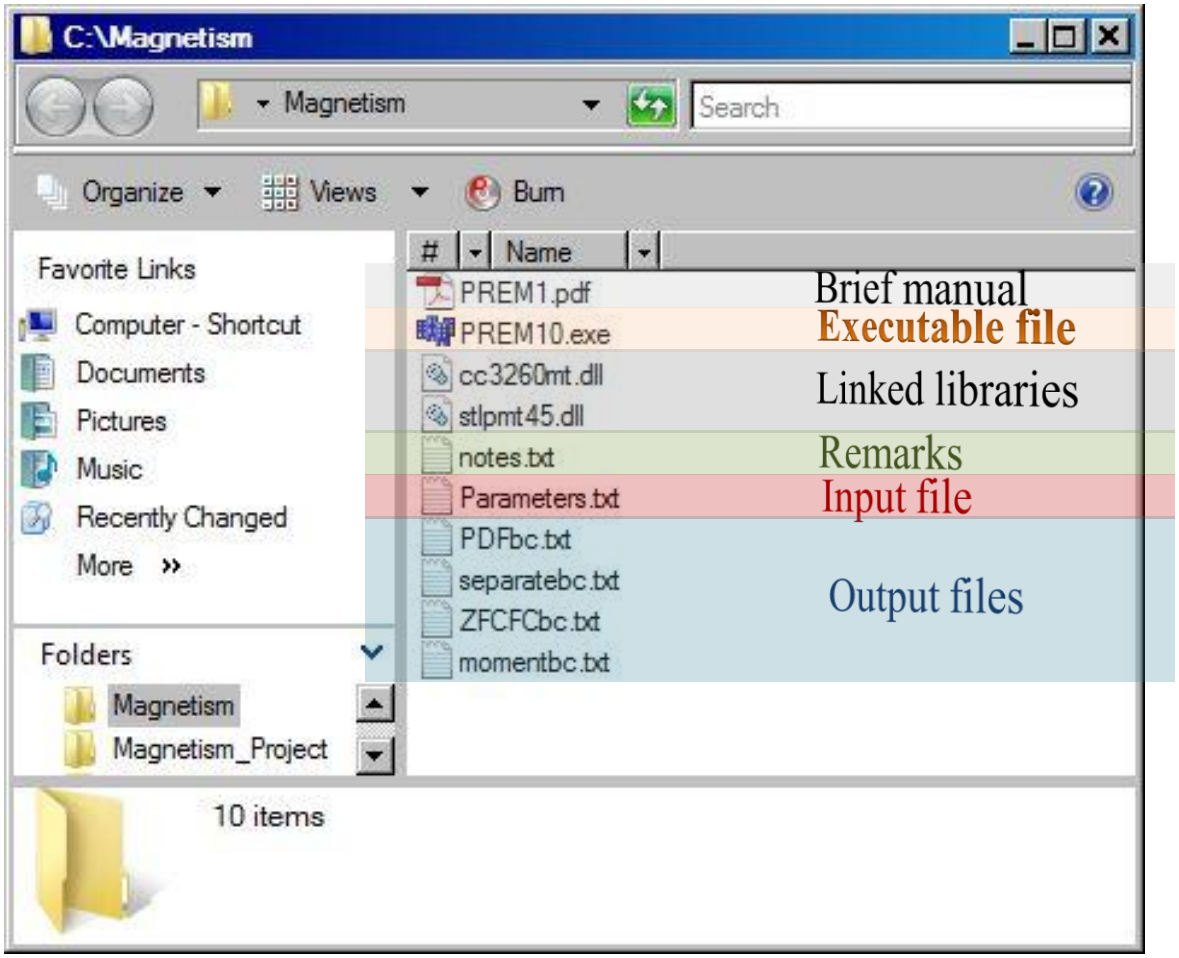


- schematic view of the Preisach distribution p(hc, hi)

Transformation of the Preisach diagram during isothermal measurement of a major hysteresis loop. (a) – maximal external field, h_a^{max}, is applied; (b) – external field h_a is between 0 and h_a^{max}; (c) – minimal (negative) external field, h_a^{min}, is applied.

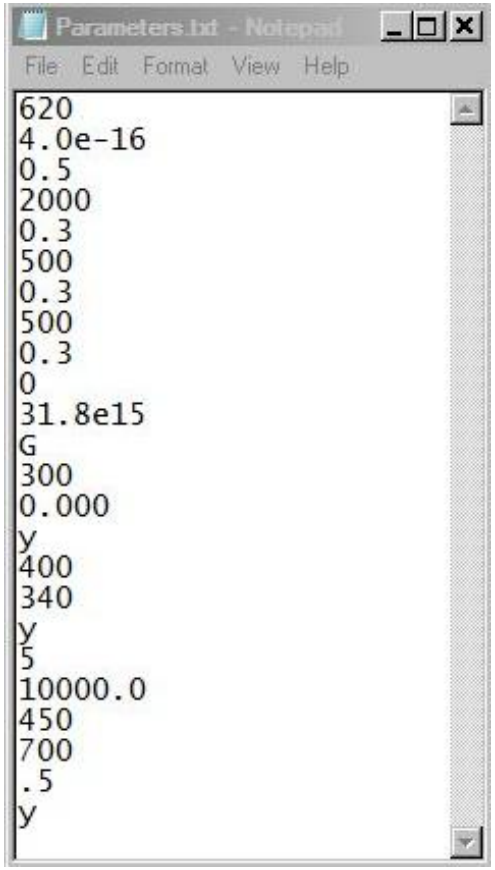
PREM1.0: Files

1. Copy folder "Magnetism" on drive C:\.
2. The path to the files must be "C:\Magnetism\...".



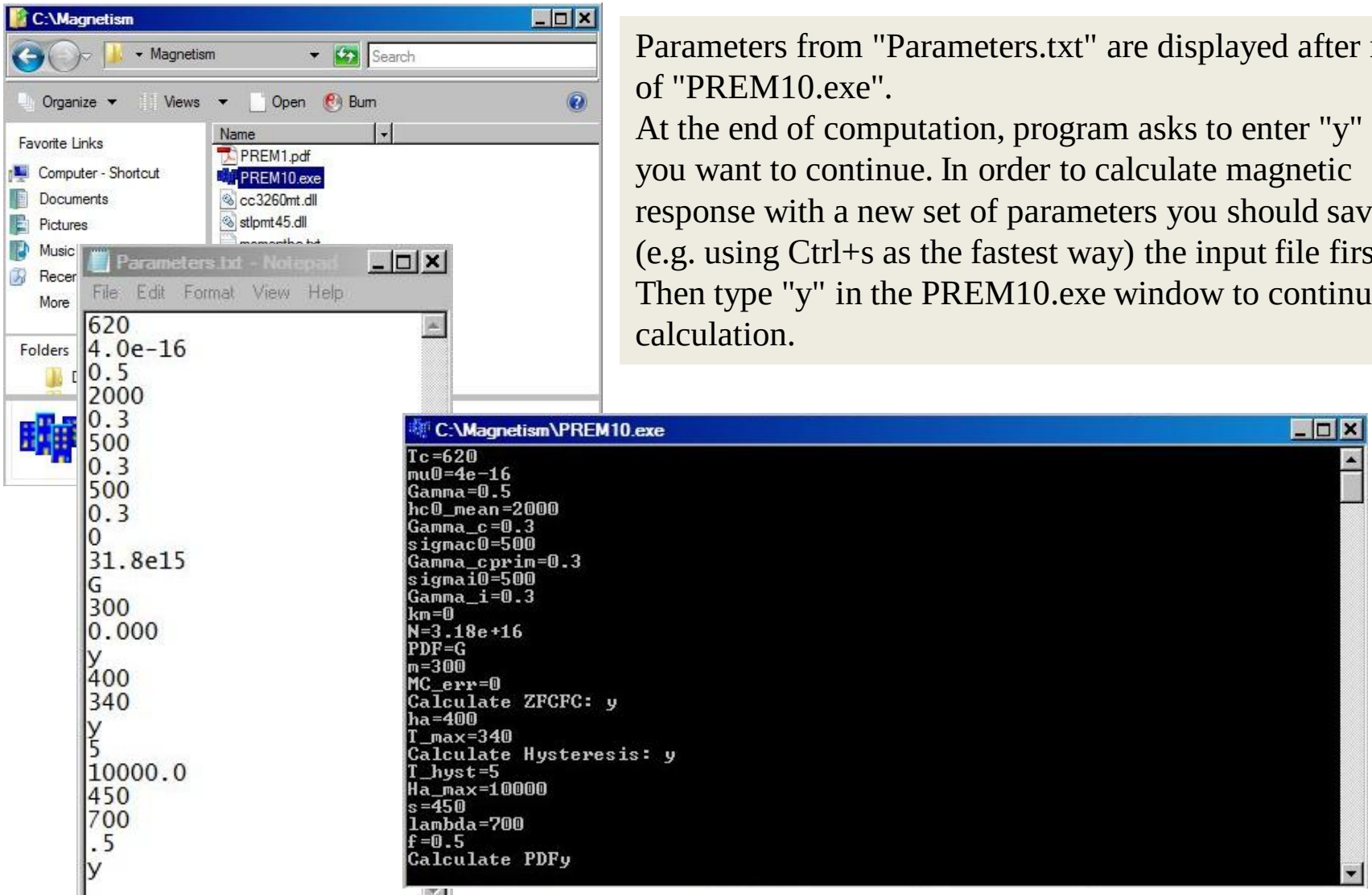
PREM1.0: Files

- 24 input lines
- Symbol parameters are case sensitive
- Digital parameters are accepted in forms:
  - 4e16; 4.0e16; 4.0e-16;
  - 500; 500.0; 5e2; 5.0e2;
  - 0.4; .4; 0; 0.0; .0



"Parameters.txt"	
Tc	Critical temperature
mu0	Spontaneous moment
Gamma	Critical exp. for μ
hc0_mean	Coercive field at 0K
Gamma_c	Critical exp. for h_{c0}
sigmac0	Distribution of coercive field
Gamma_cprim	Critical exp. for σ_{c0}
sigmai0	Local interactions field
Gamma_i	Critical exp. for σ_{i0}
km	Long-range interaction field
N	Concentration of units
PDF	Type of 2D-PDF (G or L)
m	Number of points in the grid
NULL	0
Calculate ZFCFC	y (YES) other NO
ha	Field at ZFCFC measurement
T_max	Maximal temperature
Calculate M(H)	y (YES) other NO
T_hyst	Temperature of M(H) meas.
ha_max	Maximal field
s	Shift of equilibrium states
lambda	Slope of reversible term
f	Fraction of reversible term
Calculate PDF	y (YES) other NO

PREM1.0: Files



Parameters from "Parameters.txt" are displayed after run of "PREM10.exe".
At the end of computation, program asks to enter "y" if you want to continue. In order to calculate magnetic response with a new set of parameters you should save (e.g. using Ctrl+s as the fastest way) the input file first. Then type "y" in the PREM10.exe window to continue the calculation.

PREM1.0: Files

Output files contain the following columns:
"momentbc.txt": h_a; M; M_{irr}; M_{rev}
"ZFCFCbc.txt": T; M_{ZFC}; M_{FC}
"PDFbc.txt": h_c; h_i; PDF
Units: Oe; emu; K

Field: h_a [Oe]	Moment: M [emu]	Moment: M_{irr} [emu]	Moment: M_{rev} [emu]

momentbc.txt - Notepad

File Edit Format View Help

```
10000.000000 1.262117e+01 6.286870e+00 6.334296e+00
9500.000000  1.262116e+01 6.286870e+00 6.334288e+00
9000.000000  1.262114e+01 6.286870e+00 6.334272e+00
8500.000000  1.262111e+01 6.286870e+00 6.334239e+00
8000.000000  1.262104e+01 6.286870e+00 6.334172e+00
7500.000000  1.262091e+01 6.286870e+00 6.334035e+00
7000.000000  1.262063e+01 6.286870e+00 6.333756e+00
6500.000000  1.262006e+01 6.286870e+00 6.333186e+00
```

Temp.: T[K]	Moment: M_{ZFC}[emu]	Moment: M_{FC}[emu]

ZFCFCbc.txt - Notepad

File Edit Format View Help

```
5.000000  1.766596e-01 7.194839e+00
10.000000 2.054553e-01 7.169759e+00
15.000000 2.388147e-01 7.169373e+00
20.000000 2.760704e-01 7.143876e+00
25.000000 3.191083e-01 7.143789e+00
30.000000 3.666686e-01 7.117874e+00
35.000000 4.189902e-01 7.091604e+00
40.000000 4.810508e-01 7.091677e+00
```

Variable: h_c [emu]	Variable: h_i [emu]	PDF value: $p(h_c, h_i)$

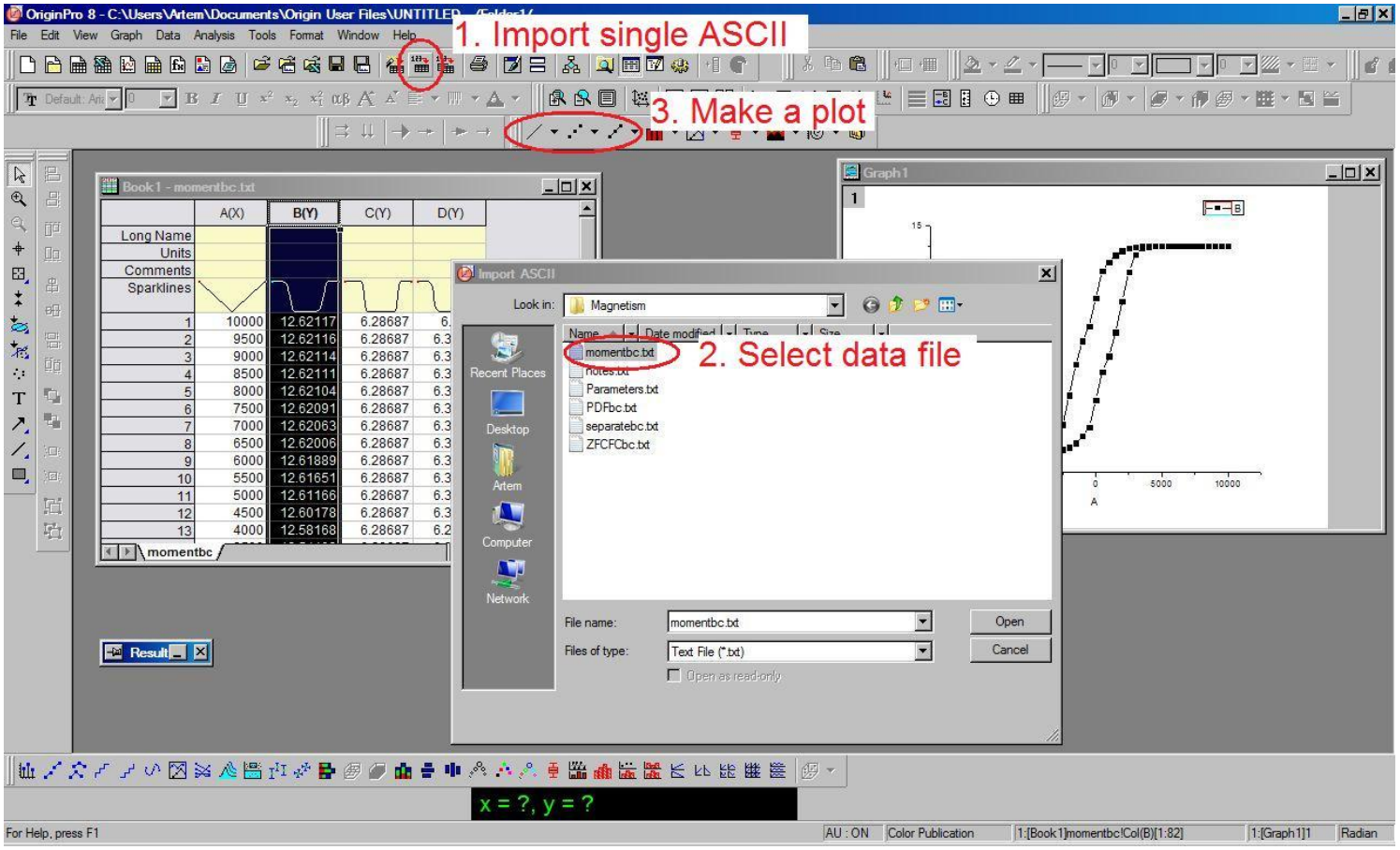
PDFbc.txt - Notepad

File Edit Format View Help

```
3.333333e+01 -9.933333e+03 6.716755e-80
3.333333e+01 -9.866667e+03 9.533875e-79
3.333333e+01 -9.800000e+03 1.329346e-77
3.333333e+01 -9.733333e+03 1.820740e-76
3.333333e+01 -9.666667e+03 2.449531e-75
3.333333e+01 -9.600000e+03 3.237248e-74
3.333333e+01 -9.533333e+03 4.202529e-73
3.333333e+01 -9.466667e+03 5.358840e-72
```

PREM1.0: Visualization

Since, PREM1.0 does not possess a graphical interface the visualization can be done in any data analysis program. For example in Origin (3 clicks only):



PREM1.0: Examples

Magnetic transitions are defined by two critical characteristics of the system:

1. Critical thermal fluctuation energy

$$W_C \equiv k_B T_C \ln\left(\frac{t_{\exp}}{\tau}\right)$$

2. Mean zero-field anisotropy barrier

$$\overline{W}_a(0) \equiv \mu_0 \overline{h}_{c0}$$

Relative strength of these two characteristic energies is:

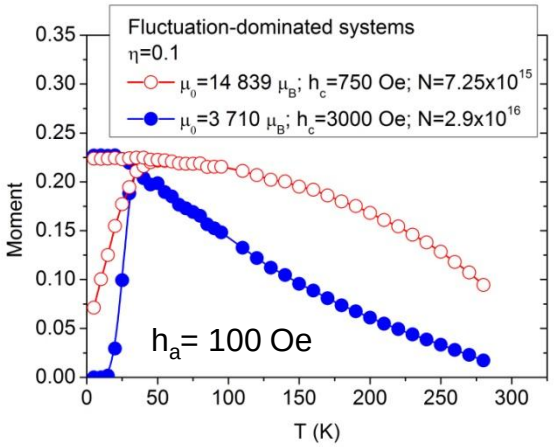
$$\eta \equiv \frac{\overline{W}_a(0)}{W_C} \equiv \frac{\mu_0 \overline{h}_{c0}}{k_B T_C \ln\left(\frac{t_{\exp}}{\tau}\right)}$$

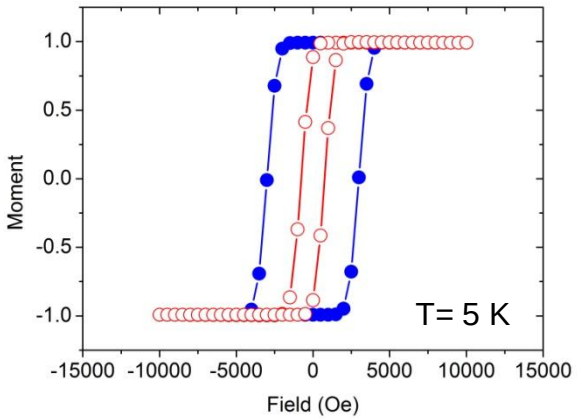
If $\eta > 1$ the system is anisotropy dominated.

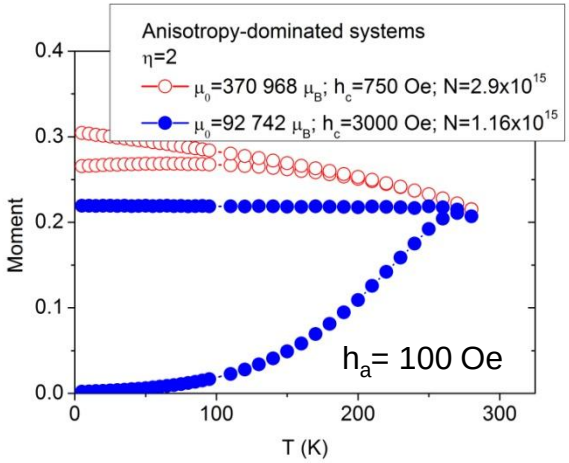
If $\eta < 1$ the system is fluctuation dominated.

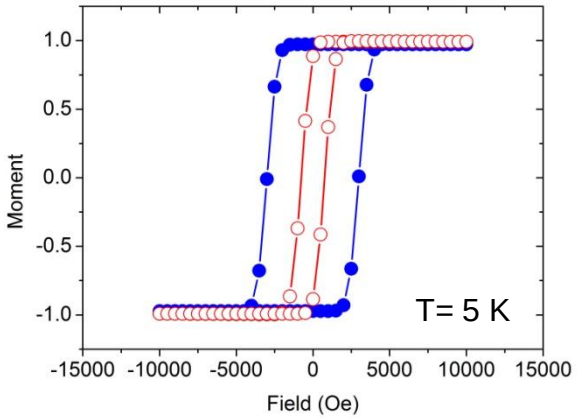
PREM1.0: Examples

Two magnetic systems η=0.1 (upper) and η=2 (lower) exhibit equal hysteresis loops! Magnetic moment of a single particle in fluctuation-dominated system is 25(!) times lower then in anisotropy dominated system.





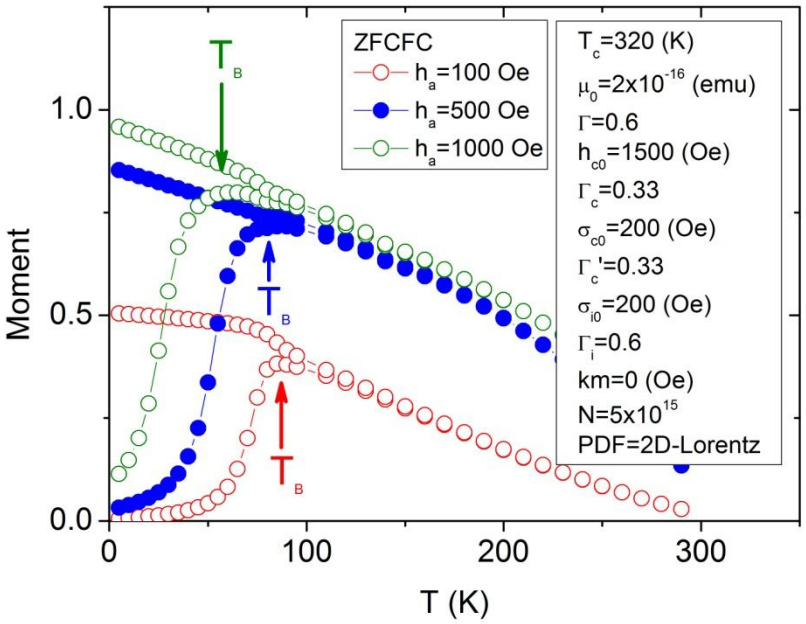


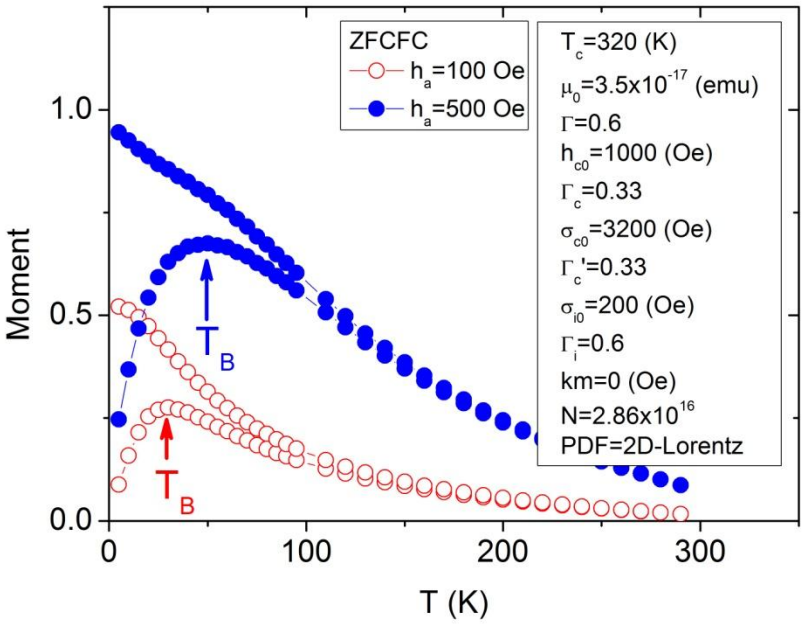


Parameters	
T_c	300 K
Γ	0.3
Γ_c	0.3
σ_{c0}	350 Oe
Γ_c'	0.3
σ_{i0}	350 Oe
Γ_i	0.3
km	0 Oe

PREM1.0: Examples

The common opinion that the blocking temperature T_B is always shifted to lower temperatures with an increase of external field is incorrect.
There is no verified approach how to predict the position of T_B in a certain field. However, T_B seems to be strongly dependent on the ratio of h_{c0}:σ_{c0}:σ_{i0}. Lower short-range interaction field σ_{i0} leads to increasing of T_B at higher external fields.

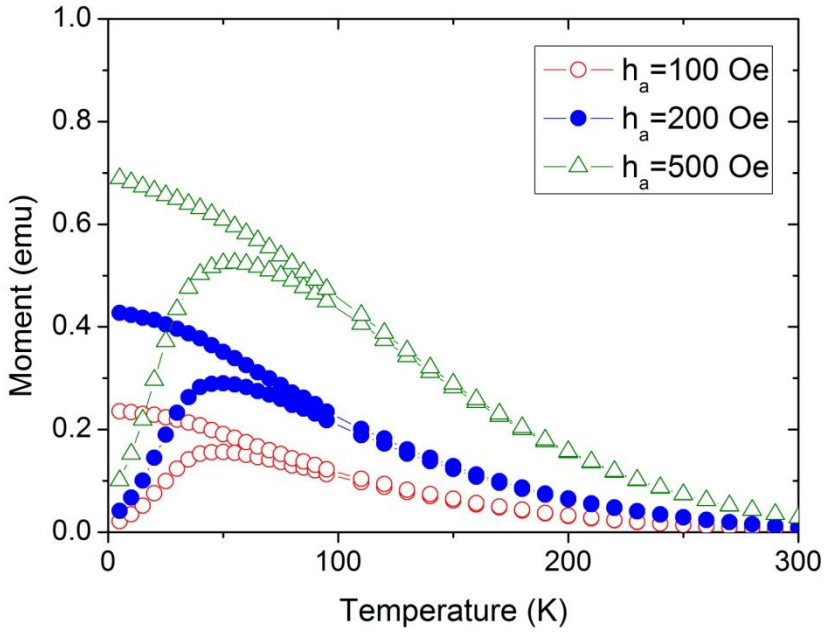


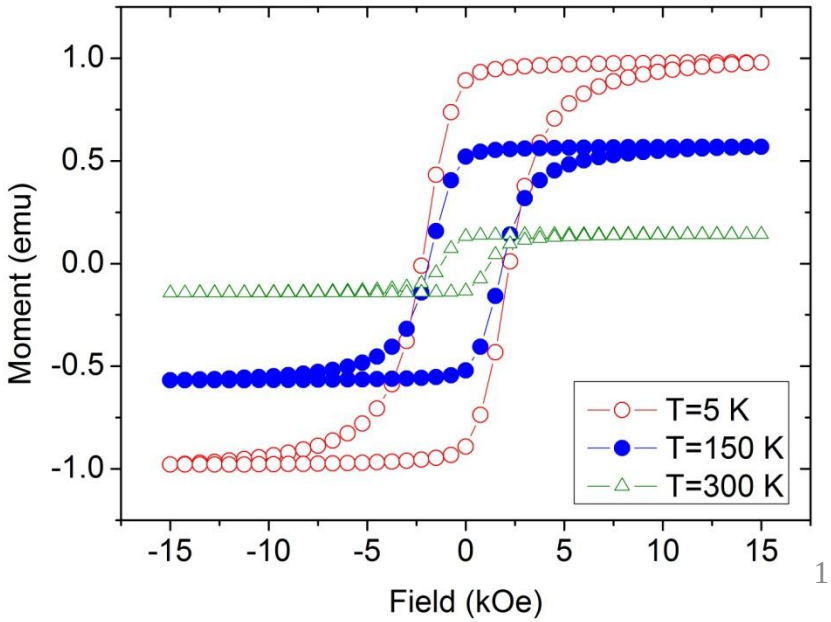


PREM1.0: Examples

M_{ZFCFC} (h_a) and M_{hyst} (T)

							Representative system			
T_c [K]	μ_0 [emu]	Γ	h_{c0} [Oe]	Γ_c	σ_{c0} [Oe]	Γ_c'	σ_{i0} [Oe]	Γ_i	km [Oe]	N
350	5×10^{-17}	1.0	2000	0.33	2000	0.33	500	0.5	0	2×10^{16}

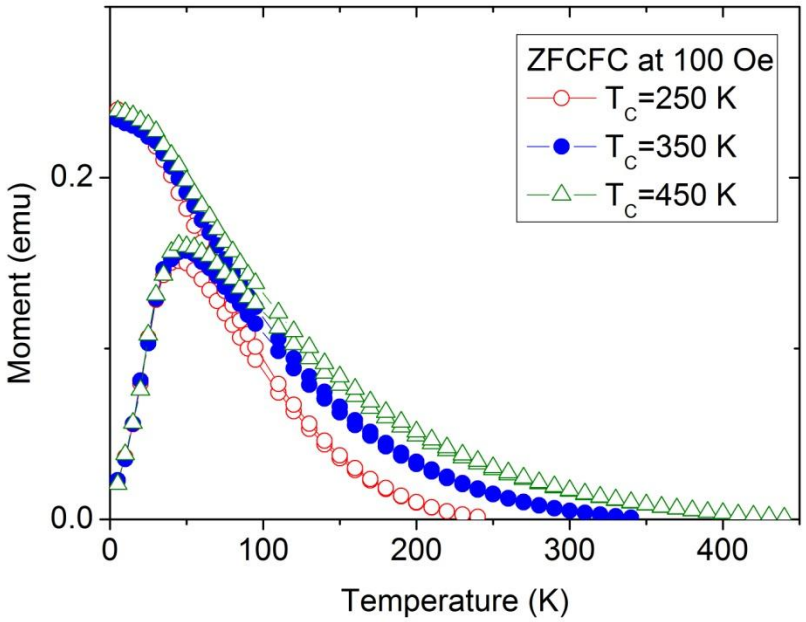


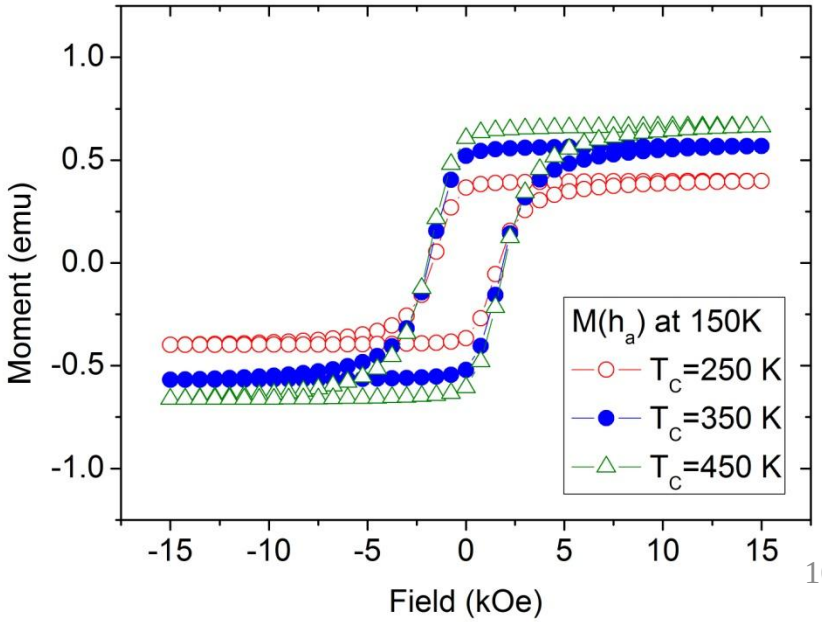


PREM1.0: Examples

M_{ZFCFC} (T_C) and M_{hyst} (T_C)

							Representative system			
T_c [K]	μ_0 [emu]	Γ	h_{c0} [Oe]	Γ_c	σ_{c0} [Oe]	Γ_c'	σ_{i0} [Oe]	Γ_i	km [Oe]	N
250 350 450	5×10^{-17}	1.0	2000	0.33	2000	0.33	500	0.5	0	2×10^{16}

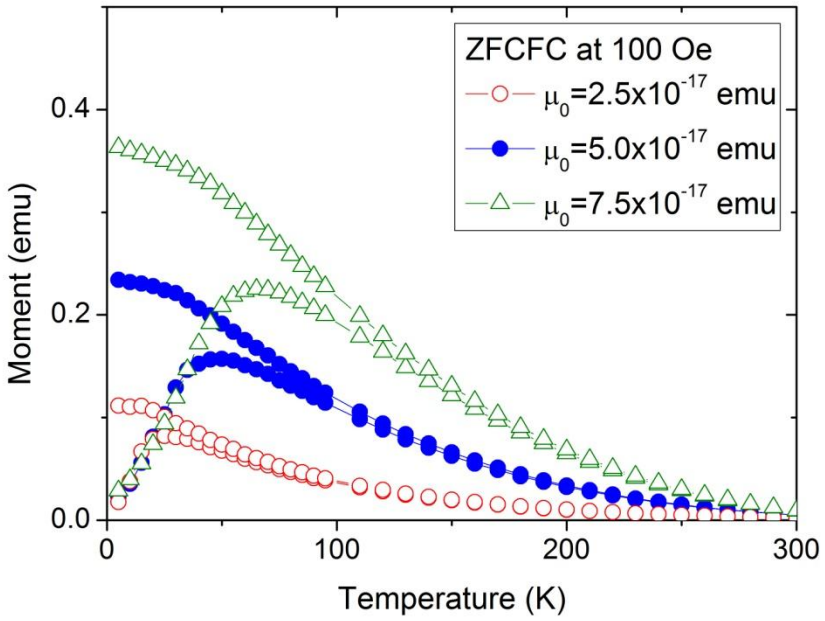


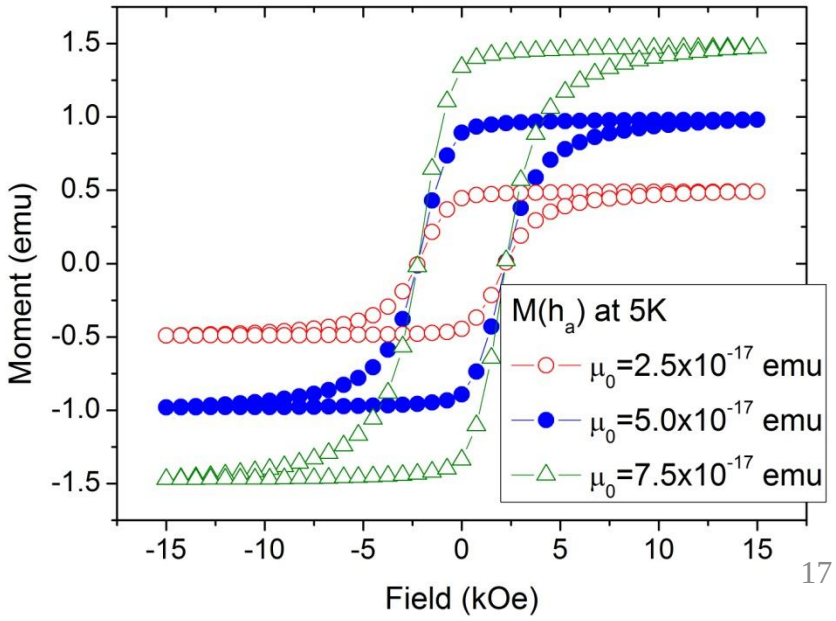


PREM1.0: Examples

M_{ZFCFC} (μ_0) and M_{hyst} (μ_0)

							Representative system			
T_c [K]	μ_0 [emu]	Γ	h_{c0} [Oe]	Γ_c	σ_{c0} [Oe]	Γ_c'	σ_{i0} [Oe]	Γ_i	km [Oe]	N
350	2.5×10^{-17} 5.0×10^{-17} 7.5×10^{-17}	1.0	2000	0.33	2000	0.33	500	0.5	0	2×10^{16}

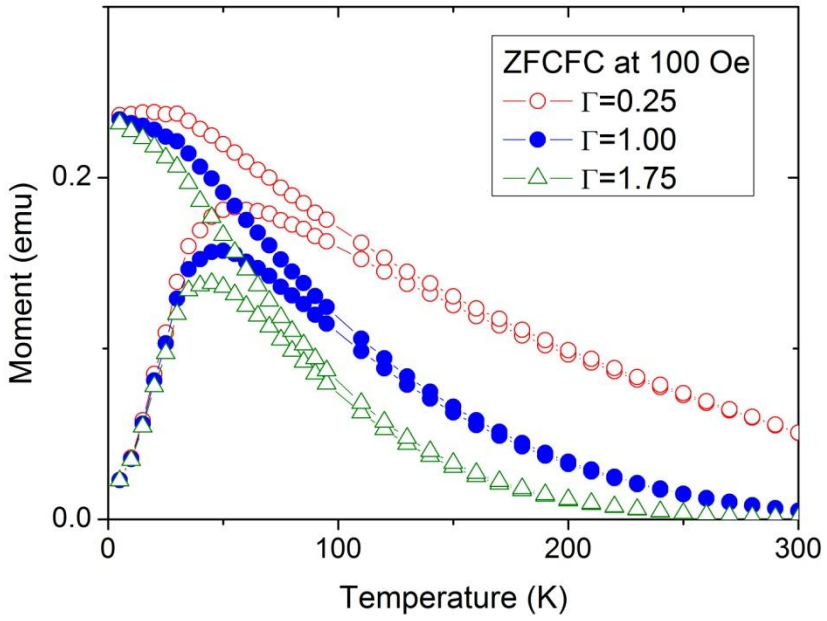


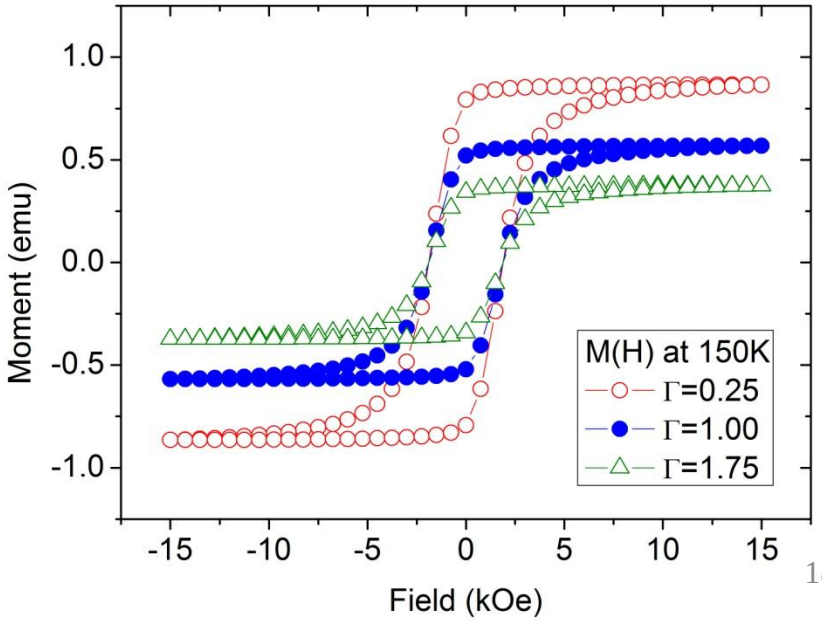


PREM1.0: Examples

M_{ZFCFC} (Γ) and M_{hyst} (Γ)

							Representative system			
T_c [K]	μ_0 [emu]	Γ	h_{c0} [Oe]	Γ_c	σ_{c0} [Oe]	Γ_c'	σ_{i0} [Oe]	Γ_i	km [Oe]	N
350	5×10^{-17}	0.25 1.00 1.75	2000	0.33	2000	0.33	500	0.5	0	2×10^{16}

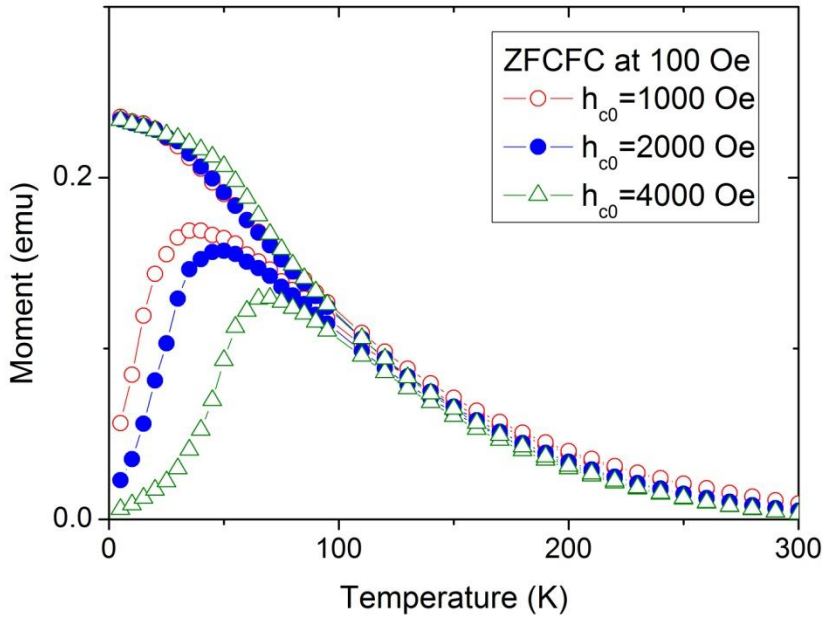


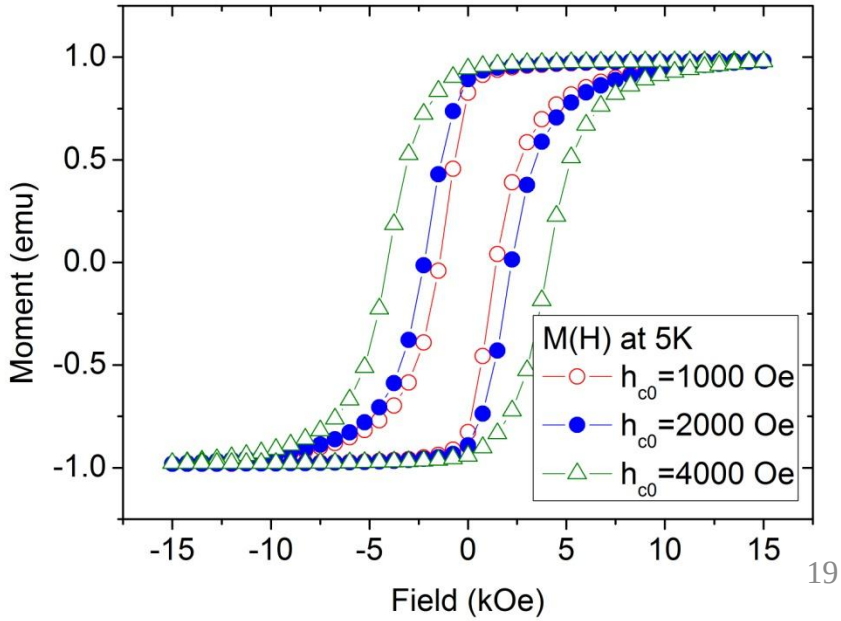


PREM1.0: Examples

$M_{ZFCFC}(\bar{h}_{c0})$ and $M_{hyst}(\bar{h}_{c0})$

							Representative system			
T_c [K]	μ_0 [emu]	Γ	$\bar{h}_{c0}$ [Oe]	Γ_c	σ_{c0} [Oe]	Γ_c'	σ_{i0} [Oe]	Γ_i	km [Oe]	N
350	5×10^{-17}	1.0	1000 2000 4000	0.33	2000	0.33	500	0.5	0	2×10^{16}

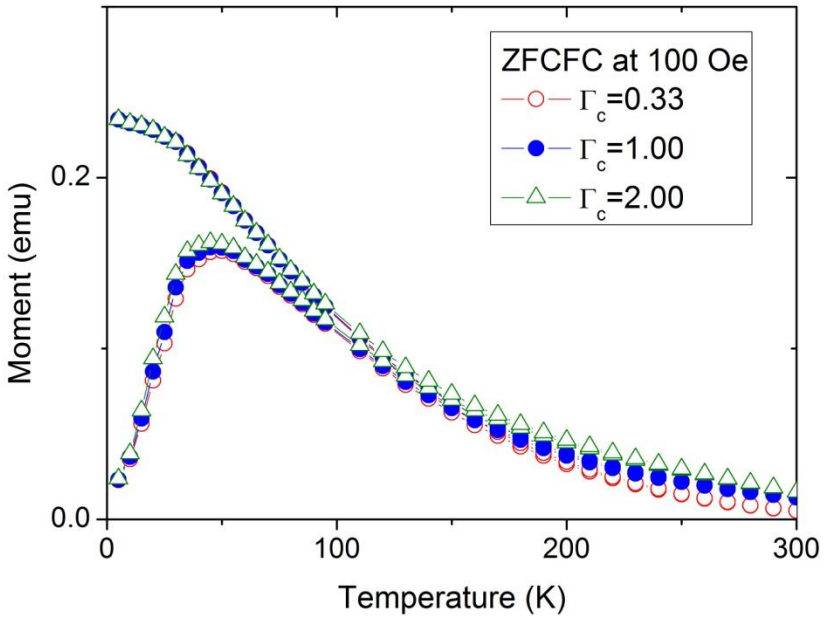


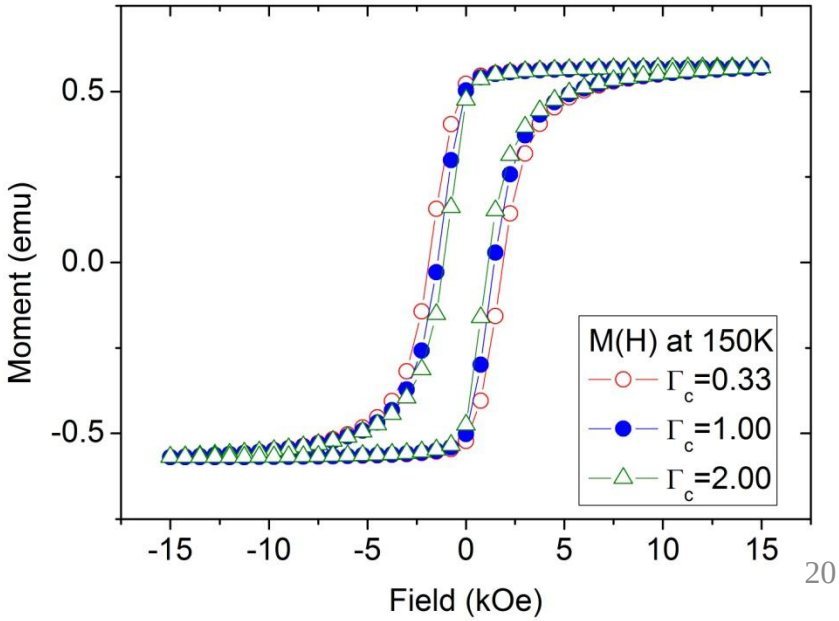


PREM1.0: Examples

M_{ZFCFC} (Γ_c) and M_{hyst} (Γ_c)

							Representative system			
T_c [K]	μ_0 [emu]	Γ	h_{c0} [Oe]	Γ_c	σ_{c0} [Oe]	Γ_c'	σ_{i0} [Oe]	Γ_i	km [Oe]	N
350	5×10^{-17}	1.0	2000	0.33 1.00 2.00	2000	0.33	500	0.5	0	2×10^{16}

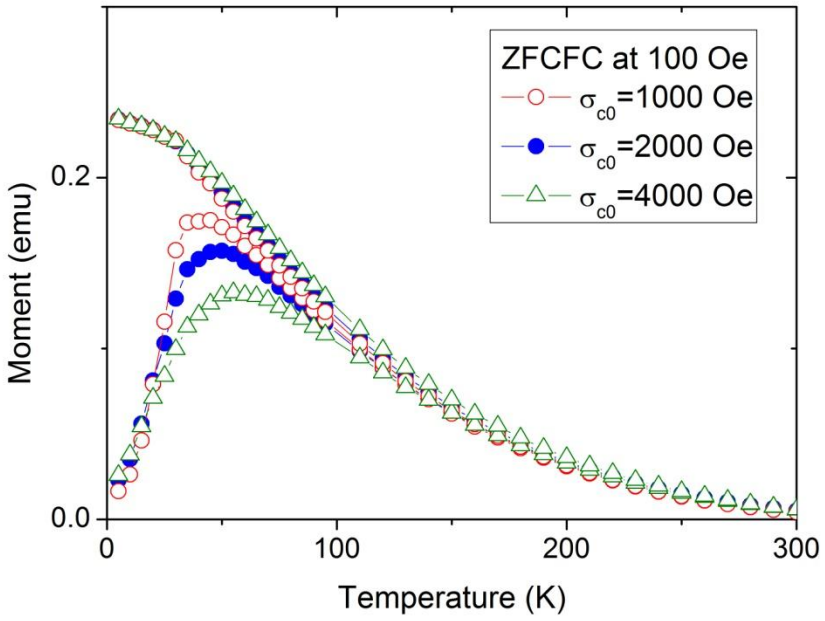


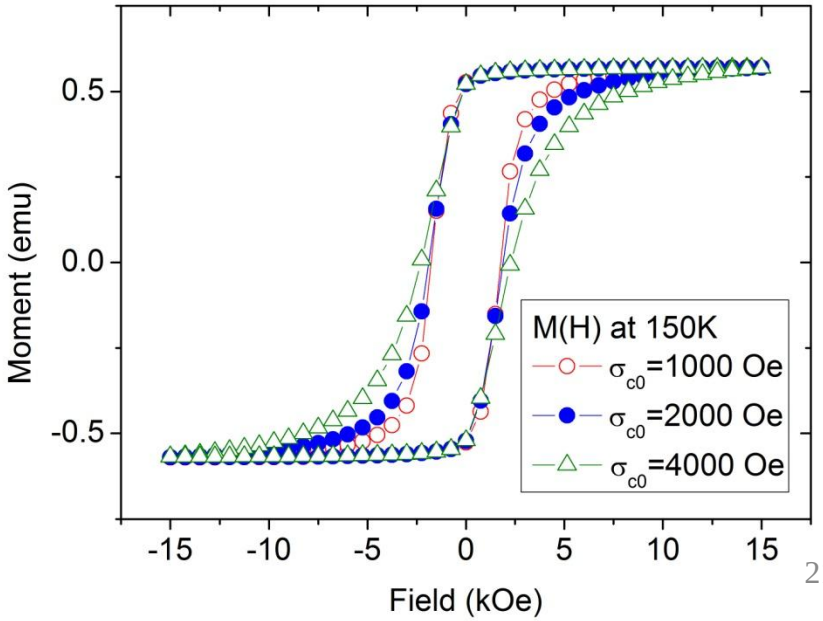


PREM1.0: Examples

M_{ZFCFC} (σ_{c0}) and M_{hyst} (σ_{c0})

							Representative system			
T_c [K]	μ_0 [emu]	Γ	h_{c0} [Oe]	Γ_c	σ_{c0} [Oe]	Γ_c'	σ_{i0} [Oe]	Γ_i	km [Oe]	N
350	5×10^{-17}	1.0	2000	0.33	1000 2000 4000	0.33	500	0.5	0	2×10^{16}

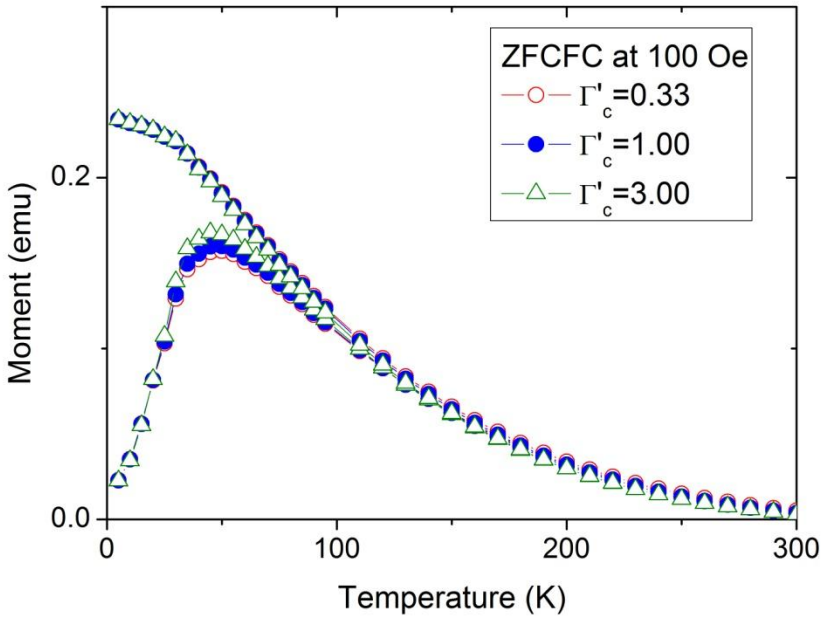


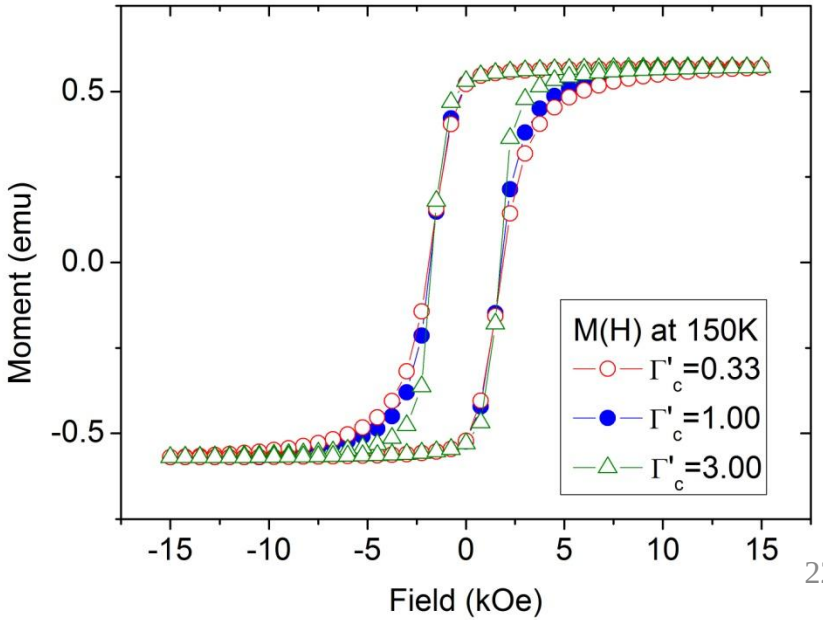


PREM1.0: Examples

M_{ZFCFC} (Γ'_c) and M_{hyst} (Γ'_c)

							Representative system			
T_c [K]	μ_0 [emu]	Γ	h_{c0} [Oe]	Γ_c	σ_{c0} [Oe]	Γ_c'	σ_{i0} [Oe]	Γ_i	km [Oe]	N
350	5×10^{-17}	1.0	2000	0.33	2000	0.33 1.00 3.00	500	0.5	0	2×10^{16}

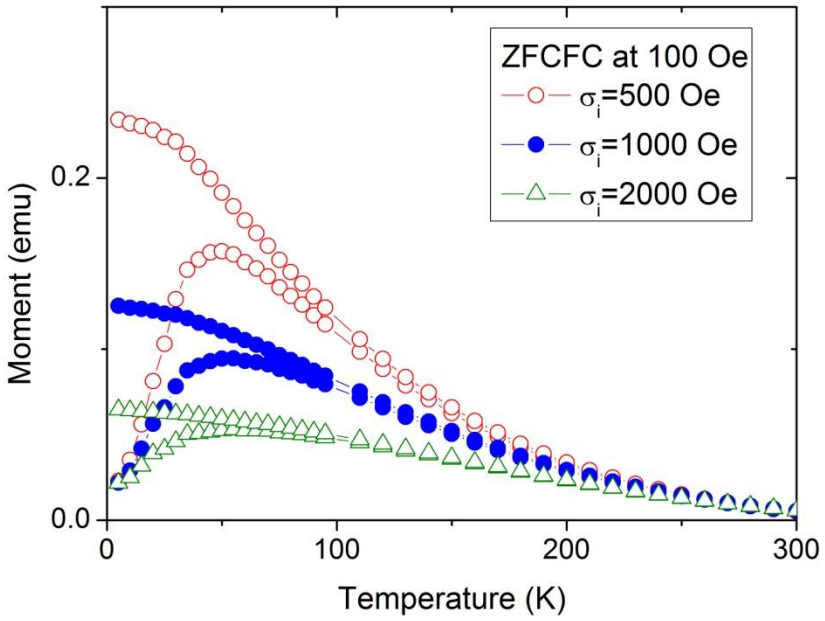


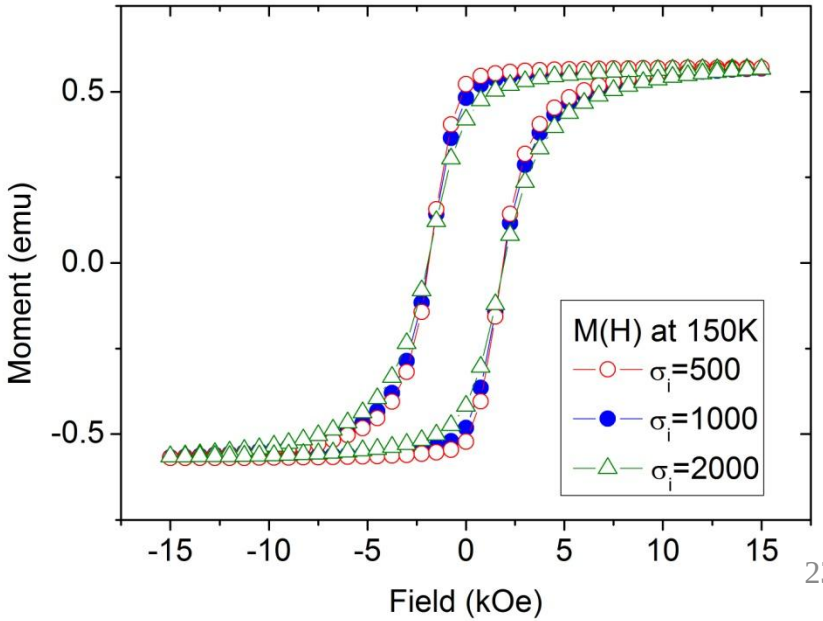


PREM1.0: Examples

M_{ZFCFC} (σ_{i0}) and M_{hyst} (σ_{i0})

							Representative system			
T_c [K]	μ_0 [emu]	Γ	h_{c0} [Oe]	Γ_c	σ_{c0} [Oe]	Γ_c'	σ_{i0} [Oe]	Γ_i	km [Oe]	N
350	5×10^{-17}	1.0	2000	0.33	2000	0.33	500 1000 2000	0.5	0	2×10^{16}

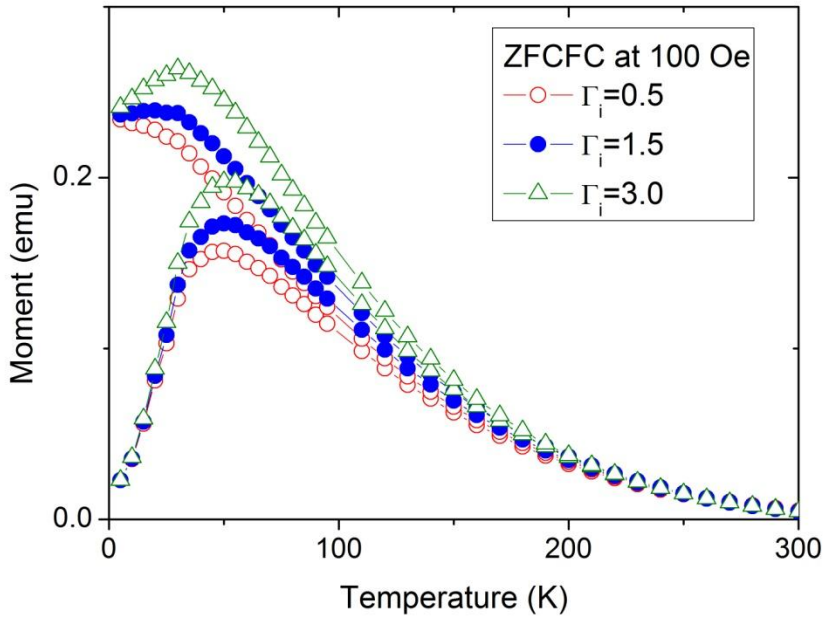


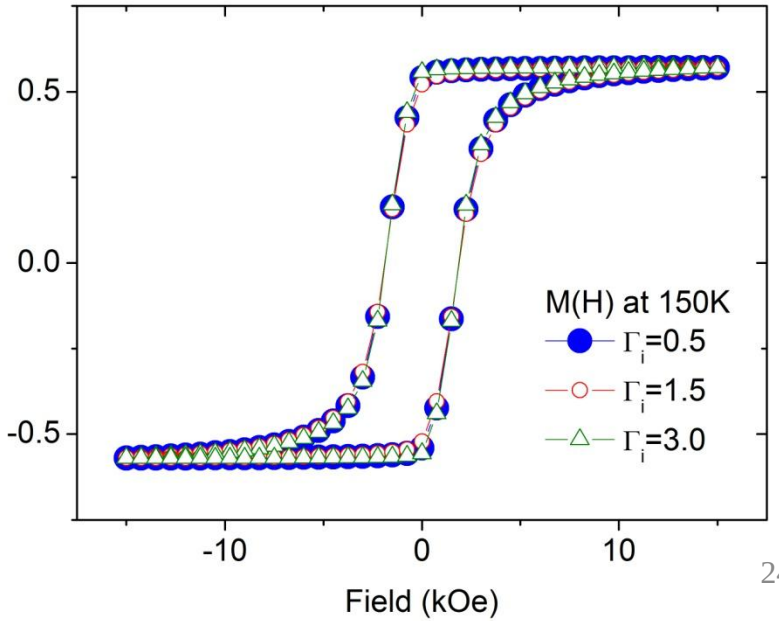


PREM1.0: Examples

M_{ZFCFC} (h_a) and M_{hyst} (T)

							Representative system			
T_c [K]	μ_0 [emu]	Γ	h_{c0} [Oe]	Γ_c	σ_{c0} [Oe]	Γ_c'	σ_{i0} [Oe]	Γ_i	km [Oe]	N
350	5×10^{-17}	1.0	2000	0.33	2000	0.33	500	0.5 1.5 3.0	0	2×10^{16}

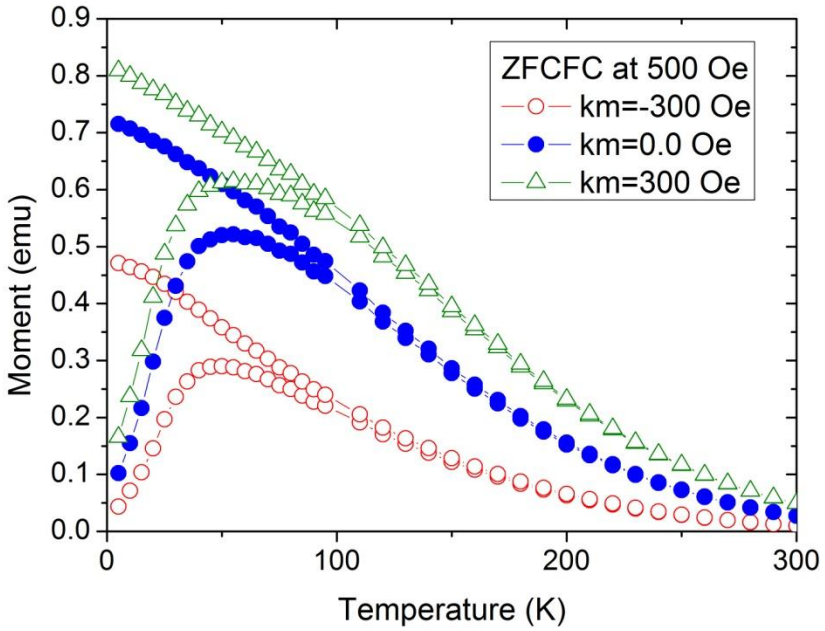


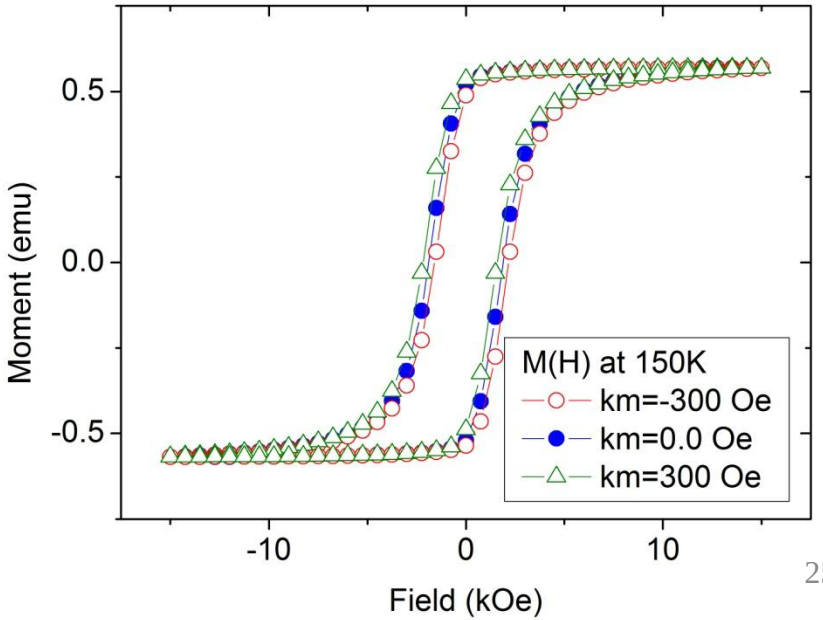


PREM1.0: Examples

M_{ZFCFC} (h_a) and M_{hyst} (T)

							Representative system			
T_c [K]	μ_0 [emu]	Γ	h_{c0} [Oe]	Γ_c	σ_{c0} [Oe]	Γ_c'	σ_{i0} [Oe]	Γ_i	km [Oe]	N
350	5×10^{-17}	1.0	2000	0.33	2000	0.33	500	0.5	-300 0.0 300	2×10^{16}





PREM1.0: Examples

Reversible term M_{rev}

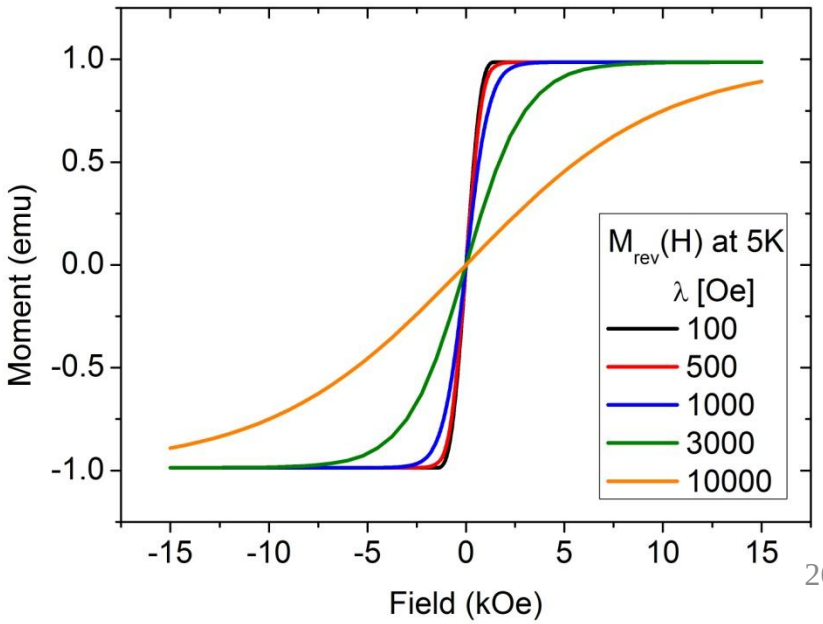
							Representative system			
T_c [K]	μ_0 [emu]	Γ	h_{c0} [Oe]	Γ_c	σ_{c0} [Oe]	Γ_c'	σ_{i0} [Oe]	Γ_i	km [Oe]	N
350	5×10^{-17}	1.0	2000	0.33	2000	0.33	500	0.5	0	2×10^{16}

Reversible term is described by the similar function as superparamagnetic response function:

$$m_{rev} = N\mu(T)\tanh\left(\frac{h_a + s}{\lambda}\right)$$

The total magnetic moment is a sum of both contributions: irreversible "Preisach" term m_P and reversible component m_{rev}:

$$m = (1 - f)\cdot m_P + f \cdot m_{rev}$$



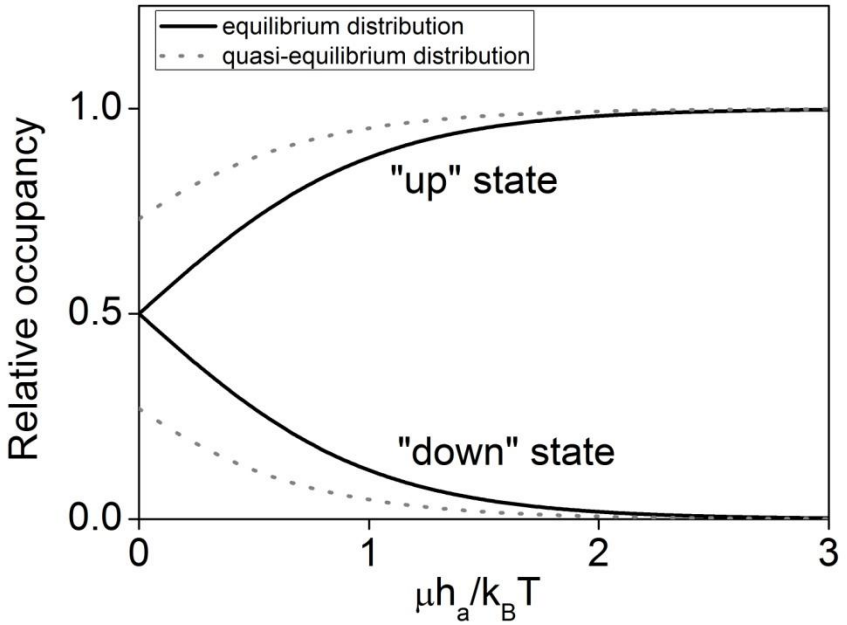
PREM1.0: Examples

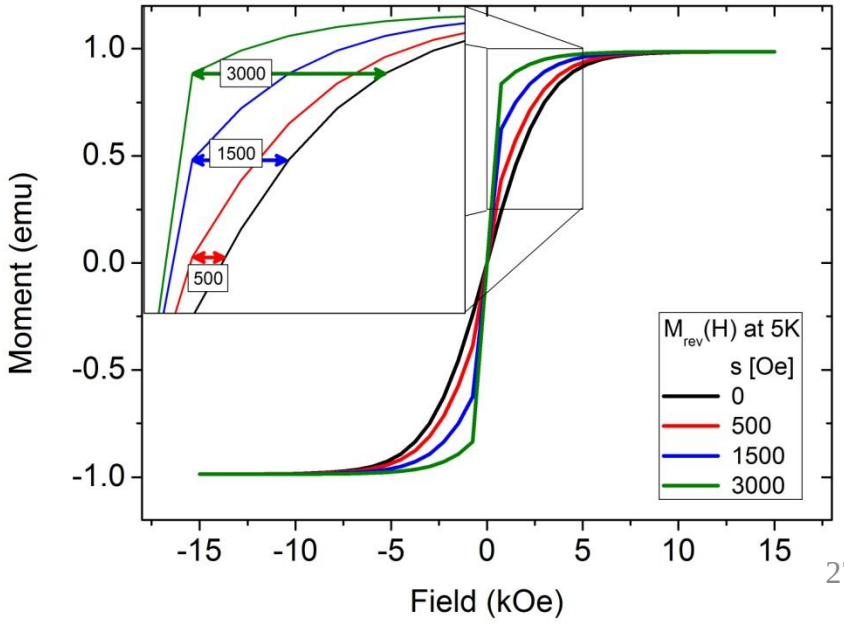
Reversible term M_{rev}

Before the introduction of M_{rev} into theoretical fit all additional contributions to magnetic response, like known diamagnetic or paramagnetic backgrounds, should be subtracted from experimental data. The usage of M_{rev} term must be argued by physical reasons (!), otherwise it leads straightforwardly to misinterpretation of the measurements.

In real systems quasi-equilibrium distribution of states strongly depends on:

1. Non-uniaxial magnetic anisotropy
2. Interactions between the magnetic units





PREM1.0: Examples

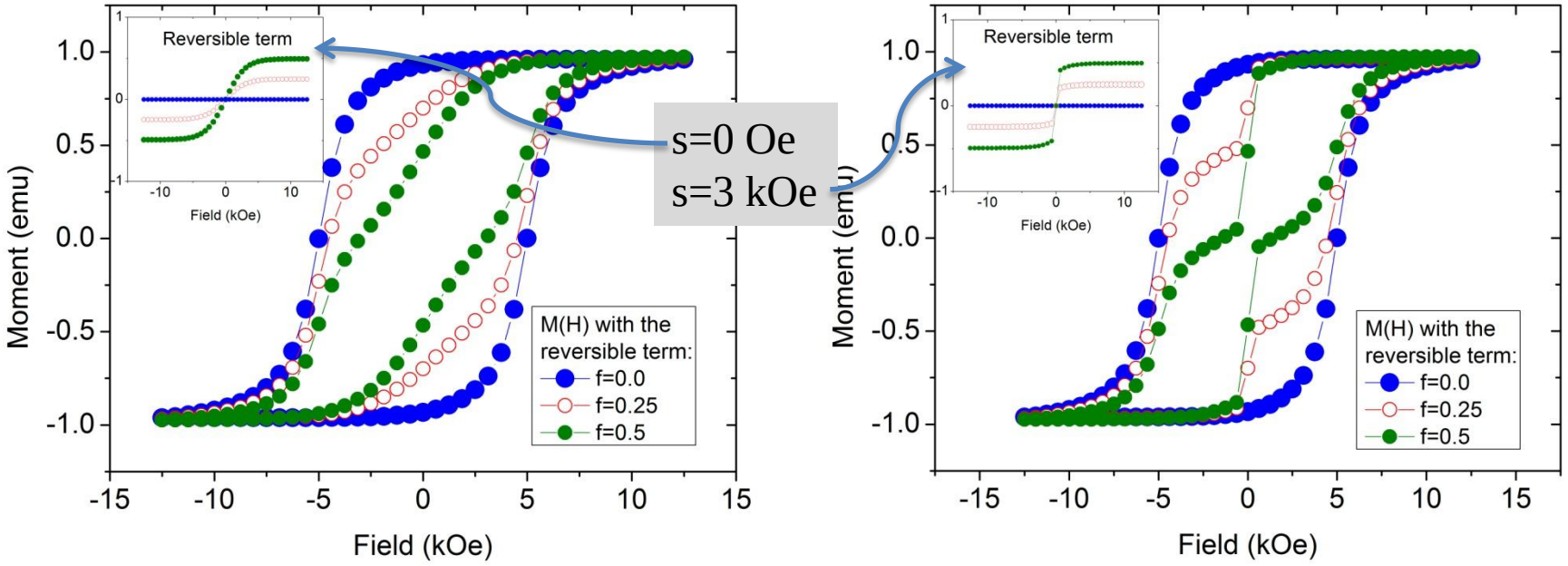
Application of M_{rev} term

Pro:

1. *M_{rev} could give very valuable information about the system*
2. *Deep understanding of the physical properties of the material; following the properties' evolution in the case of systematic investigations*

Contra:

1. *M_{rev} strongly changes hysteresis*
2. *Could lead to misinterpretation of results due to inappropriate usage.*



PREM1.0: Manual fitting

Parameters which can be estimated from the experiment:

Saturation moment: $M_{sat}(T) = \mu(T) \cdot N$

Mean-field coercive field: $\bar{h}_{C0} \approx h_c (T \to 0K)$

Critical temperature: $T_C \approx T(M = 0)$

Critical exponent Γ_i: $\Gamma_i > 1$ if M_{FC} increase with T in the range $T_{min} \ldots T_B$

Long-range interaction field: $km \neq 0$ if $M(H)$ is not symmetric in respect to zero

Shift of T_B on ZFCFC curves performed at different temperatures depends on strength of short-range interactions

PREM1.0: Manual fitting

General recommendations on magnetometry experiments and its theoretical modeling:

1. Complete characterization of material's magnetic behavior should include field- and temperature - dependent experiments.
2. Magnetic history effects should be vanished or taken into account (e.g. small external field applied during sample alignment might introduce strong changes in ZFCFC measurement).
3. μN, h_{c0}, T_C can be estimated directly from the experiments.
4. It is recommended to start fitting from the estimation of μ using known μN and position of T_B.
5. Fitting of M_{ZFCFC} with a certain μ can be achieved via optimization of σ_i parameter.
6. ZFCFC bifurcation is strongly affected by *PDF*, σ_c, σ_i, Γ_c, Γ_i.
7. Atypical shape of hysteresis loop can be defined by reversible component of magnetic response.

PREM1.0: Literature

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