# MAGNETISM IN MATERIALS

Lecture 9: Experimental Techniques
Magnetization & Susceptibility

Ivica Zivkovic

29.04.2025

EPFL

- magnetization
- susceptibility

- magnetization
- magnetic susceptibility
- (magnetic) specific heat

$$F = \ldots + MH + \cdots - TS$$

$$M = \frac{\partial F}{\partial H}$$

$$\chi = \frac{\partial M}{\partial H} = \frac{\partial^2 F}{\partial H^2}$$

- magnetization
- magnetic susceptibility
- (magnetic) specific heat

$$F = \ldots + MH + \cdots - TS$$

$$M = \frac{\partial F}{\partial H}$$

$$\chi = \frac{\partial M}{\partial H} = \frac{\partial^2 F}{\partial H^2}$$

experiment

$$M = \sum \uparrow - \sum \downarrow$$

$$\chi = \frac{\partial M}{\partial H} = magnetic\ freedom$$

- stray fields
- non-selective (sample, background, impurities,…)
- $\Delta\Phi$-based
- 90+% SQUID (the rest is induction in Cu-coils)
- most often a simple characterization technique

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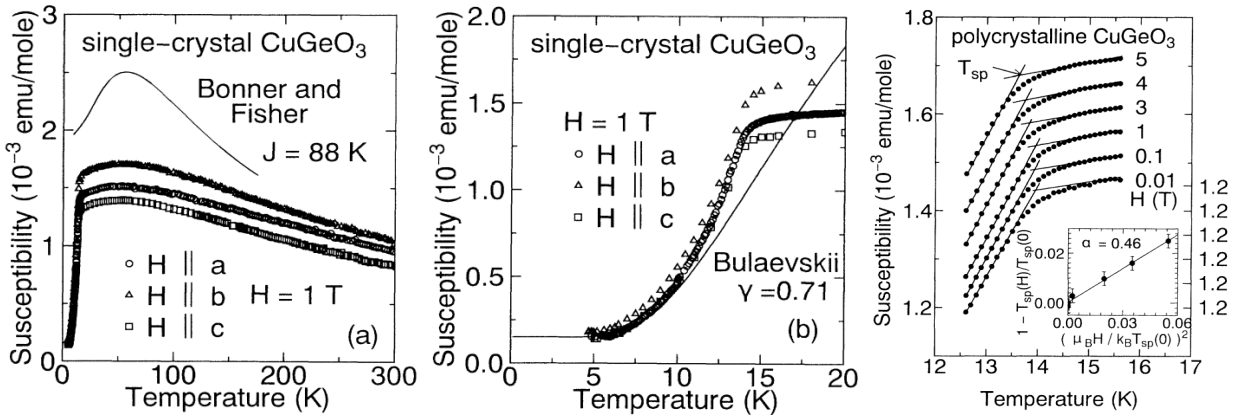
VOLUME 70, NUMBER 23 PHYSICAL REVIEW LETTERS 7 JUNE 1993

**Observation of the Spin-Peierls Transition in Linear $Cu^{2+}$ (Spin-$\frac{1}{2}$) Chains in an Inorganic Compound $CuGeO_3$**

1400+ citations

Masashi Hase, Ichiro Terasaki, and Kunimitsu Uchinokura
*Department of Applied Physics, The University of Tokyo, 7-3-1 Hongo, Bunkyo-Ku, Tokyo 113, Japan*
(Received 4 January 1993)

The magnetic susceptibility of single-crystal $CuGeO_3$, a linear $Cu^{2+}$ (spin-$\frac{1}{2}$) chain compound, was measured. The susceptibilities in all the directions rapidly drop to small constant values with decreasing temperature below a phase transition temperature near 14 K. The magnetic-field dependence of the transition temperature quantitatively agrees with both theoretical predictions and experimental results for organic spin-Peierls systems. This Letter is the first report of an unambiguous determination of the existence of the spin-Peierls transition in an inorganic compound.



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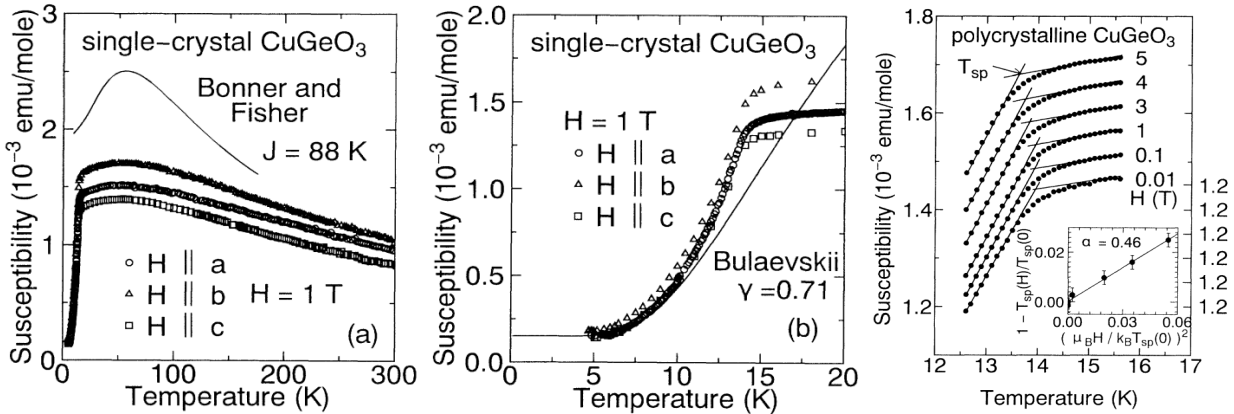


## Magnetic bistability in a metal-ion cluster

**R. Sessoli*, D. Gatteschi*‡, A. Caneschi* & M. A. Novak‡§**

* Department of Chemistry, University of Florence, Via Maragliano 77, 50144 Firenze, Italy
‡ Instituto de Fisica, Universidade Federal do Rio de Janeiro, Rio de Janeiro 21944, Brasil
§ Centre de Recherches sur les Tres Basses Temperatures, CNRS, 38042 Grenoble, France
† To whom correspondence should be addressed

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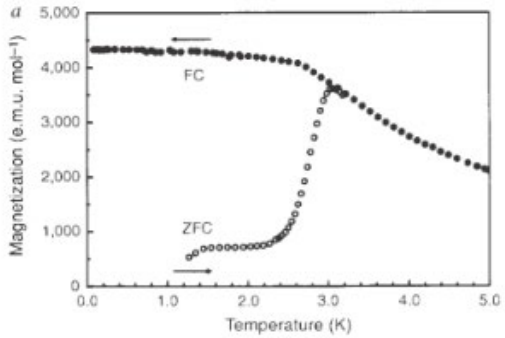
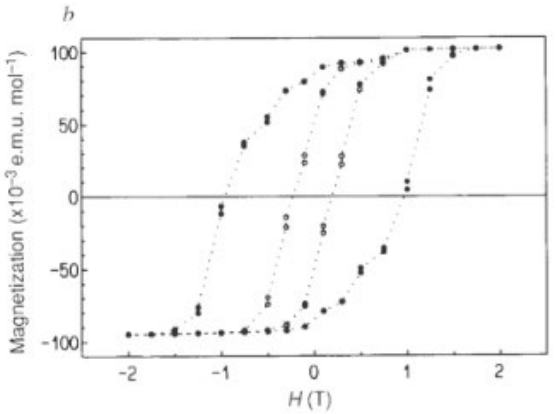
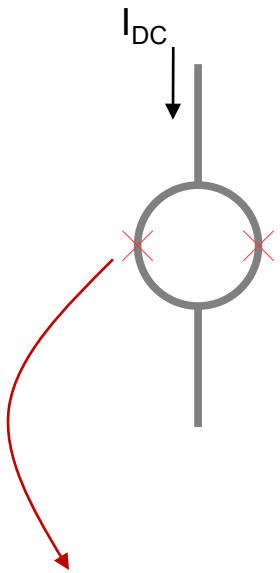


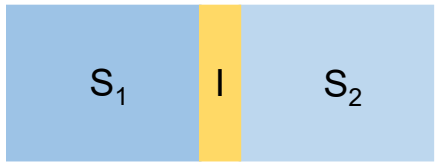

3500+ citations



- superconducting quantum interference device
- converts nanoAmps to Volts




Josephson junction

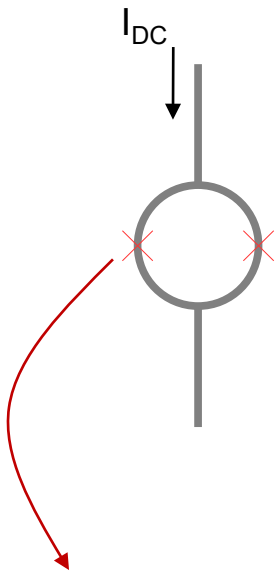



$$I_{DC} = I_C \sin(\varphi_1 - \varphi_2)$$

AC: $$\frac{\partial(\varphi_1 - \varphi_2)}{\partial t} = \frac{2\pi}{\Phi_0} V = \omega$$

voltage-frequency converter

- superconducting quantum interference device
- converts nanoAmps to Volts

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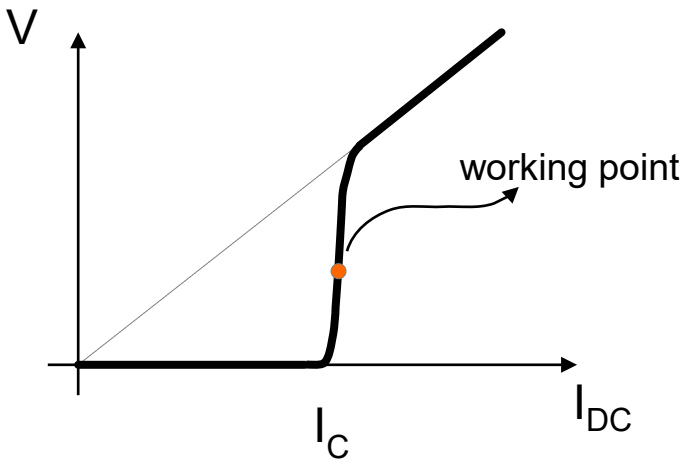
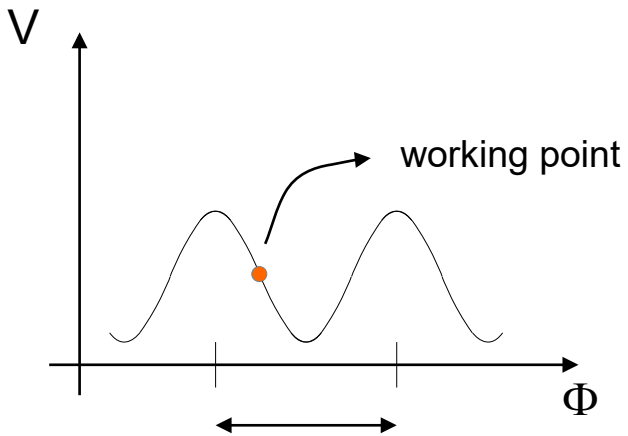
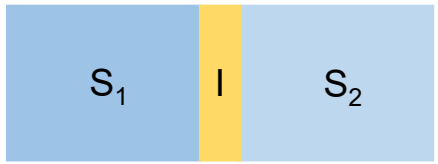



$$\Phi_0 = \frac{h}{2e} = 2.068 \cdot 10^{-15}\ \text{Wb}$$

[1 T = 1 Wb/m$^2$]

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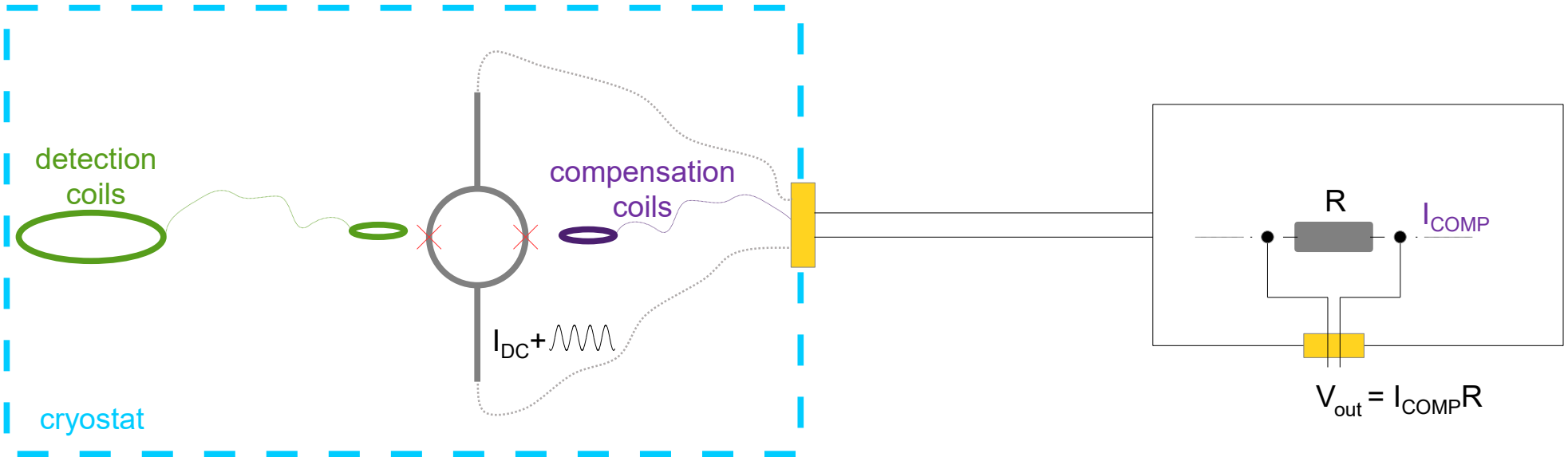
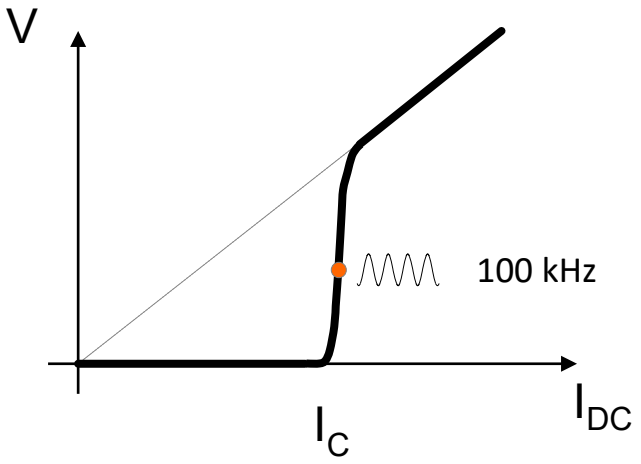
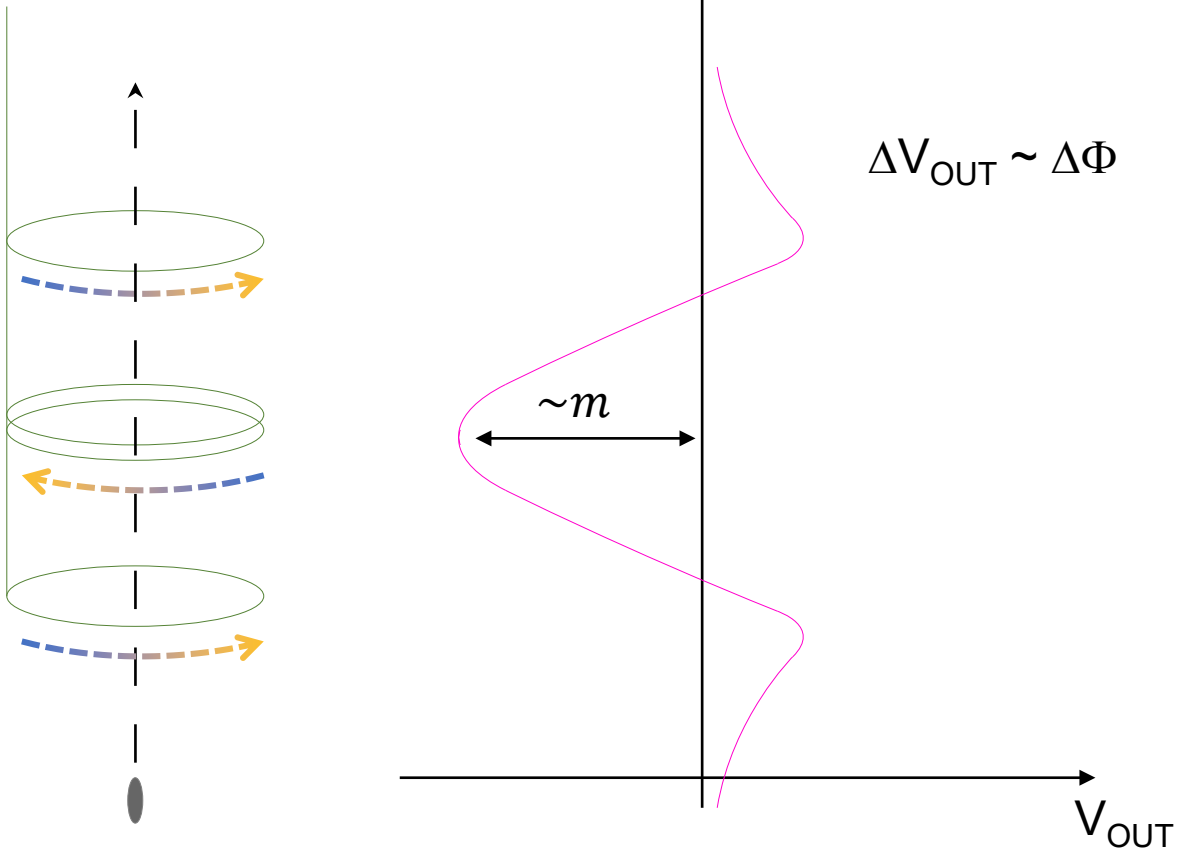



$$\Delta\Phi \rightarrow \Delta V \rightarrow \Delta I_{COMP} \rightarrow \Delta V = 0$$

feedback loop keeps
the working point fixed



detection coils



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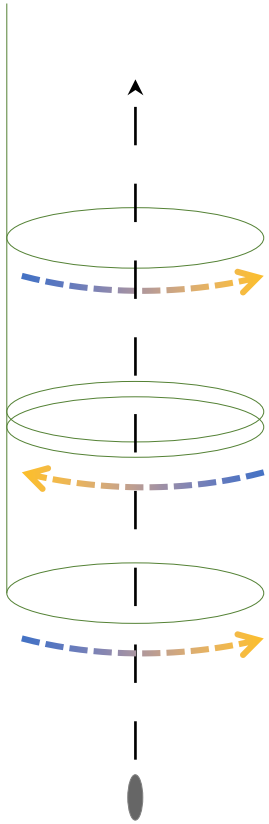
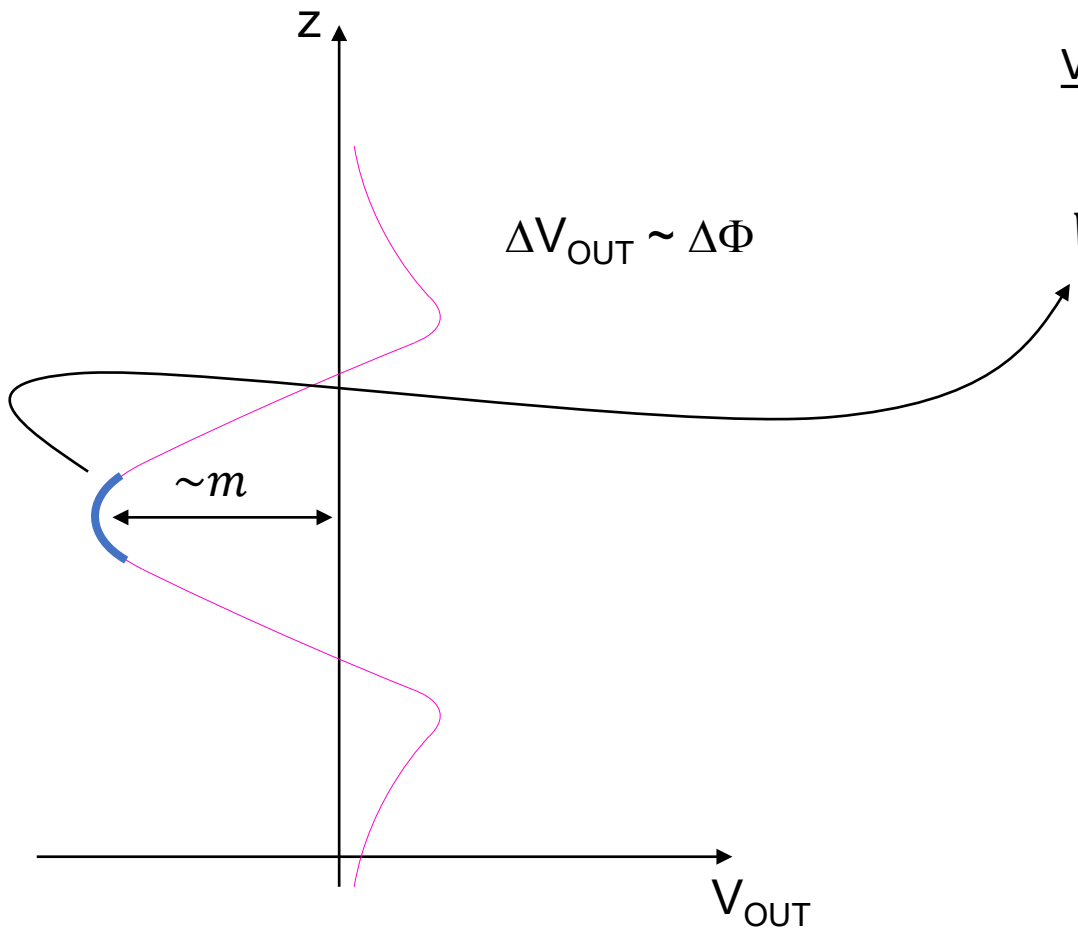
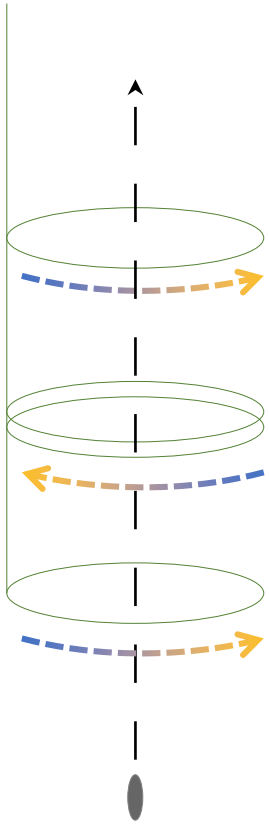


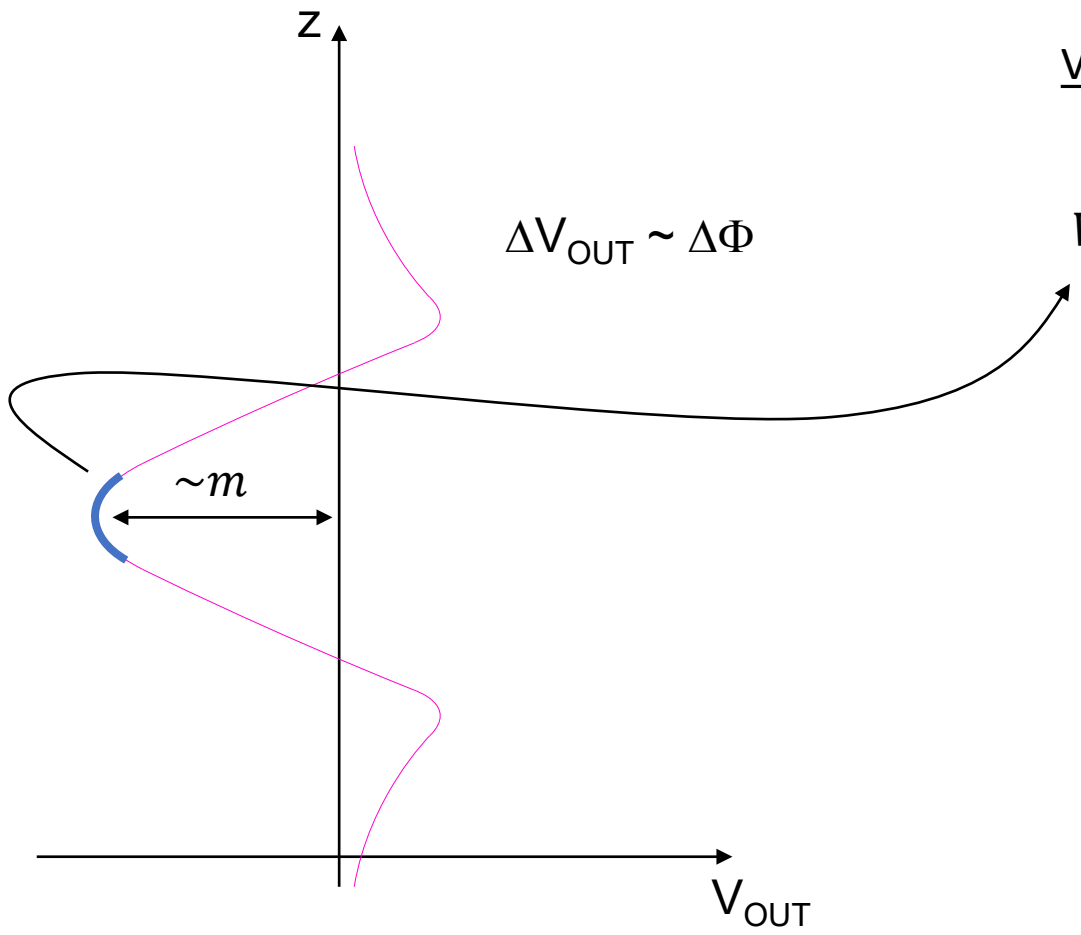



VSM option

$V = kz^2$

detection coils

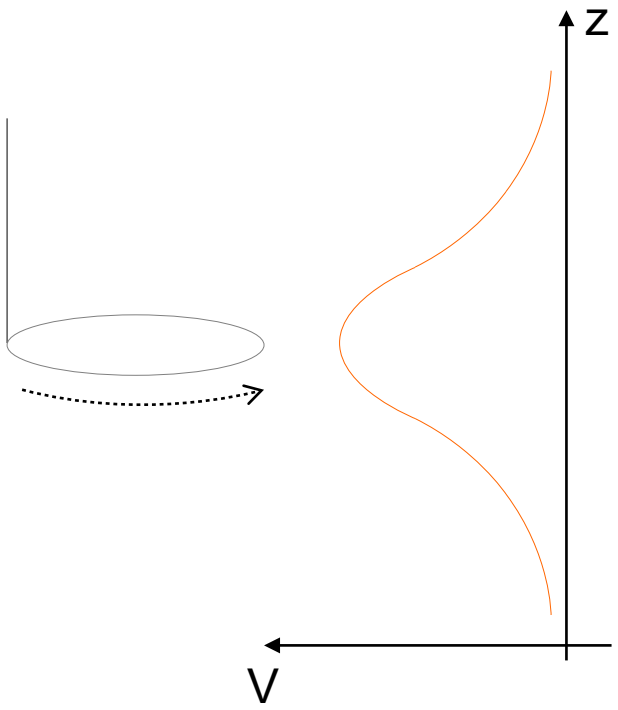


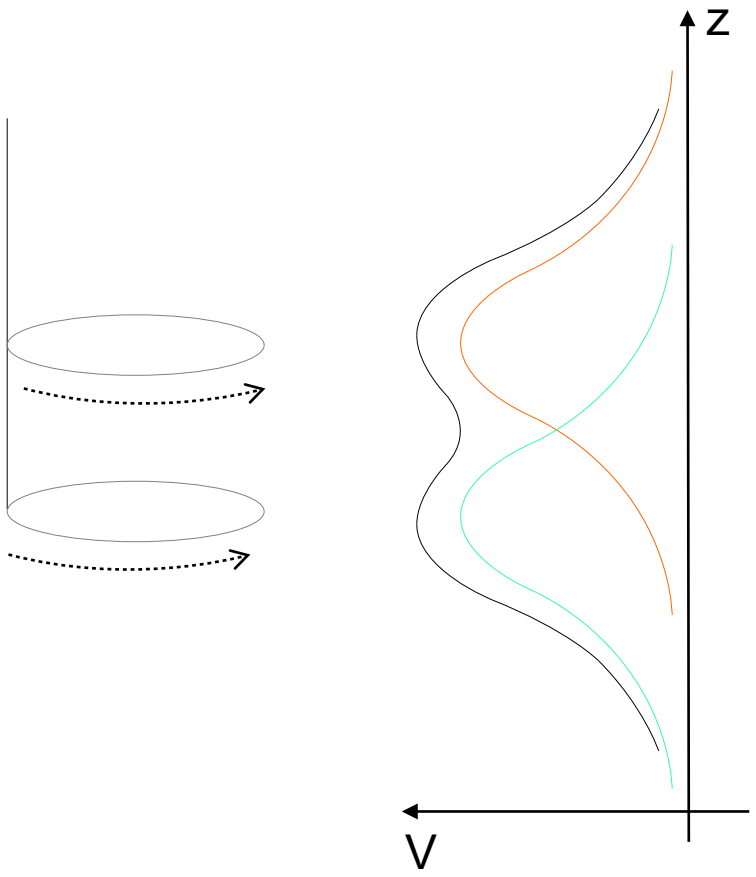


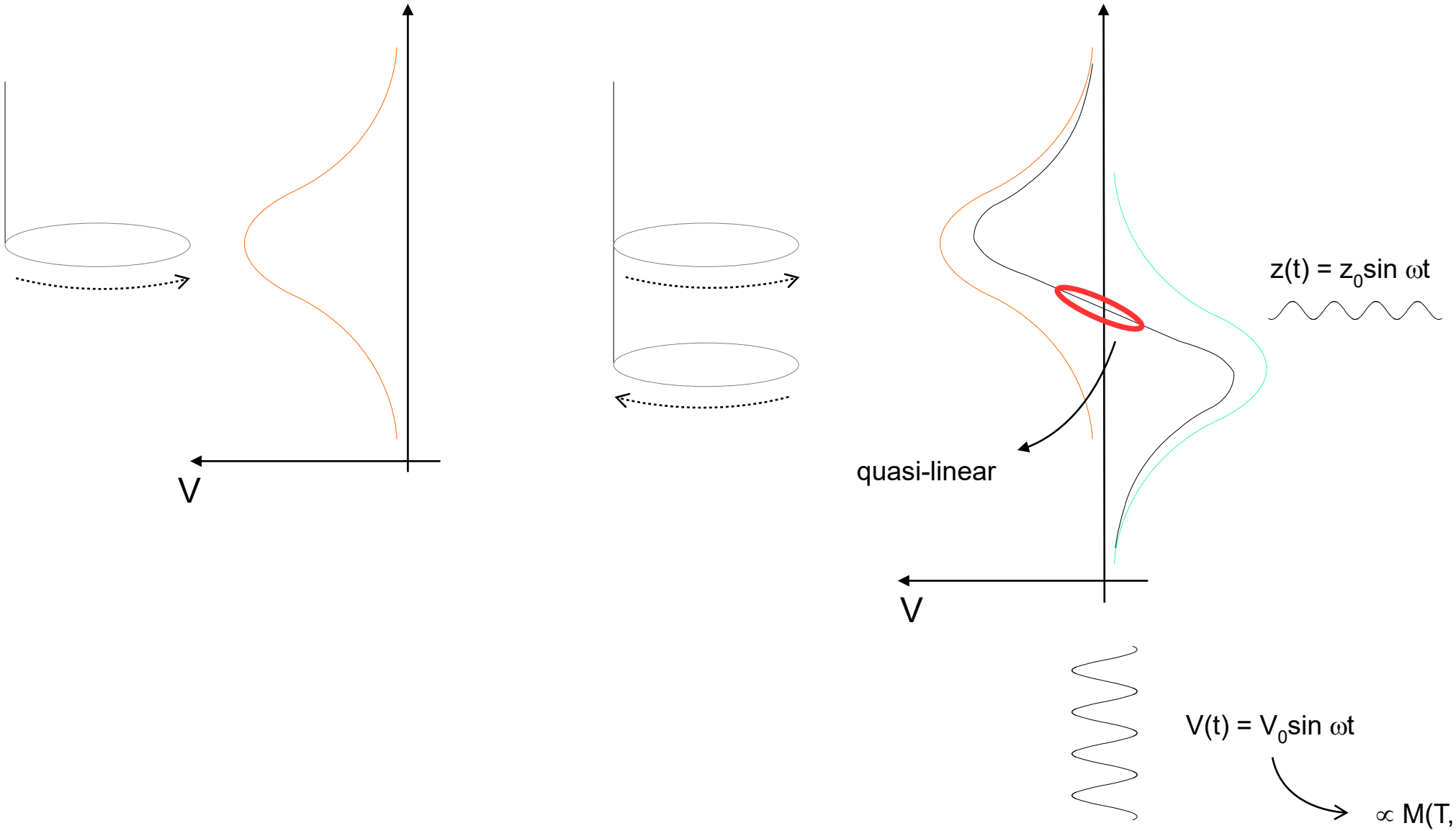

VSM option

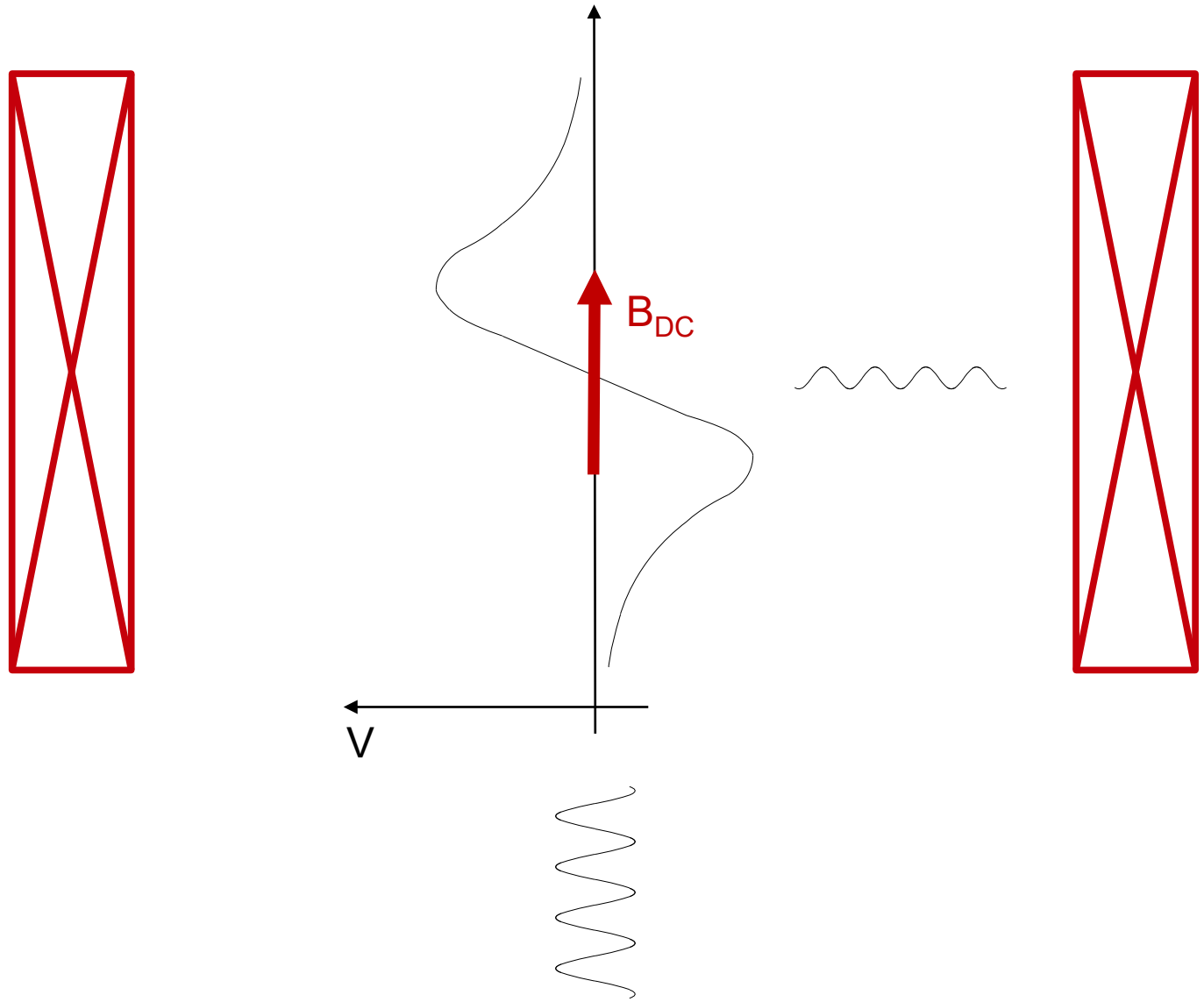
$V = kz^2$

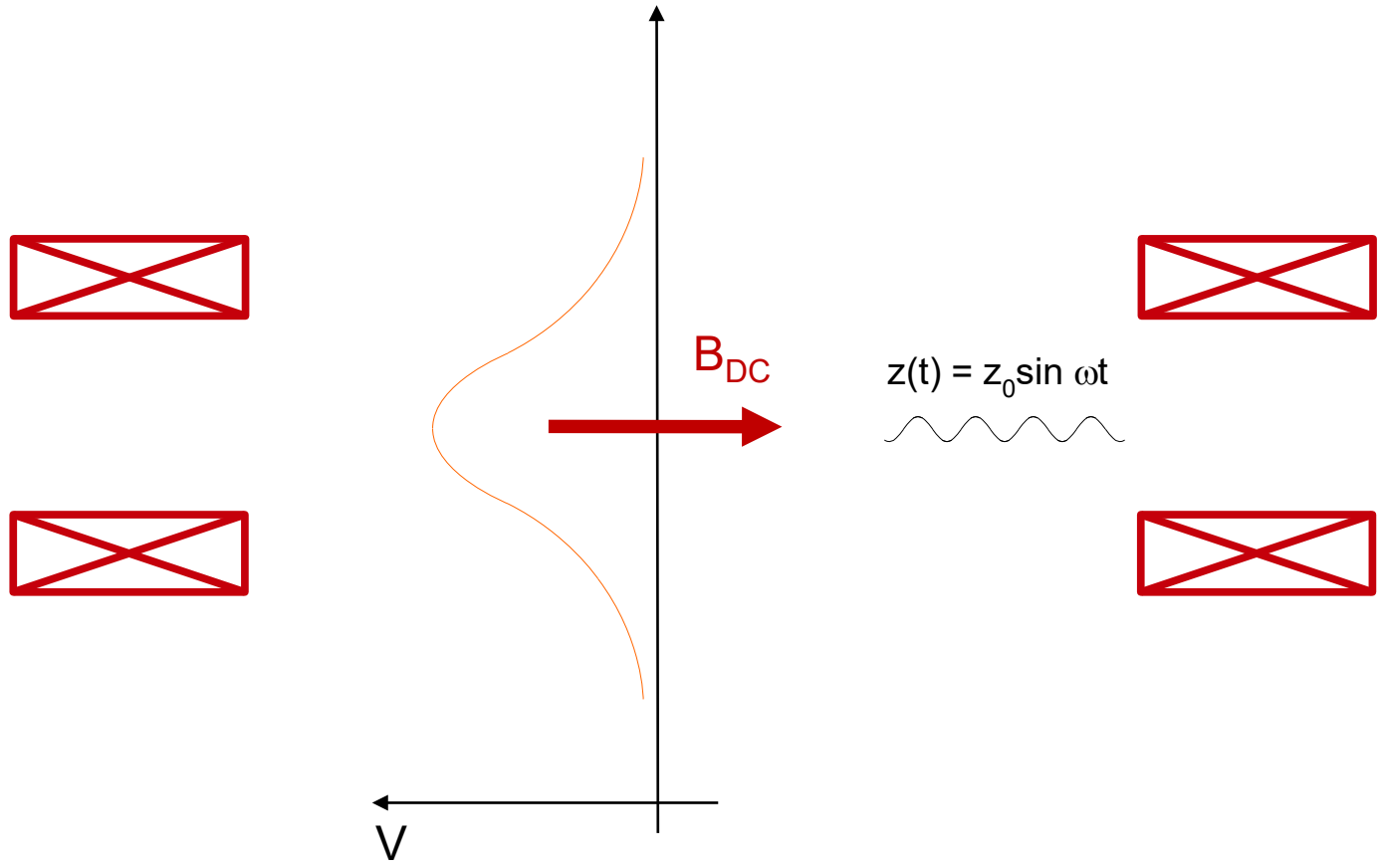
sensitivity: $10^{-8}$ emu


z
V


z
V

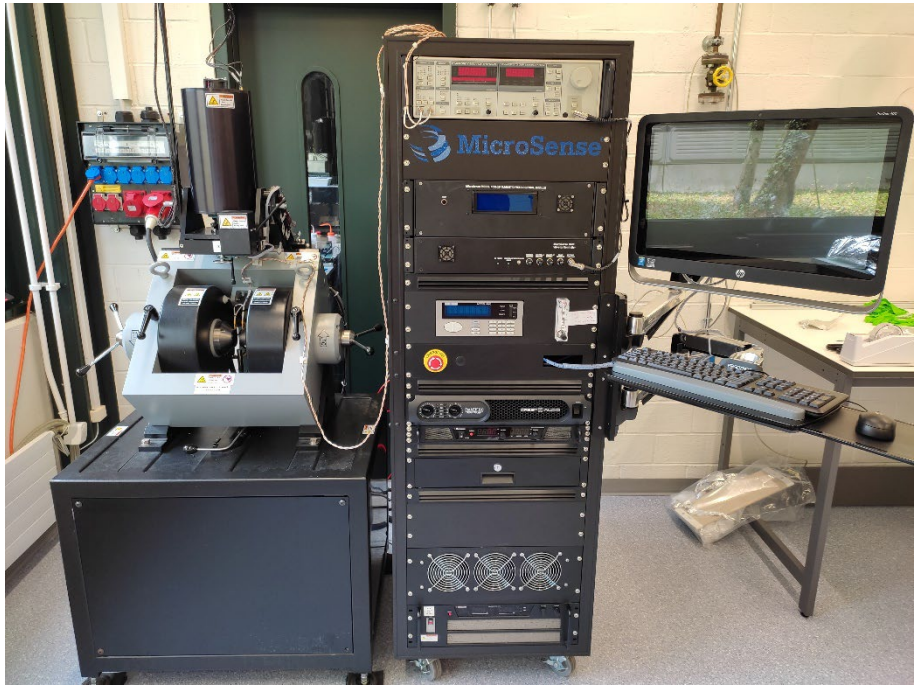

V
z(t) = z0sin ωt
quasi-linear
V
V(t) = V0sin ωt
∝ M(T,H)

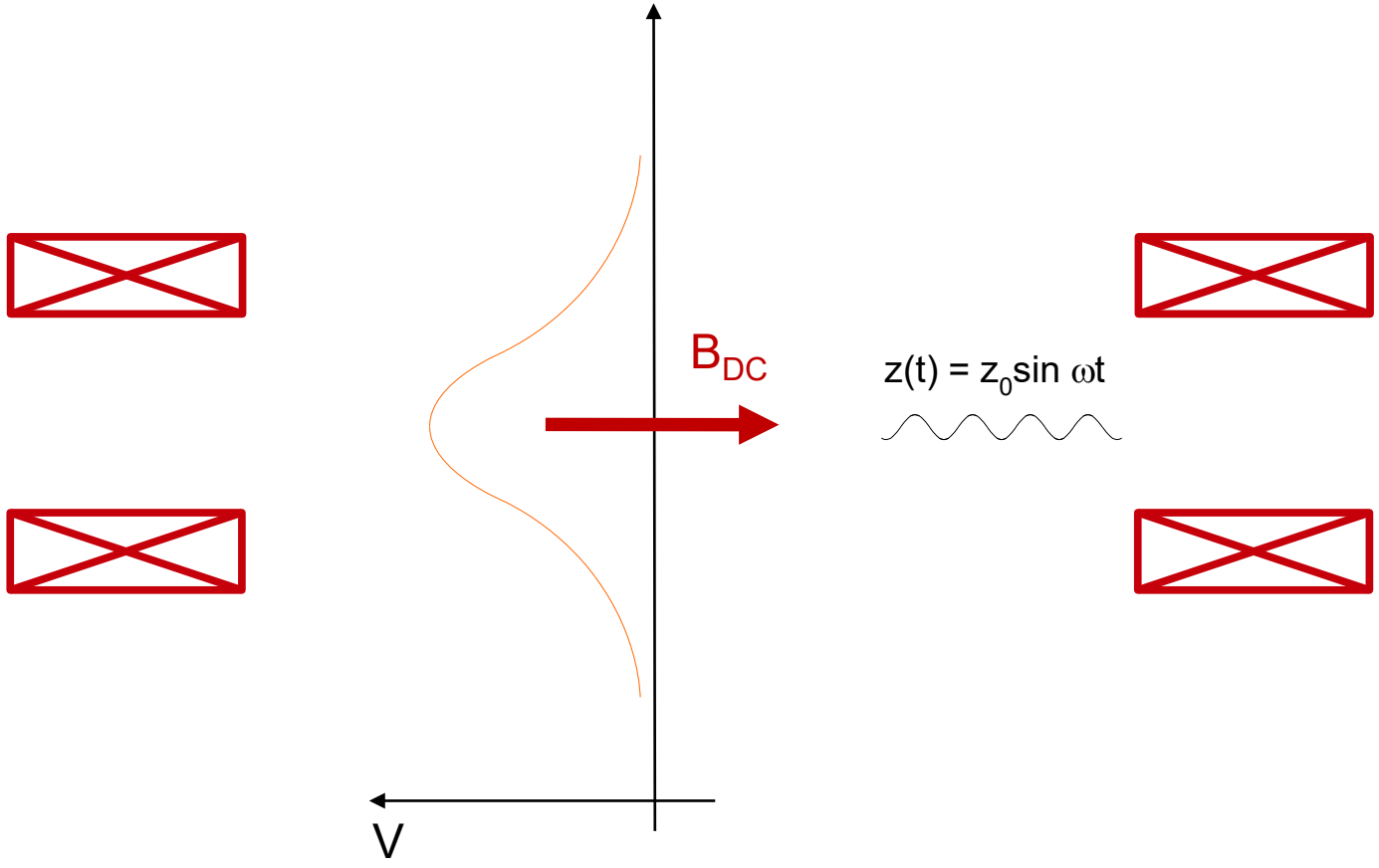

$B_{DC}$
V




allows easy sample rotation

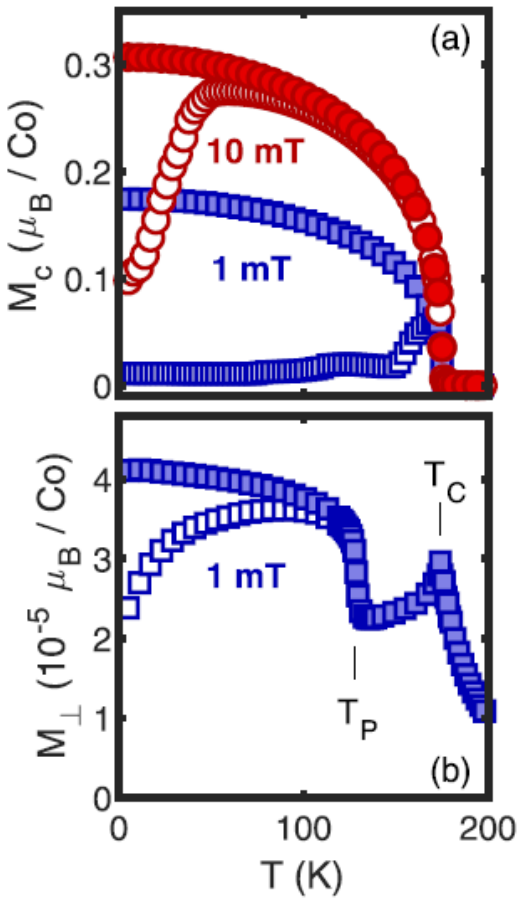
sensitivity: $10^{-6}$ emu

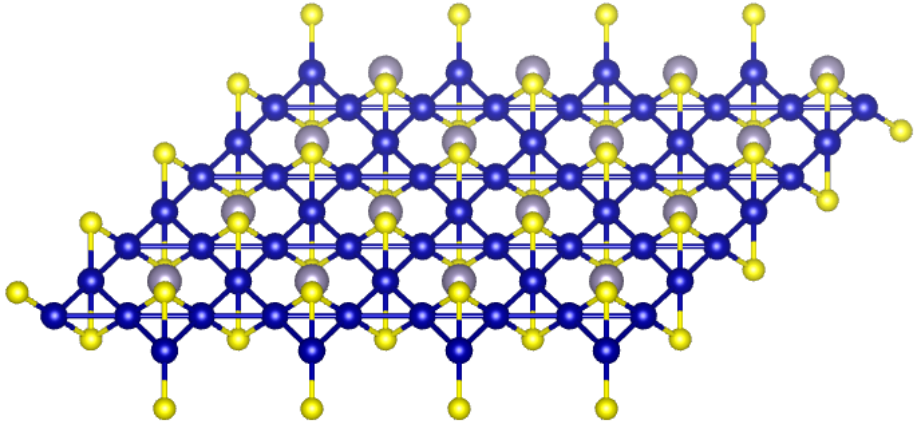



allows easy sample rotation

ferromagnet



$Co_3Sn_2S_2$

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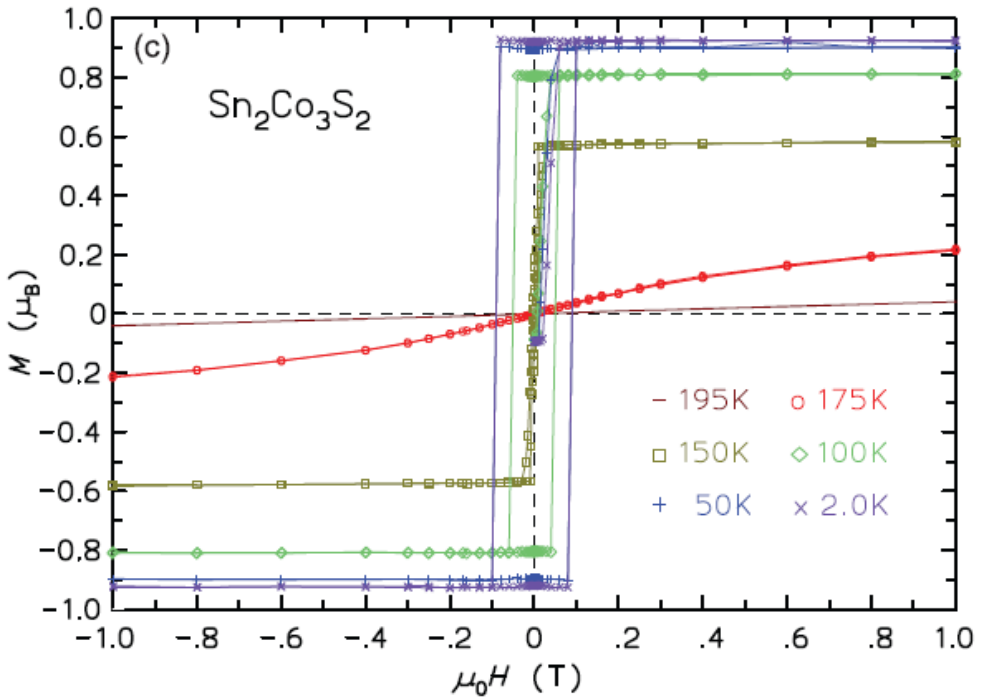
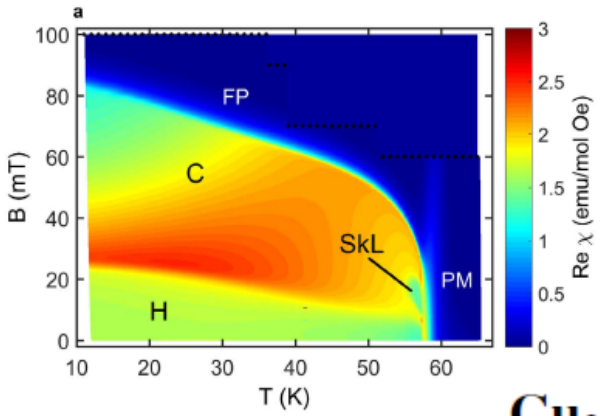
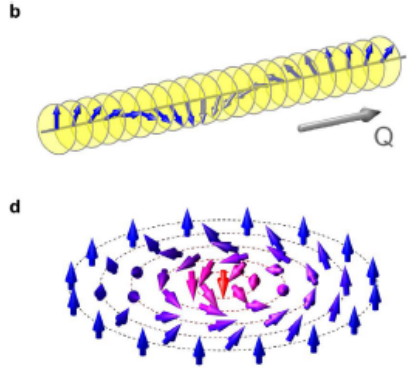
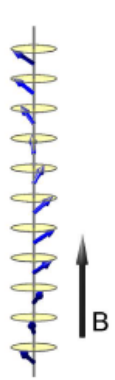
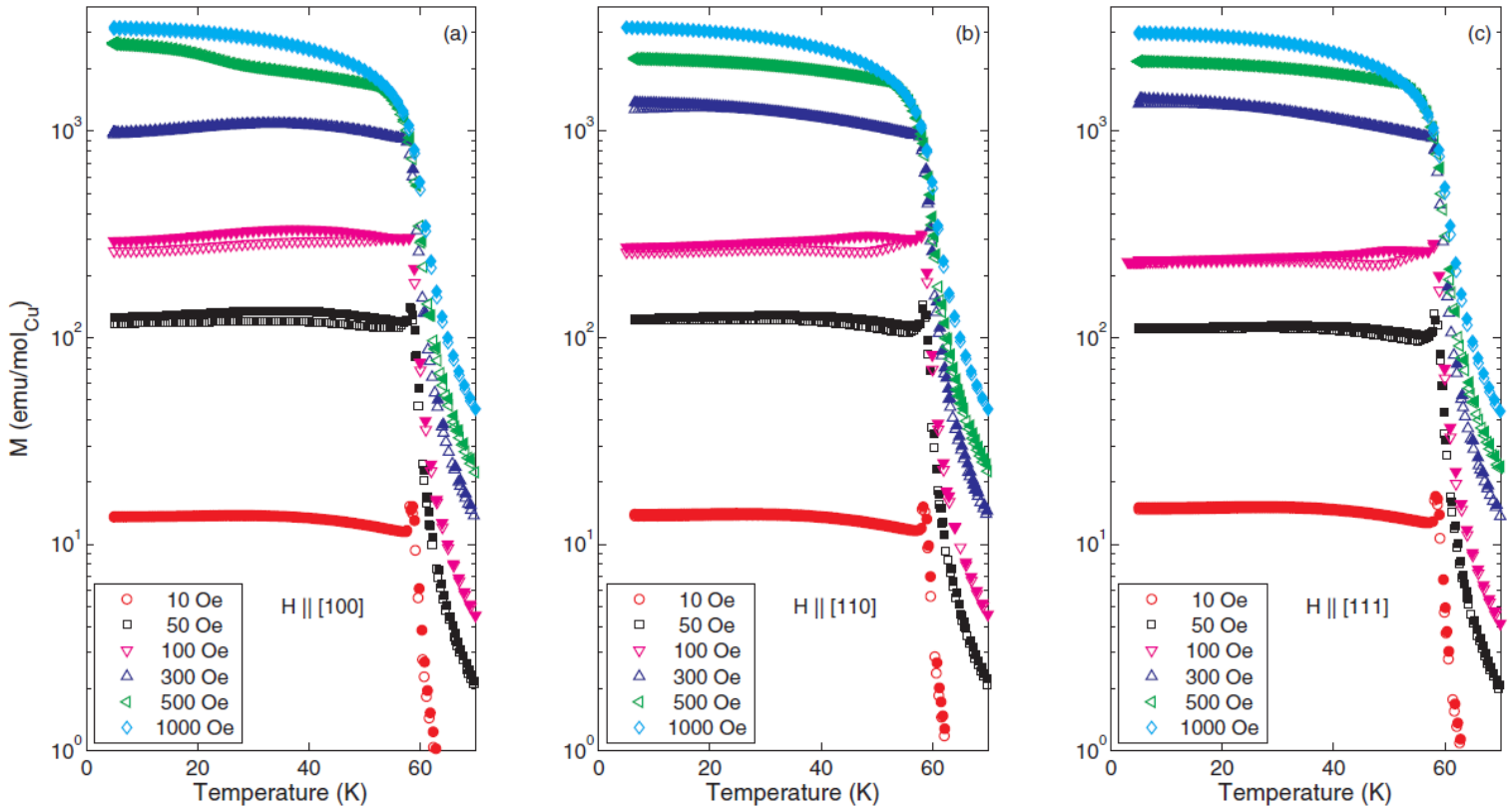


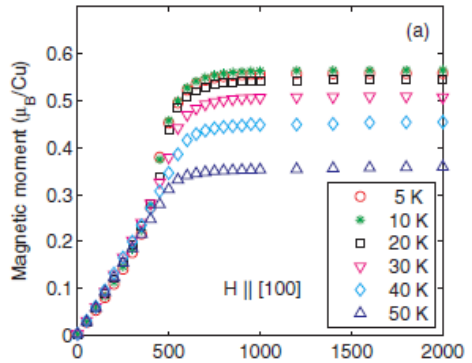

a
FP
C
SkL
PM
H
B (mT)
T (K)
Re χ (emu/mol Oe)

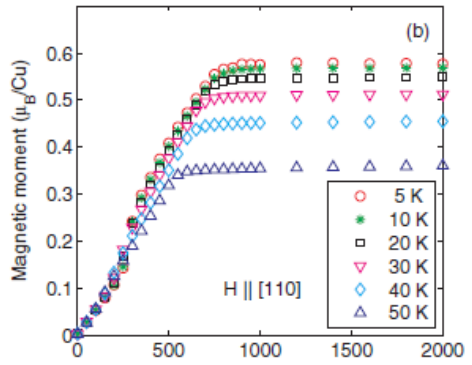

b
Q
d

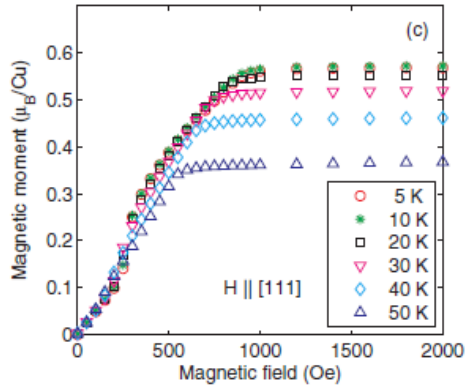

c
B

$Cu_2OSeO_3$

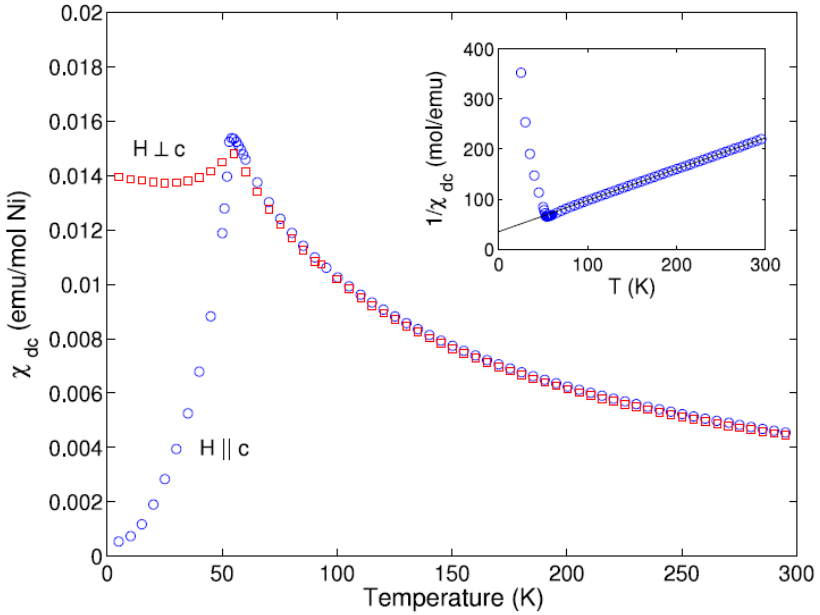

(a)
(b)
(c)
M (emu/mol$_{Cu}$)
Temperature (K)
10 Oe
50 Oe
100 Oe
300 Oe
500 Oe
1000 Oe
H || [100]
H || [110]
H || [111]


(a)
Magnetic moment (μB/Cu)
H || [100]
5 K
10 K
20 K
30 K
40 K
50 K

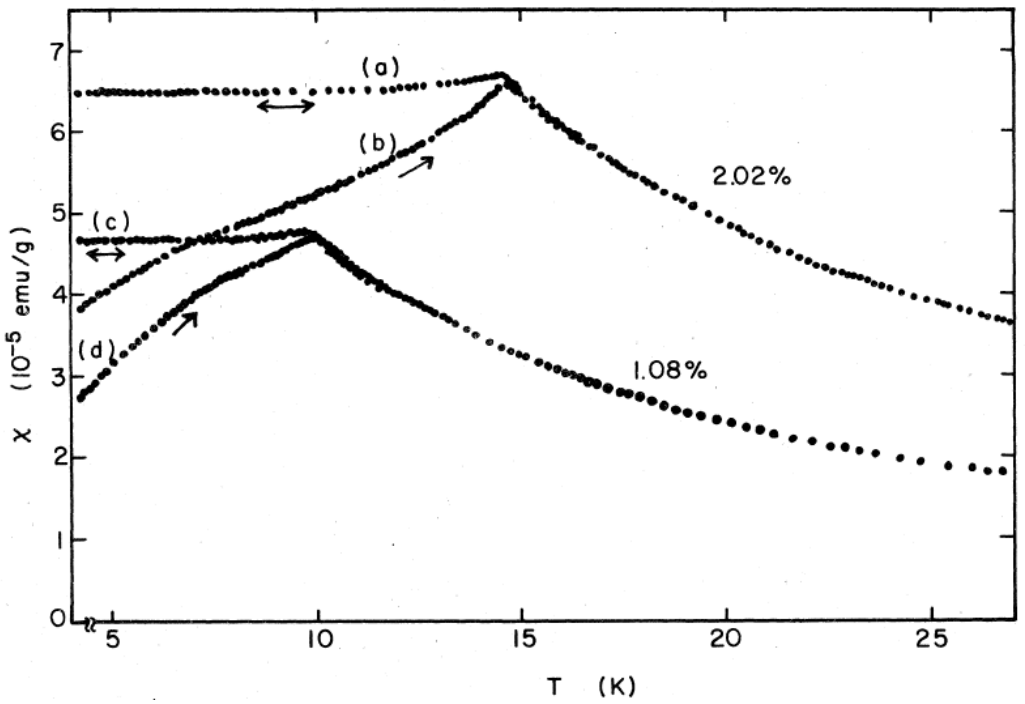

(b)
Magnetic moment (μB/Cu)
H || [110]
5 K
10 K
20 K
30 K
40 K
50 K


(c)
Magnetic moment (μB/Cu)
H || [111]
5 K
10 K
20 K
30 K
40 K
50 K
Magnetic field (Oe)

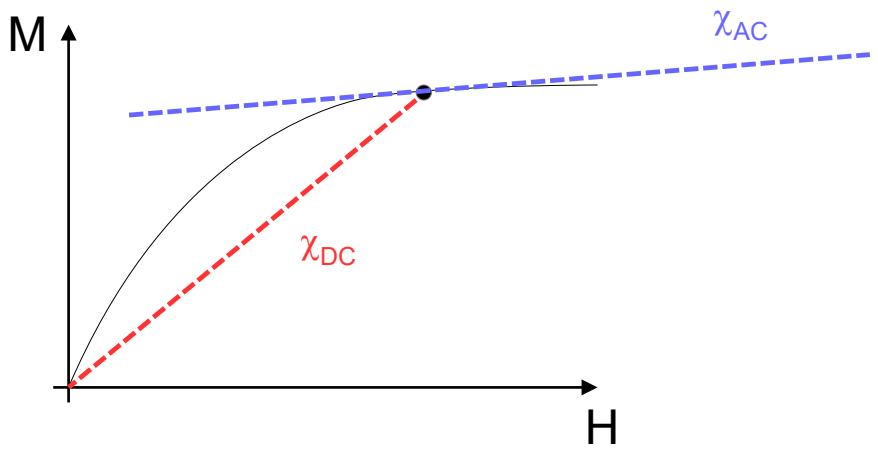
antiferromagnet




spin-glass



- dc = M/H
- ac = dM/dH



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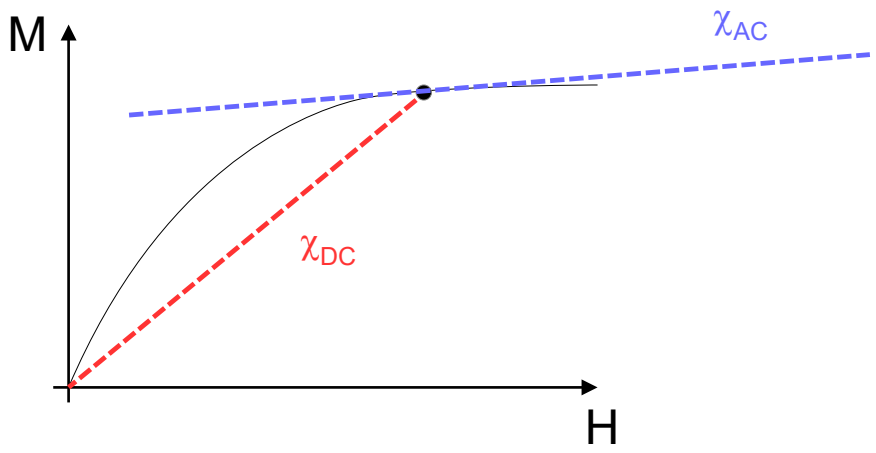
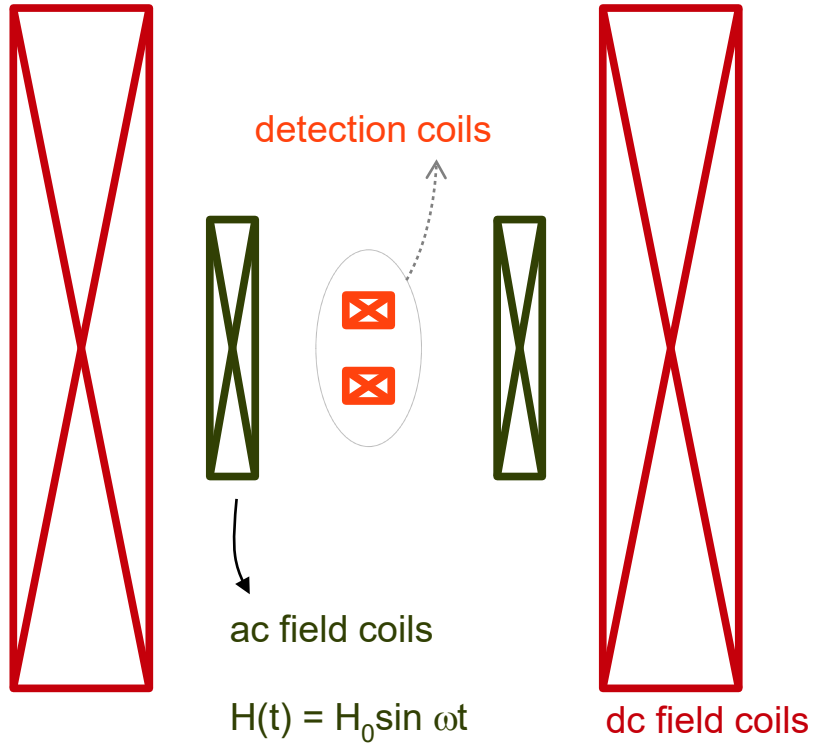
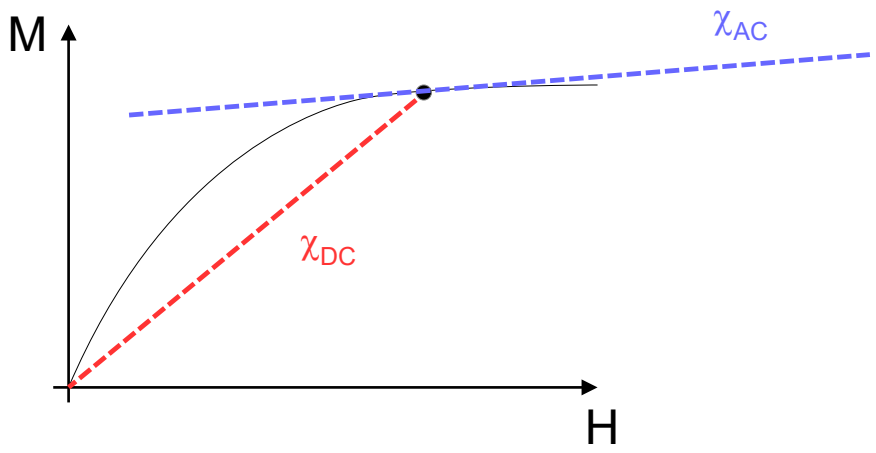
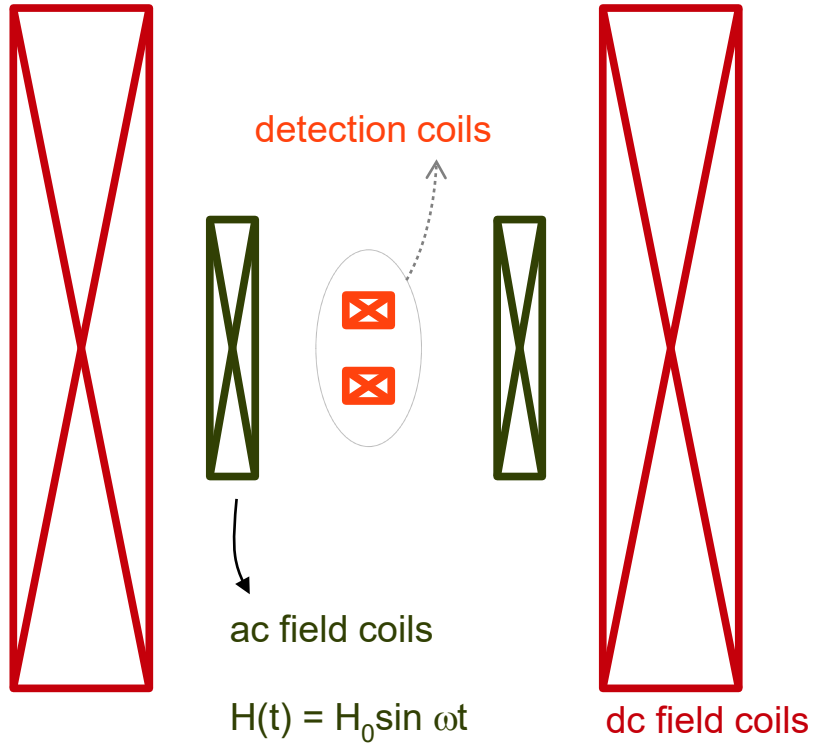

M
H
$\chi_{AC}$
$\chi_{DC}$


detection coils
ac field coils
$H(t) = H_0 \sin \omega t$
dc field coils

- dc = M/H
- ac = dM/dH


M
H
$\chi_{AC}$
$\chi_{DC}$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ac field coils
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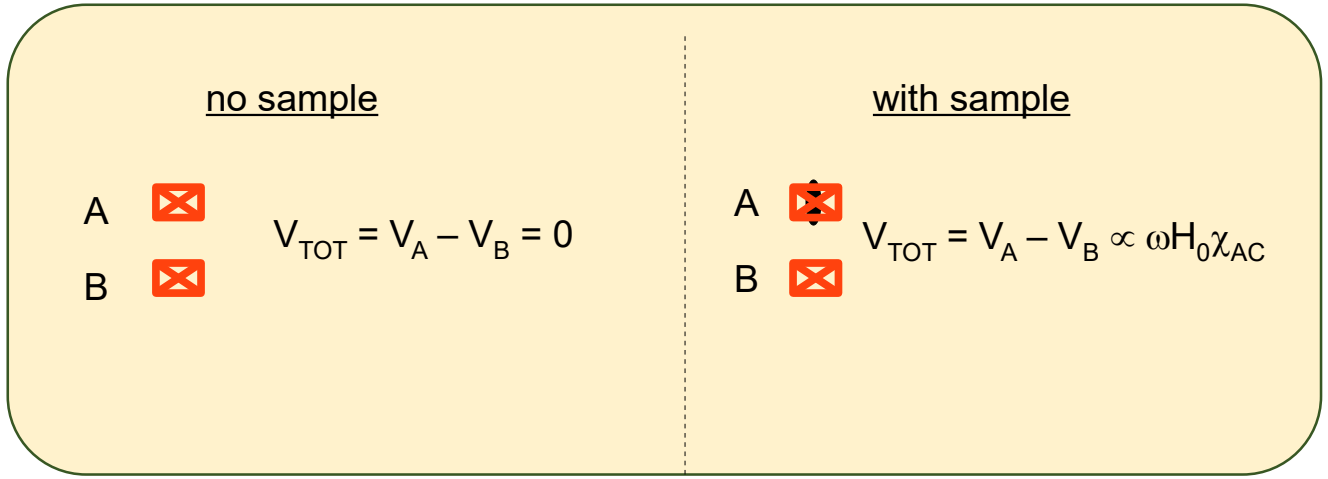
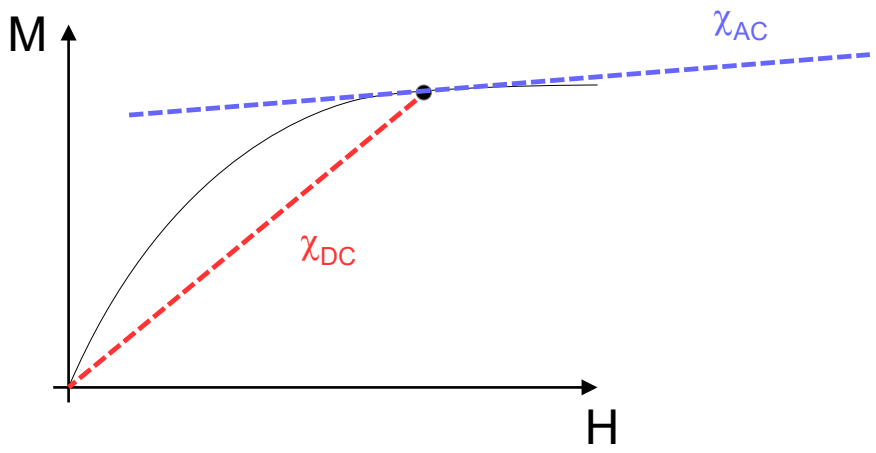
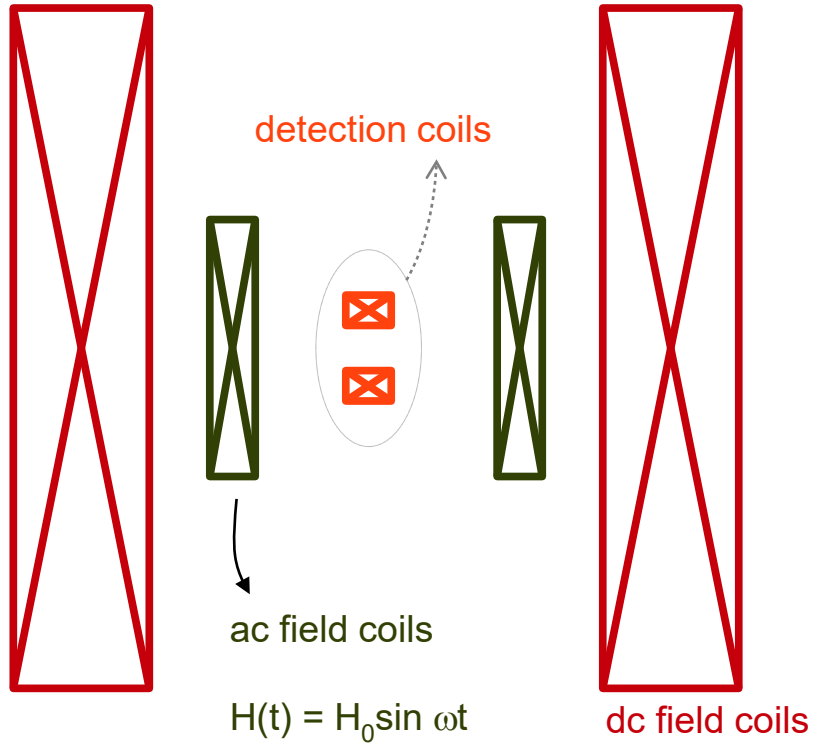
dc field coils

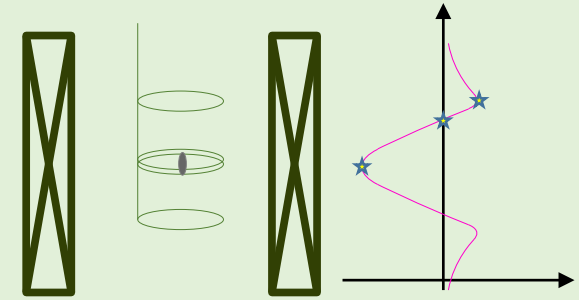

no sample
A
B
$V_{TOT} = V_A - V_B = 0$
with sample
A
B
$V_{TOT} = V_A - V_B \propto \omega H_0 \chi_{AC}$

- dc = M/H
- ac = dM/dH




SQUID-based ac



no sample

A
B

$V_{TOT} = V_A - V_B = 0$

with sample

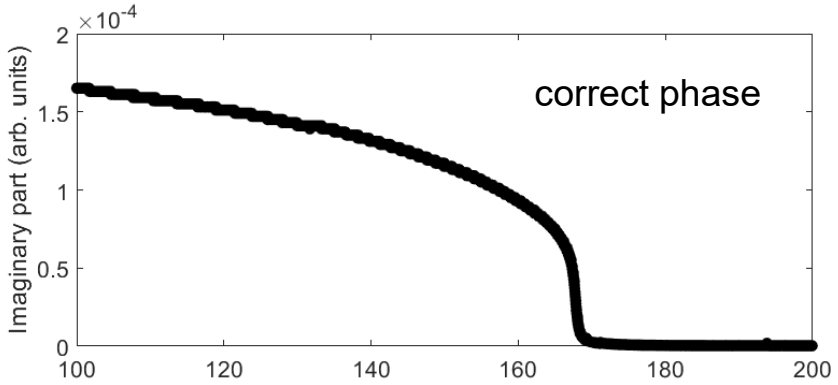
A
B

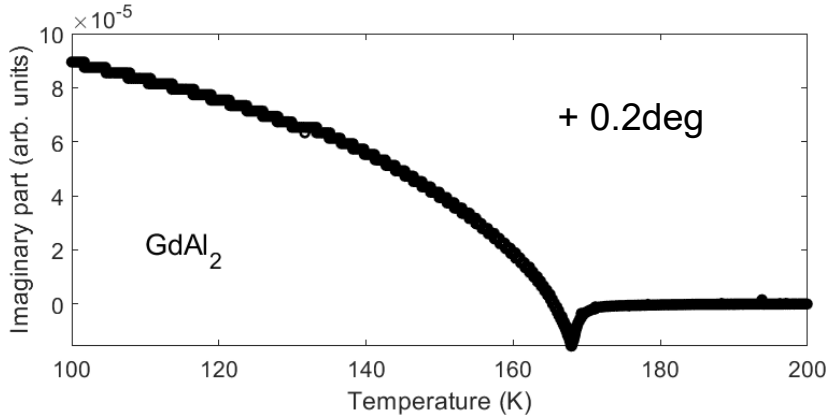
$V_{TOT} = V_A - V_B \propto \omega H_0 \chi_{AC}$

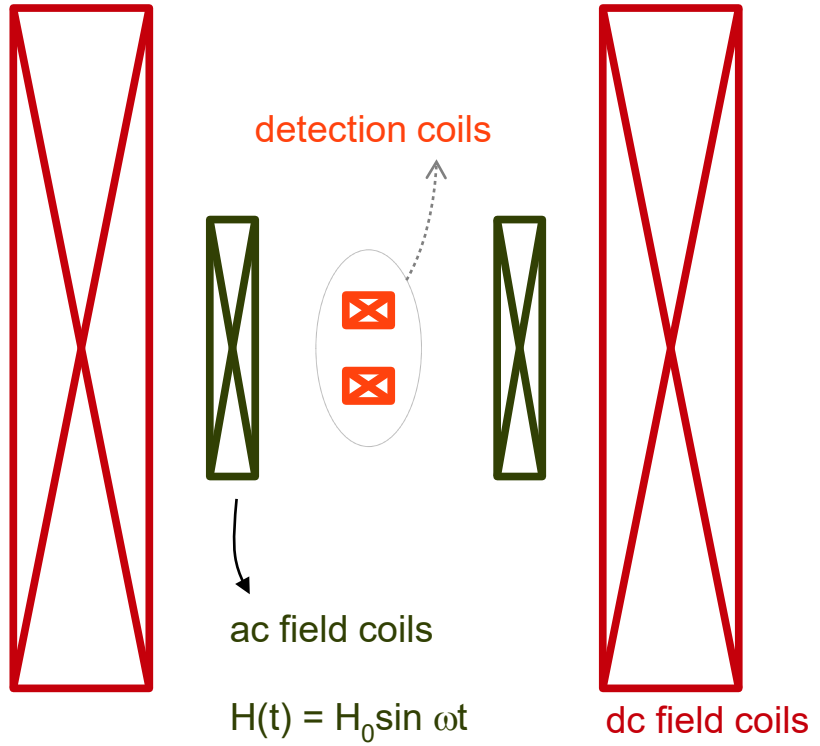
## ❖ phase issues

$\chi_{AC} = \chi' + i\chi''$

energy dissipation > 0




<u>no sample</u>

A
B

$V_{TOT} = V_A - V_B = 0$

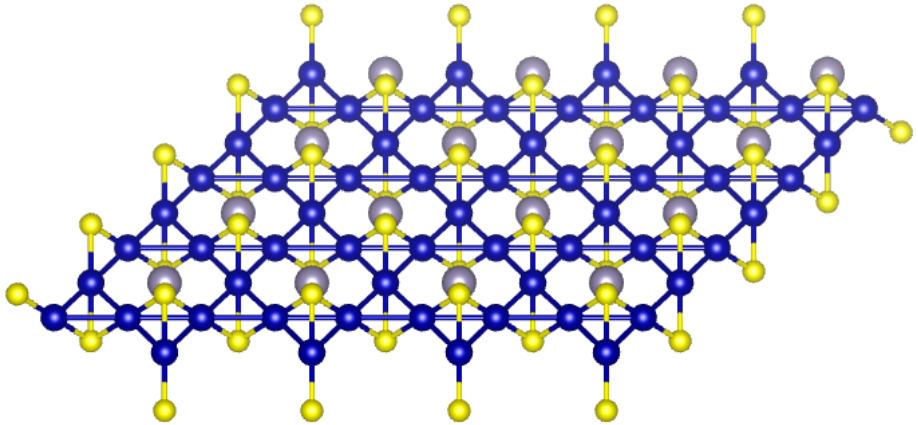
<u>with sample</u>

A
B

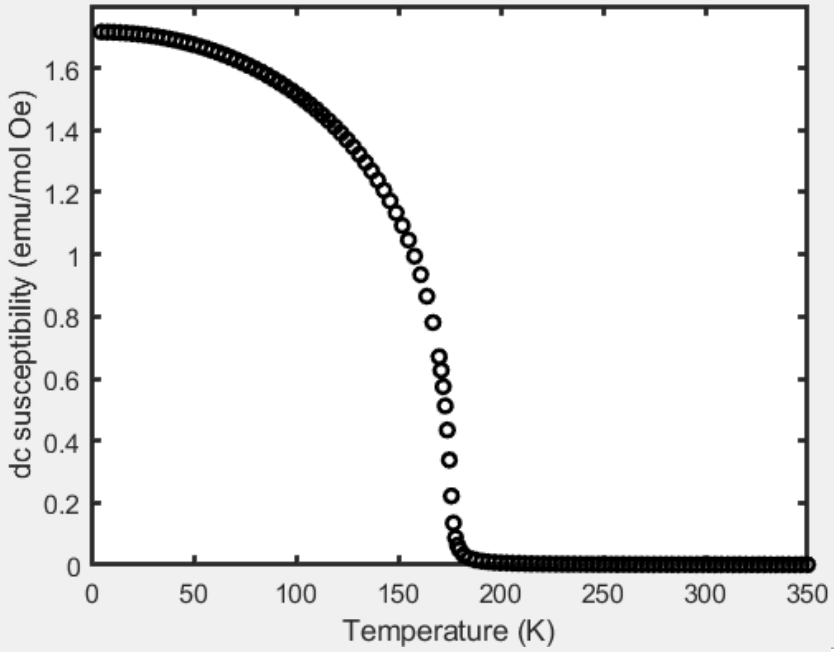
$V_{TOT} = V_A - V_B \propto \omega H_0 \chi_{AC}$

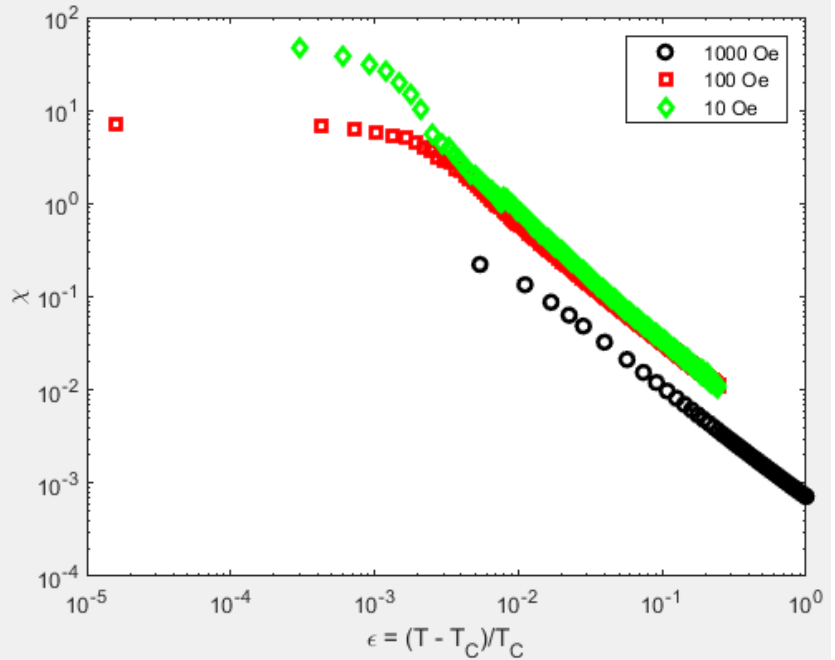
❖ why/when AC?

$B = 0$ ⟶ ❖ critical behavior



$Co_3Sn_2S_2$



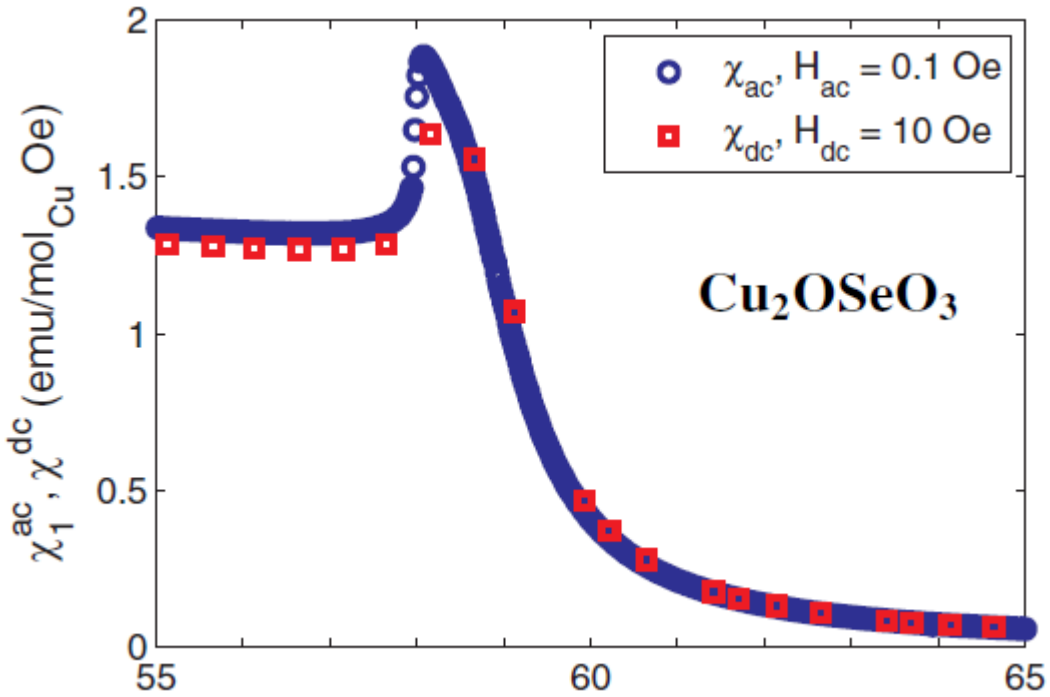



❖ why/when AC?

$B = 0$ ⟶

❖ critical behavior

❖ faster measurements



❖ why/when AC?

$$\tau = \tau_0 e^{\frac{E_B}{k_B T}}$$ Arrhenius law

$$H(t) = H_0 \sin \omega t \longrightarrow$$

- ❖ characteristic time-scale(s)
- ❖ (spin-glass, superparamagnets, single-molecule magnets, domain walls,…)

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## Dynamics of an Interacting Particle System: Evidence of Critical Slowing Down

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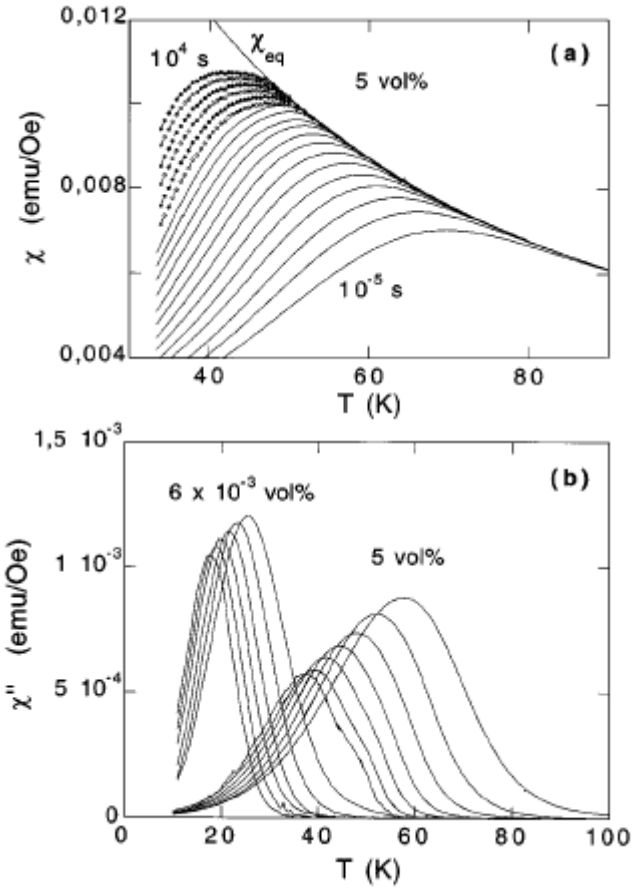
(Received 15 August 1997)

The dynamics of a magnetic particle system consisting of ultrafine Fe-C particles of monodisperse nature has been investigated in a large time window, $10^{-9}$–$10^{4}$ s, using Mössbauer spectroscopy, ac susceptibility, and zero field cooled magnetic relaxation measurements. By studying two samples from the same dilution series, with concentrations of 5 and $6 \times 10^{-3}$ vol %, respectively, it has been found that dipole-dipole interaction increases the characteristic relaxation time of the particle system at all temperatures investigated. The results for the most concentrated particle assembly are indicative of collective magnetic dynamics and critical slowing down at a finite temperature, $T_g \approx 40$ K. Close to and below the transition temperature, an aging phenomenon is observed, another manifestation of collective magnetic dynamics. [S0031-9007(97)04826-6]



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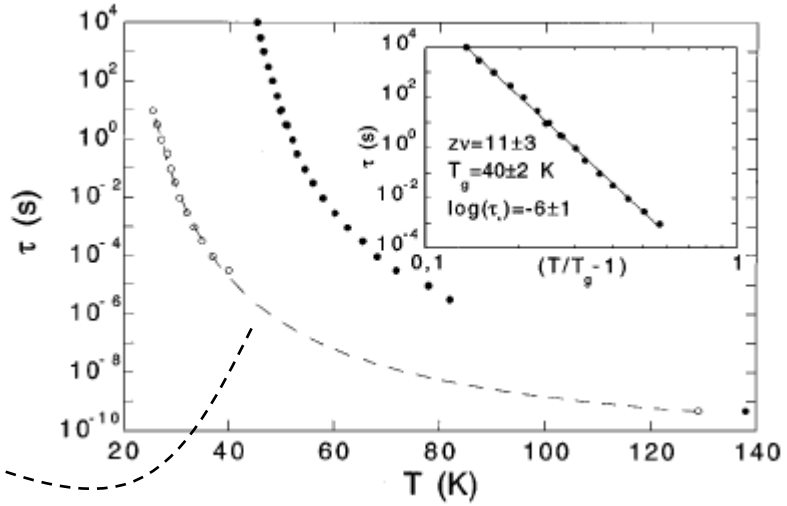
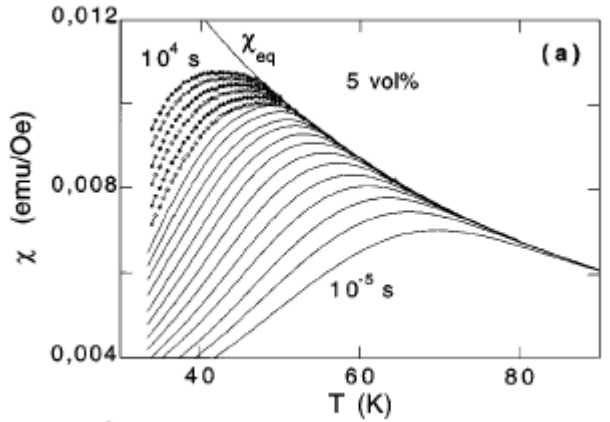
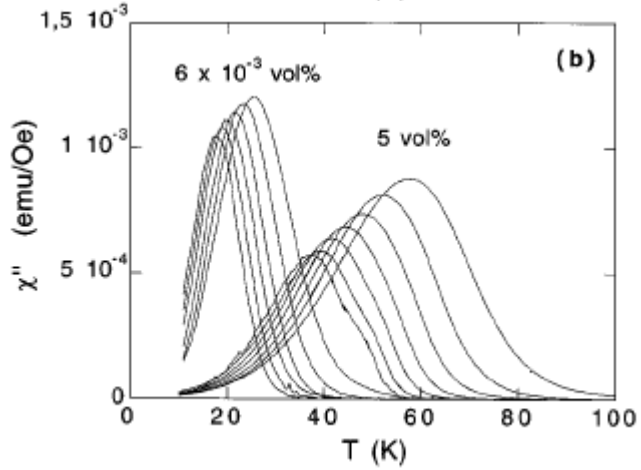
**Dynamics of an Interacting Particle System: Evidence of Critical Slowing Down**

$$\tau = \tau_*(T/T_g - 1)^{-z\nu}, \qquad T > T_g$$




$$\tau = \tau_0 e^{\frac{E_B}{k_B (T - T_0)}}$$

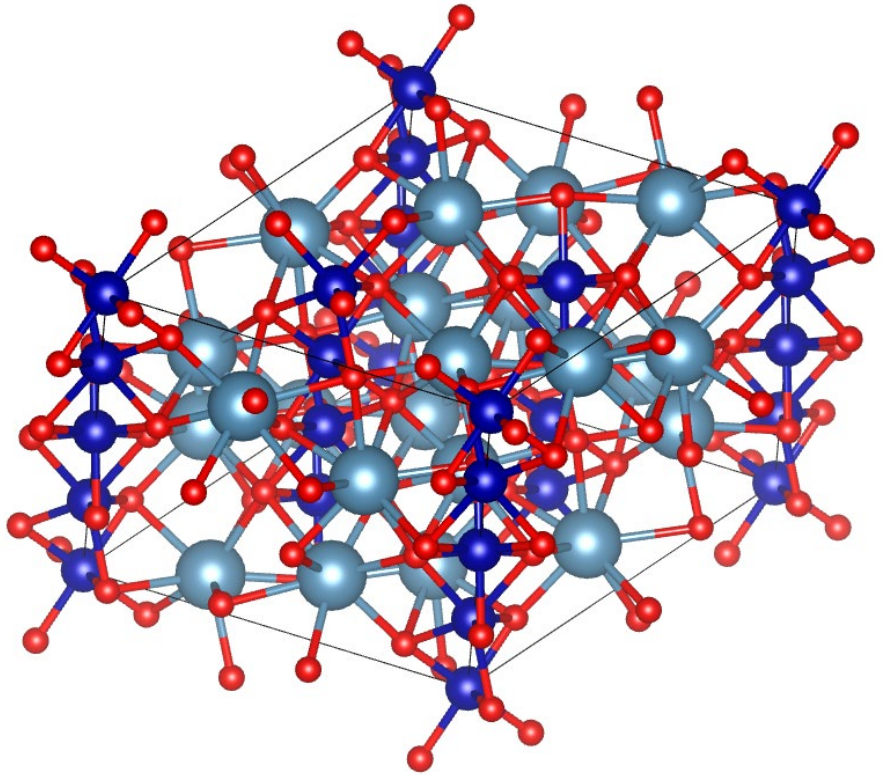


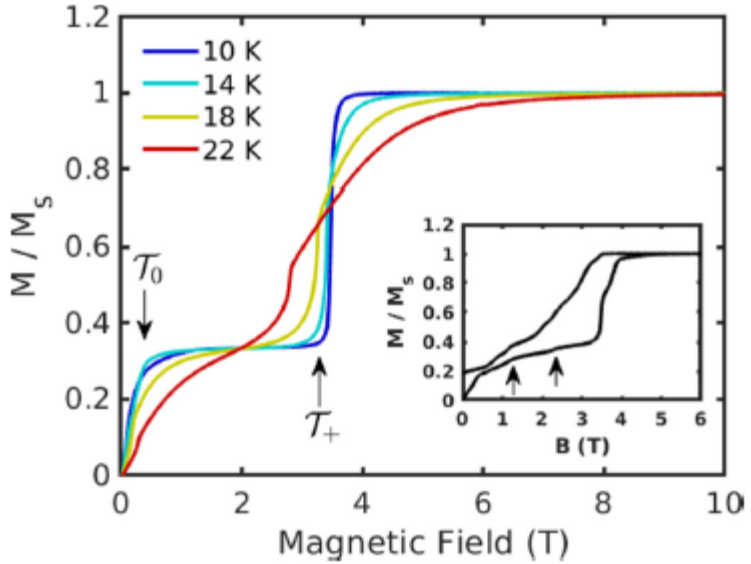
❖ why/when AC?

$$H(t) = H_0 \sin \omega t \longrightarrow$$

❖ characteristic time-scale(s)
❖ (spin-glass, superparamagnets, single-molecule magnets, domain walls,…)



$Ca_3Co_2O_6$



- why/when AC?

$$H(t) = H_0 \sin \omega t \longrightarrow$$

- characteristic time-scale(s)
- (spin-glass, superparamagnets, single-molecule magnets, domain walls,…)