Experimental techniques

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Indo – French School and Conference on the "Magnetism of Molecular Systems"
28th November

Magnetic Materials and Switches Lab

Outline

1) Introduction

2) Molecular Magnetic Materials (MMM)

3) Magnetic Measurement Techniques

a) **SQUID Magnetometers;** b) **PPMS Susceptometer**

4) DC Measurement techniques

a) Usual DC and RSO; b) Solution; c) Horizontal and Vertical Rotators; d) (Photo)magnetic measurements

5) AC Measurement techniques

Acknowledgements

IISc Start-up Grant

Solid State and Structural Chemistry Unit

Prof. Rodrigue Lescouëzec
Dr. Hab. Rodolphe Clérac
Dr. Hab. Yves Journaux
Dr. Yangling Li
Prof. Miguel Julve
Prof. Francisco Lloret
Dr. Pierre Dechambenoit
Prof. Corine Mathonière
Dr. Matias Urdampilleta
Mr. Mathieu Rouzières
Dr. Eric Rivière

“Definition “

Molecular Magnetism (MM) can be defined, according to **Prof. O. Kahn**, as a discipline, which designs, synthesizes, **studies** and applies molecular magnetic materials with new but predictable properties at the crossroads of quantum theory, chemistry, physics and biology.[1]

[1] O. Kahn, O. *Molecular Magnetism*, New York: VCH, **1993**; b) D. Gatteschi, R. Sessoli, R. J. Villain *Molecular nanomagnets*. Oxford: Oxford University Press, **2006**.

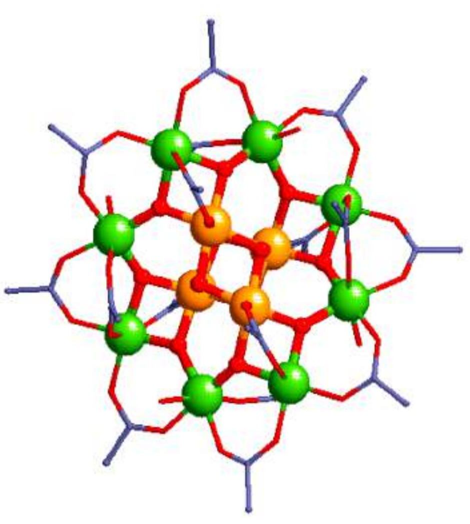
Molecular (Magnetic) Materials

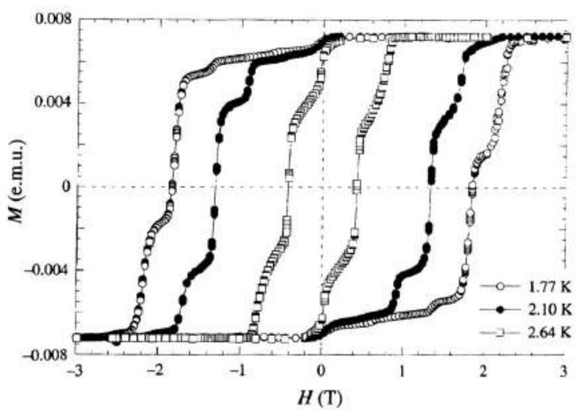
"Molecular magnetism is the research field devoted to the design, the synthesis, the study and the use of molecular magnetic materials with new original and predictable properties"

Prof M. Verdaguer, Emeritus professor
Université Pierre et Marie Curie

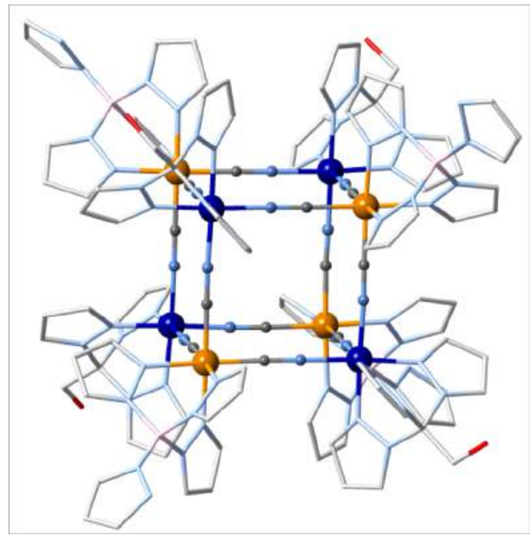
Molecular Magnets…

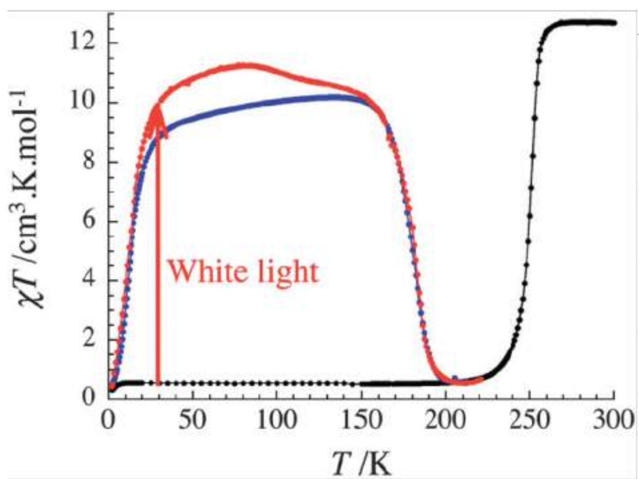
Nano-Magnets (SMMs and SCMs)



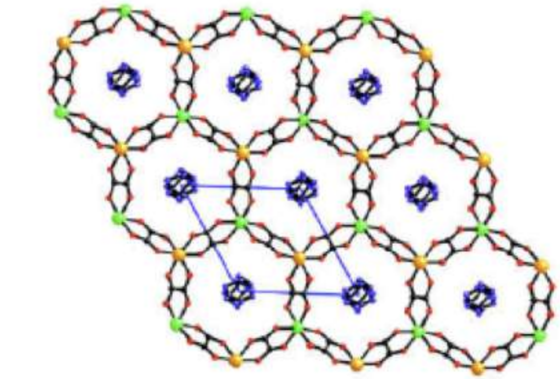


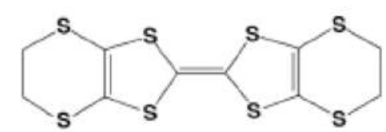
Switchable Materials

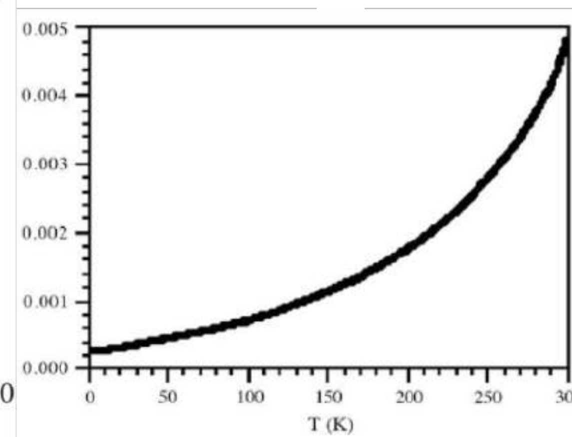




Multi-functional Materials







What is SQUID?

Superconducting Quantum Interference Device

SQUID magnetometers, UPMC, Paris-6

MPMS 3_ Quantum Design's

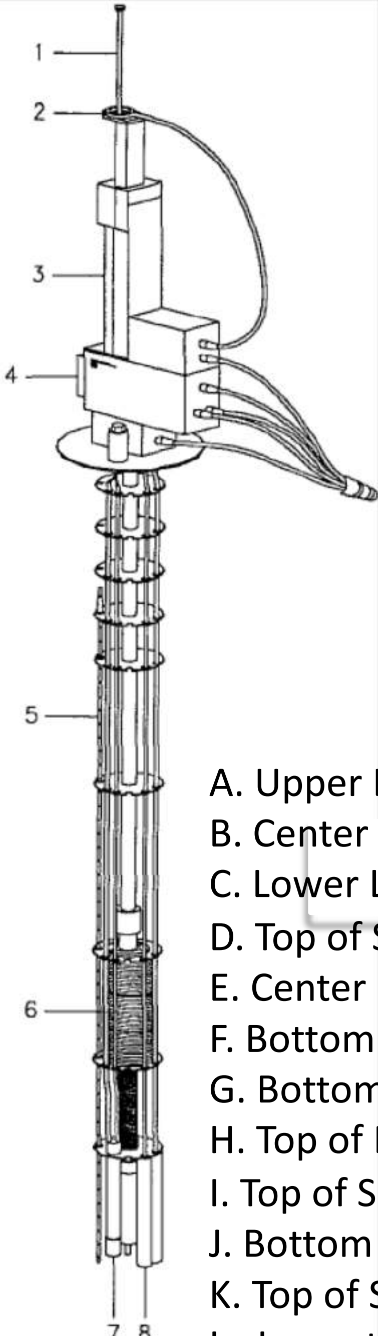
Comparison SQUID/PPMS for DC and AC magnetic measurements

Measurement type	MPMS SQUID-XL	PPMS VSM	PPMS ACMS	MPMS 3 SQUID-VSM
DC; M=f(H)	-7 – 7 T	-7 – 7 T	-7 – 7 T	-7 – 7 T
DC; M=f(T)	1,8 – 400 K (10 K / min)	4 (2) – 350 K (20 K / min)	3 (2) – 325 K	1,8 – 400 K
AC M=f(T,F, H)	A < 3.5 Oe and F =0.1 – 1,000 Hz		A ≤ 10 Oe and F=10 – 10,000 Hz	A < 3,5 Oe and F =0.1 – 1000 Hz
Sensibility (emu)	≈10^{-7} for DC ≈3,3 10^{-8} for AC	< 10^{-6}	≈2,5 10^{-5}	≈10^{-8} for VSM
Comments	Slow H variation; Very slow AC measurement T very stable	Very fast H Variation* Difficult to stabilize at T=2 K	Fast AC measurement; Difficult to stabilize at T=2 K	Advantages SQUID + PPMS

*For a hysteresis loop with H_{max}= 5T and ΔH = 0.25 T, it takes 30 min on VSM and > 3 h on SQUID-XL

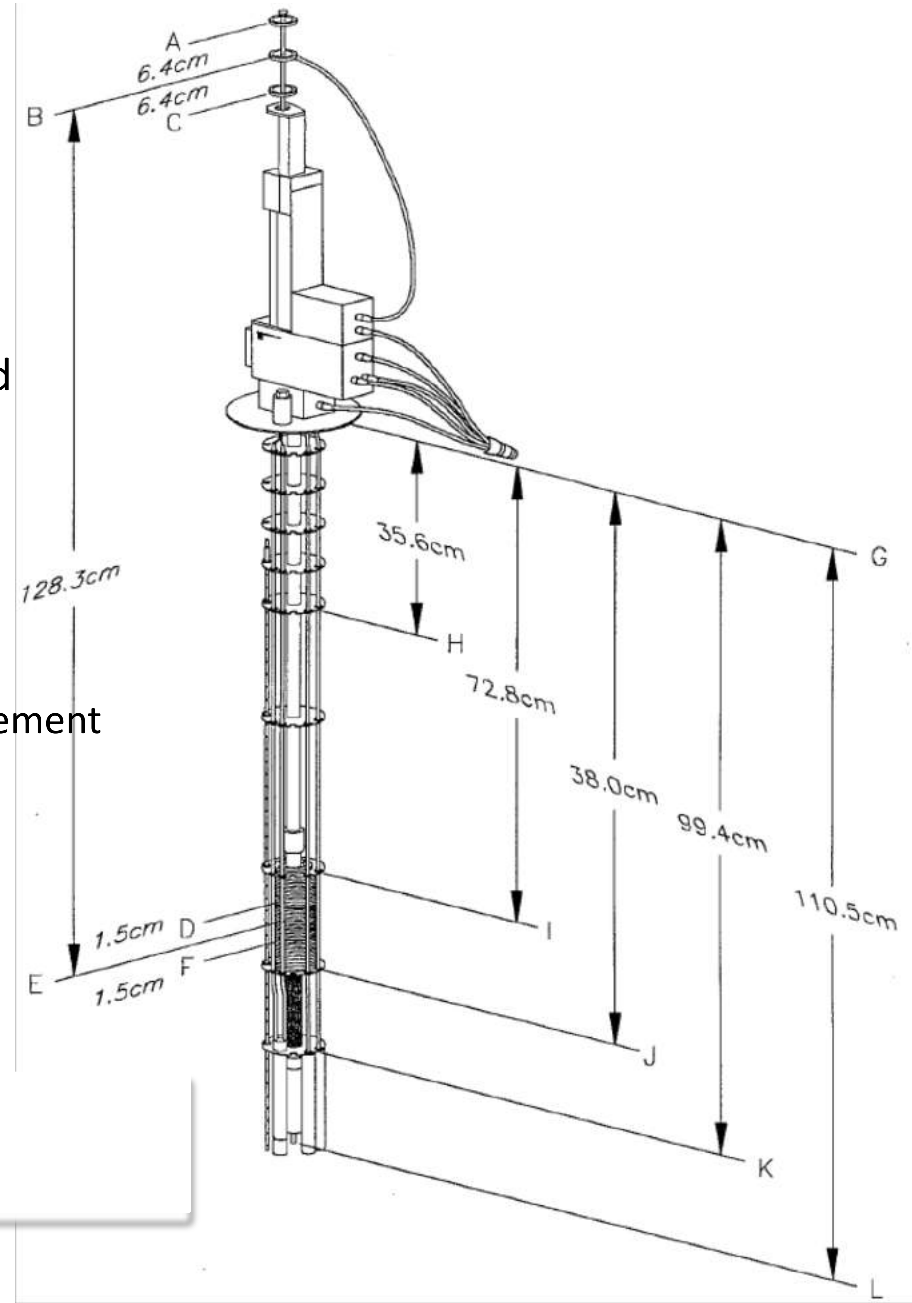
Slide Courtesy Dr. Yangling Li

SQUID Magnetometer

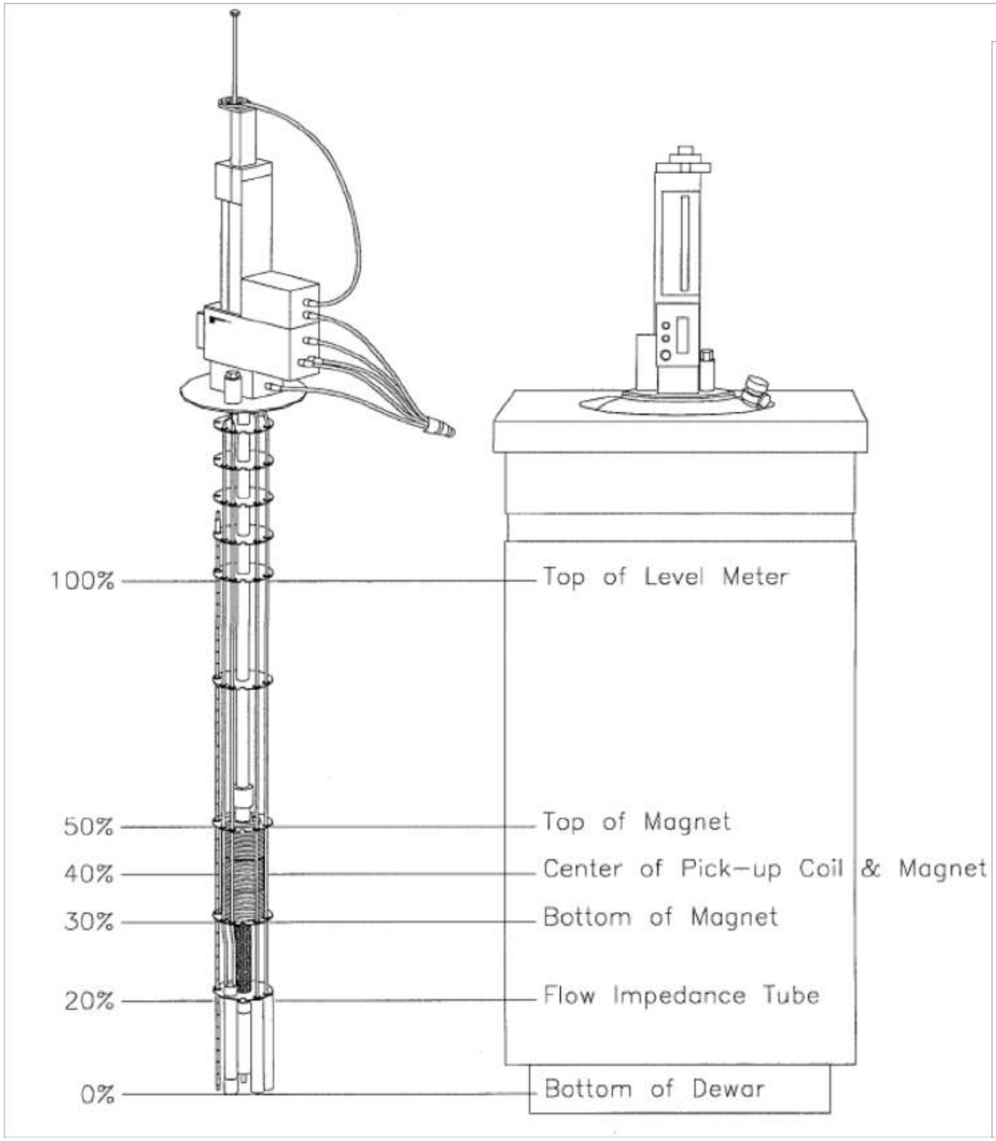


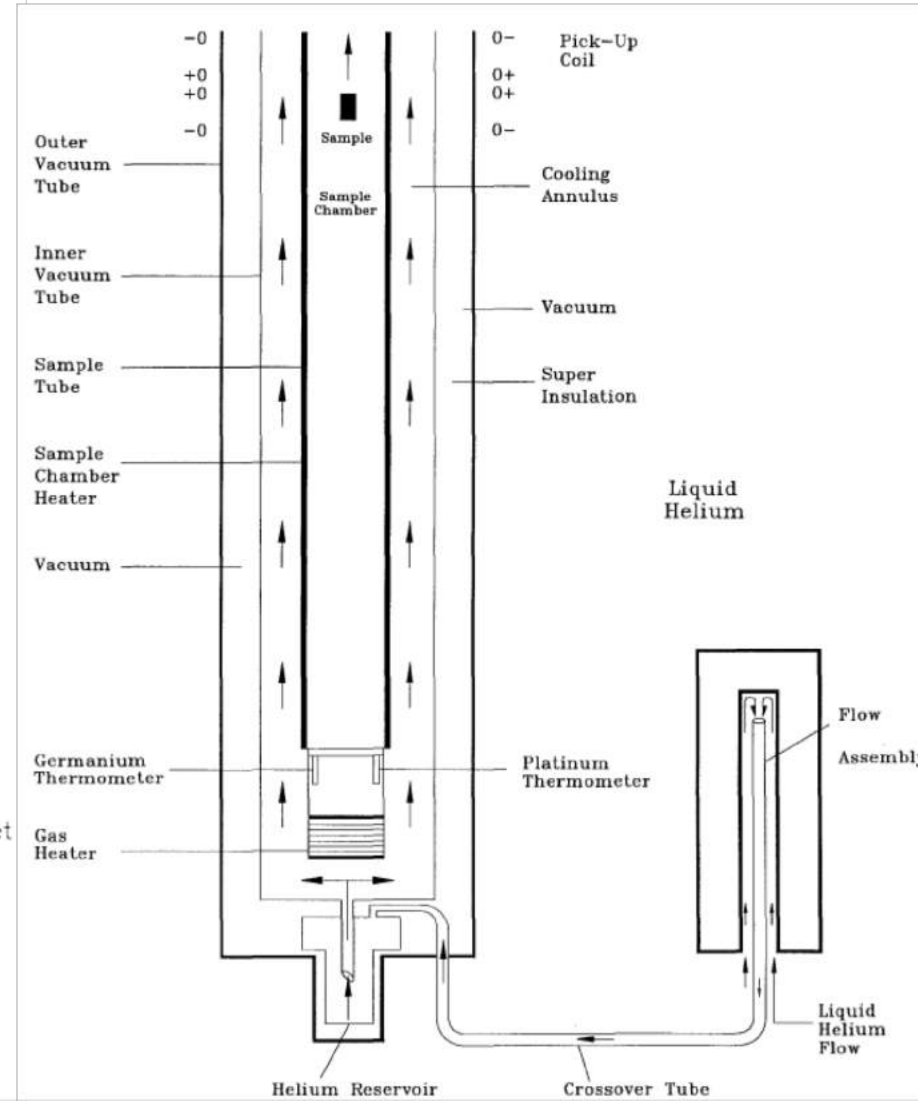
1. Sample Rod
2. Sample Rotator
3. Sample Transport
4. Probe
5. Helium Level Sensor
6. Superconducting Solenoid
7. Flow impedance
8. SQUID Capsule

A. Upper Limit of Vertical Translator Movement
B. Center of Translator Movement
C. Lower Limit of Translator Movement
D. Top of Sensing Coils
E. Center of Sensing Coils
F. Bottom of Sensing Coils
G. Bottom of Dewar Top Plate
H. Top of Dewar Belly
I. Top of Superconducting Solenoid
J. Bottom of superconducting Solenoid
K. Top of SQUID Housing
L . Lowest Point of the Plate



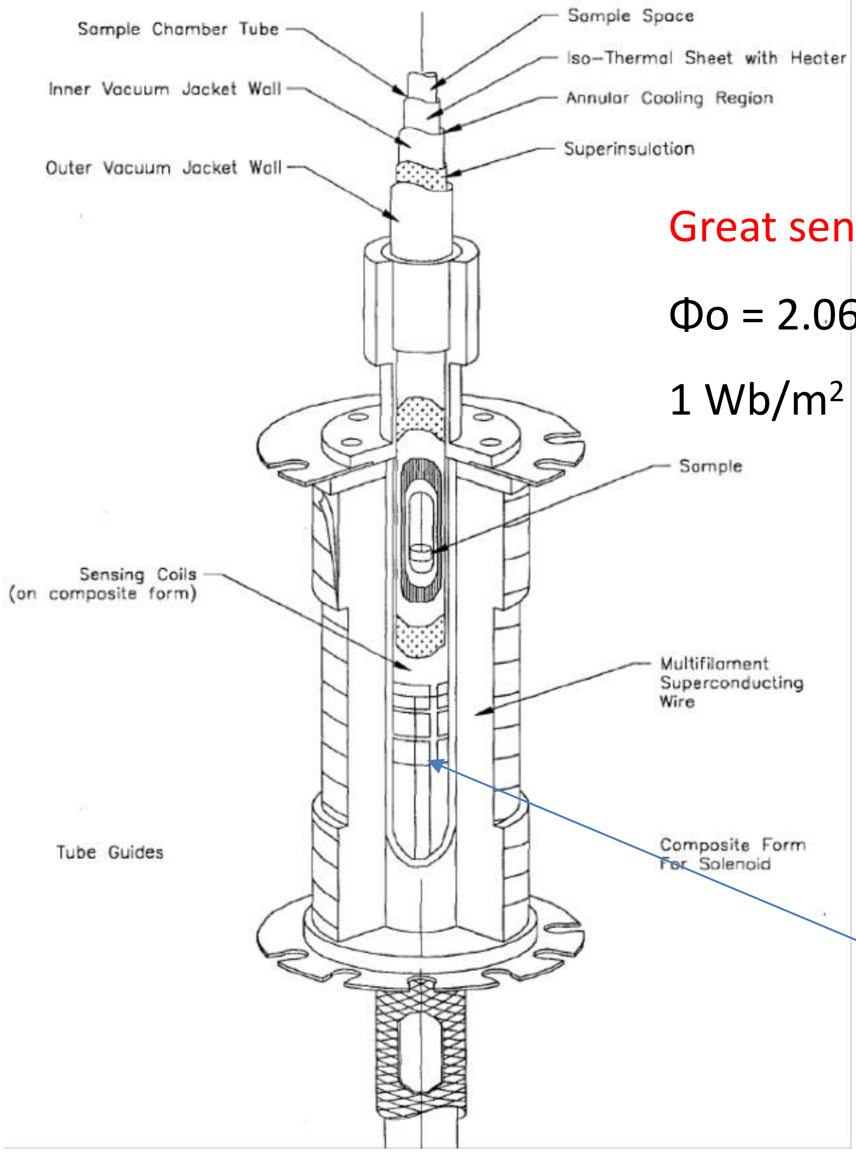
SQUID Magnetometer





Reference : Magnetic Property Measurement System (MPMS-XL) hardware Reference Manual

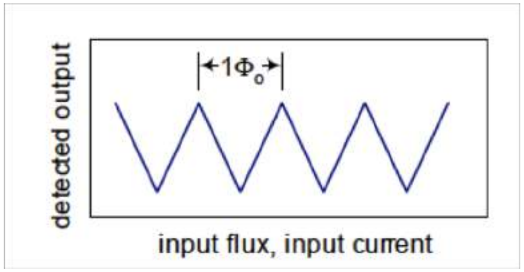
DC measurement on SQUID

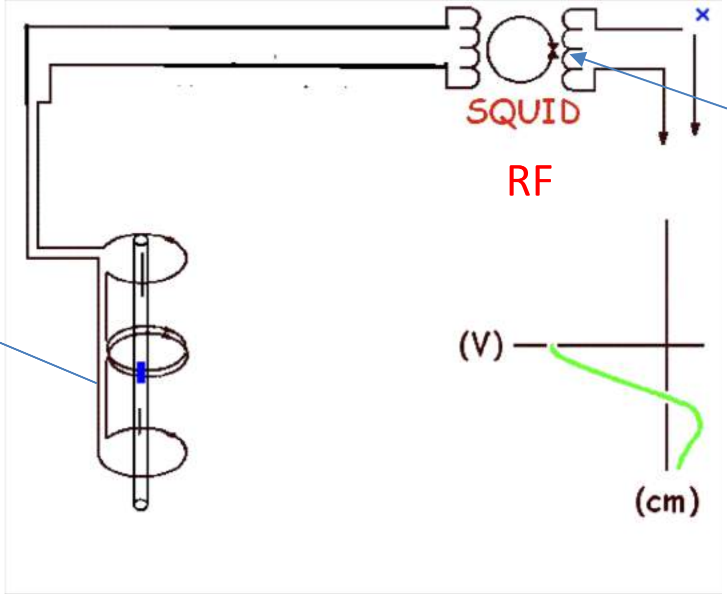


Great sensitivity of SQUID detection

$\Phi o = 2.068 \times 10^{-15}$ Weber

$1\ Wb/m^2 = 1$ Tesla





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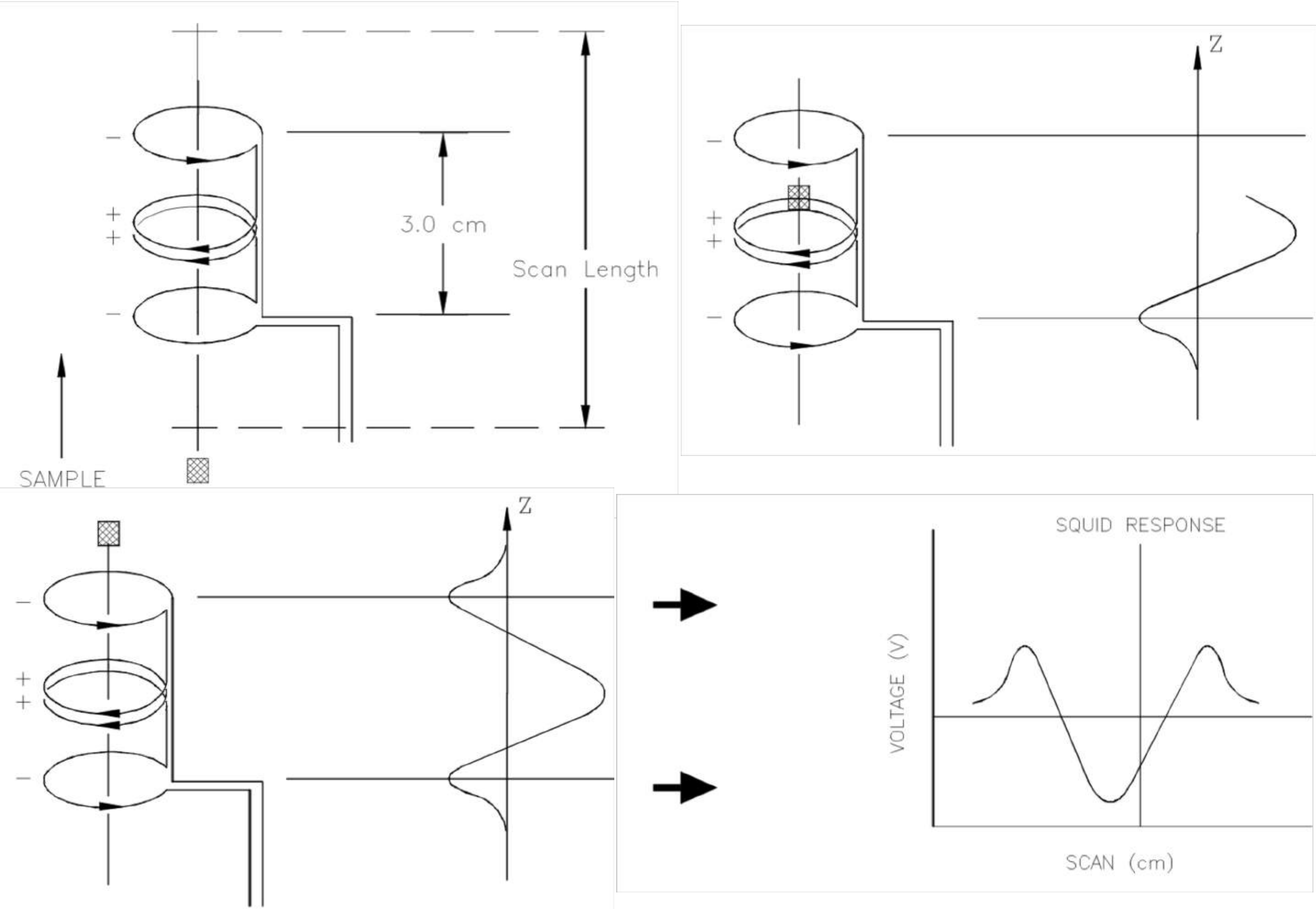
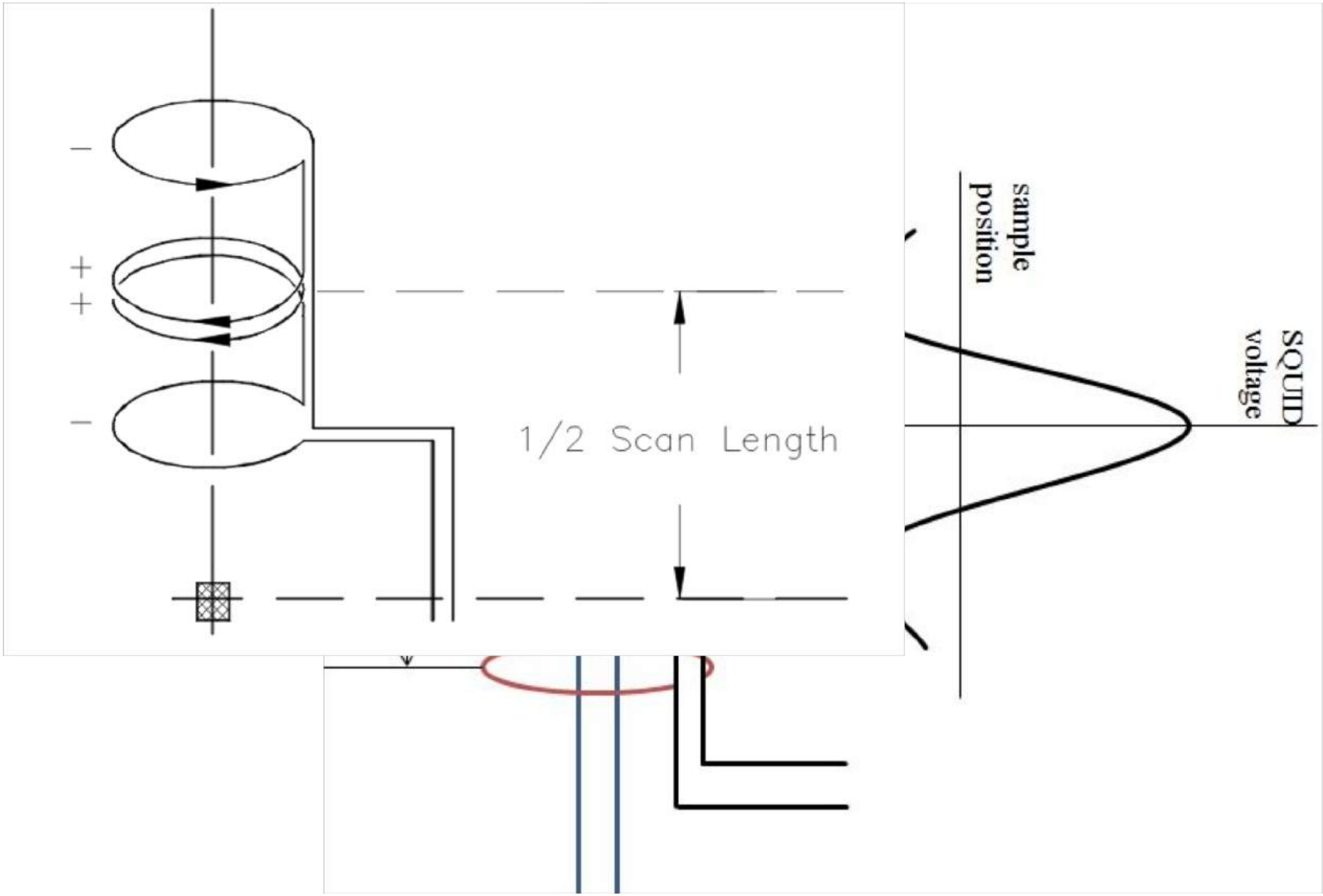
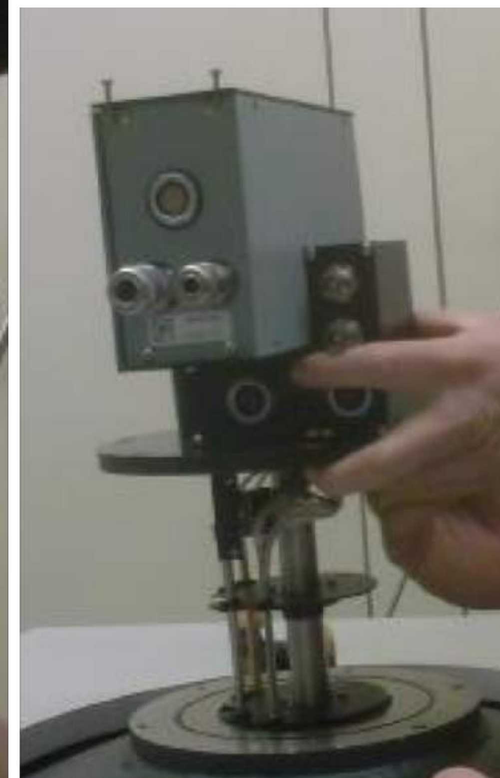
DC measurement on SQUID



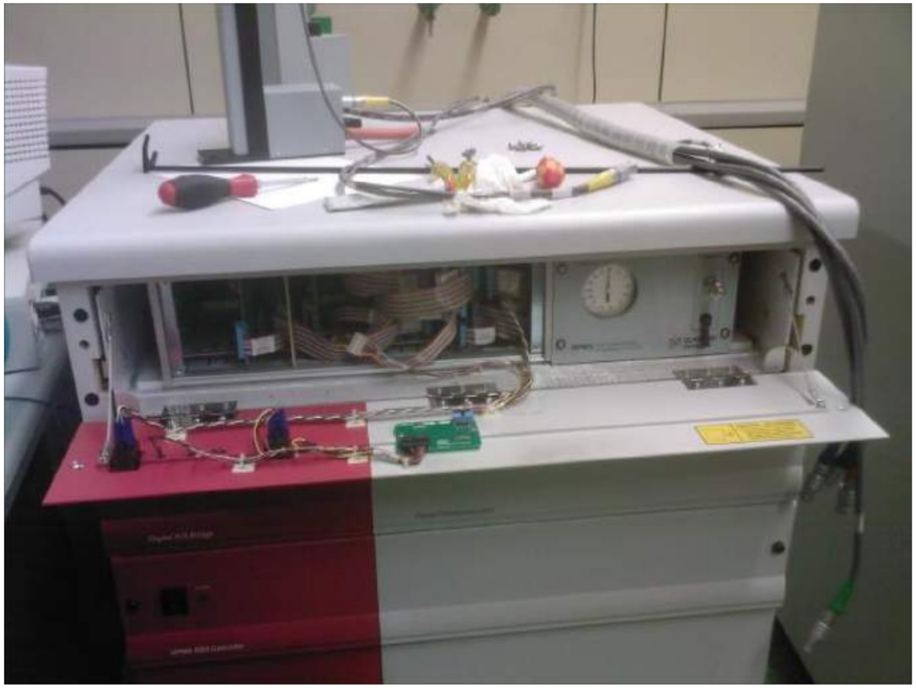
DC measurement on SQUID

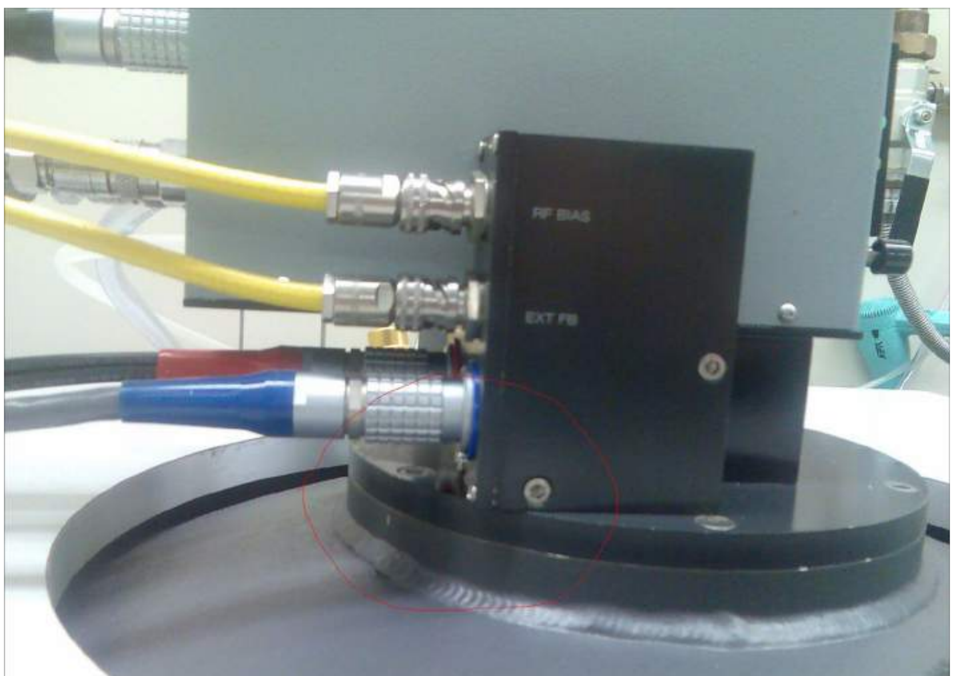


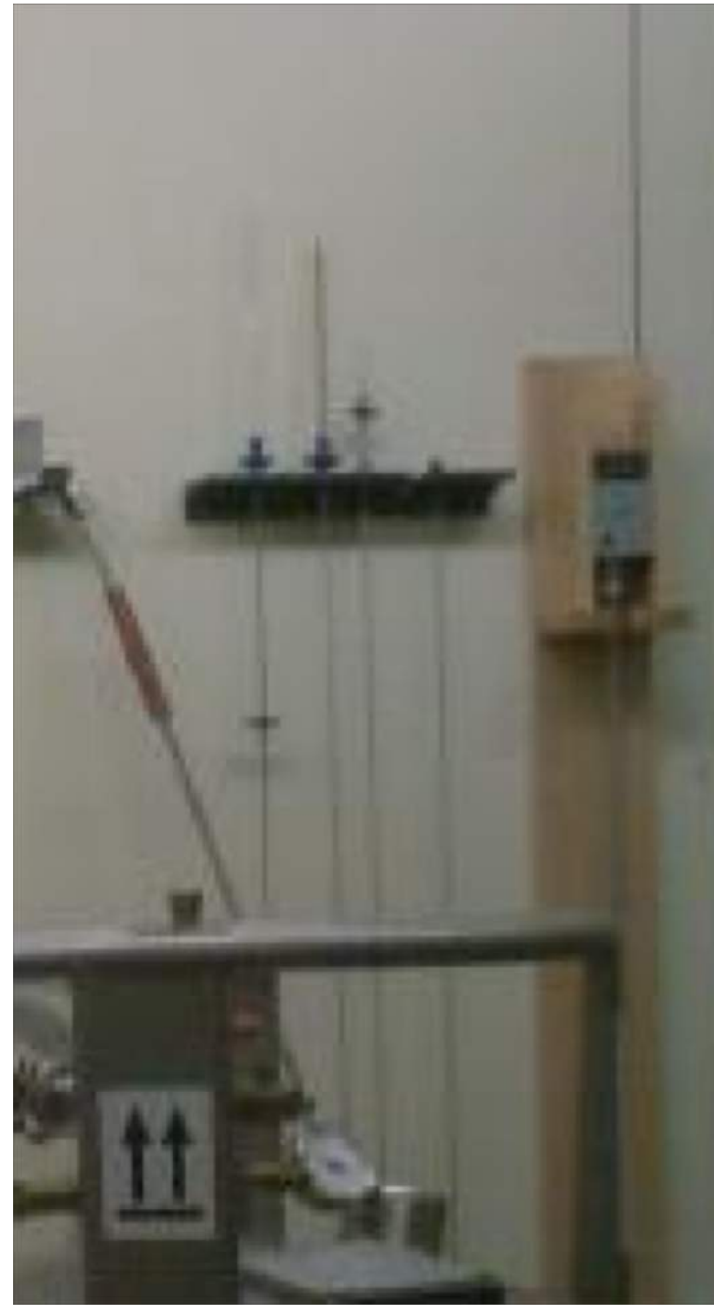


SQUID Magnetometer,
KIT, Germany



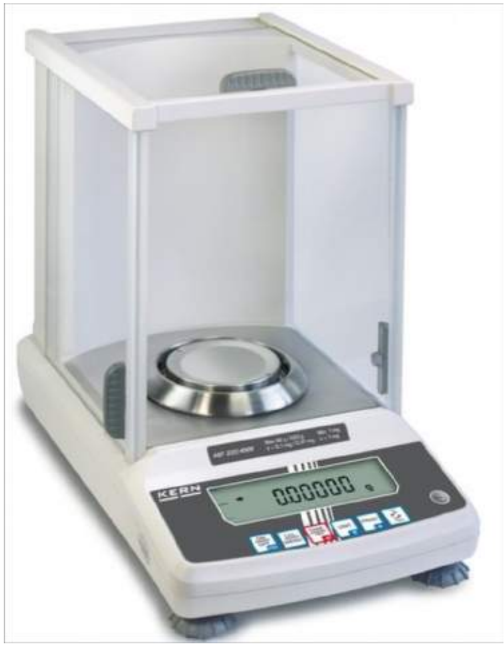




SQUID Magnetometer,
KIT, Germany

Before Sample Preparation: Some essential tools

microscope



good quality analytical balance

Glass rod

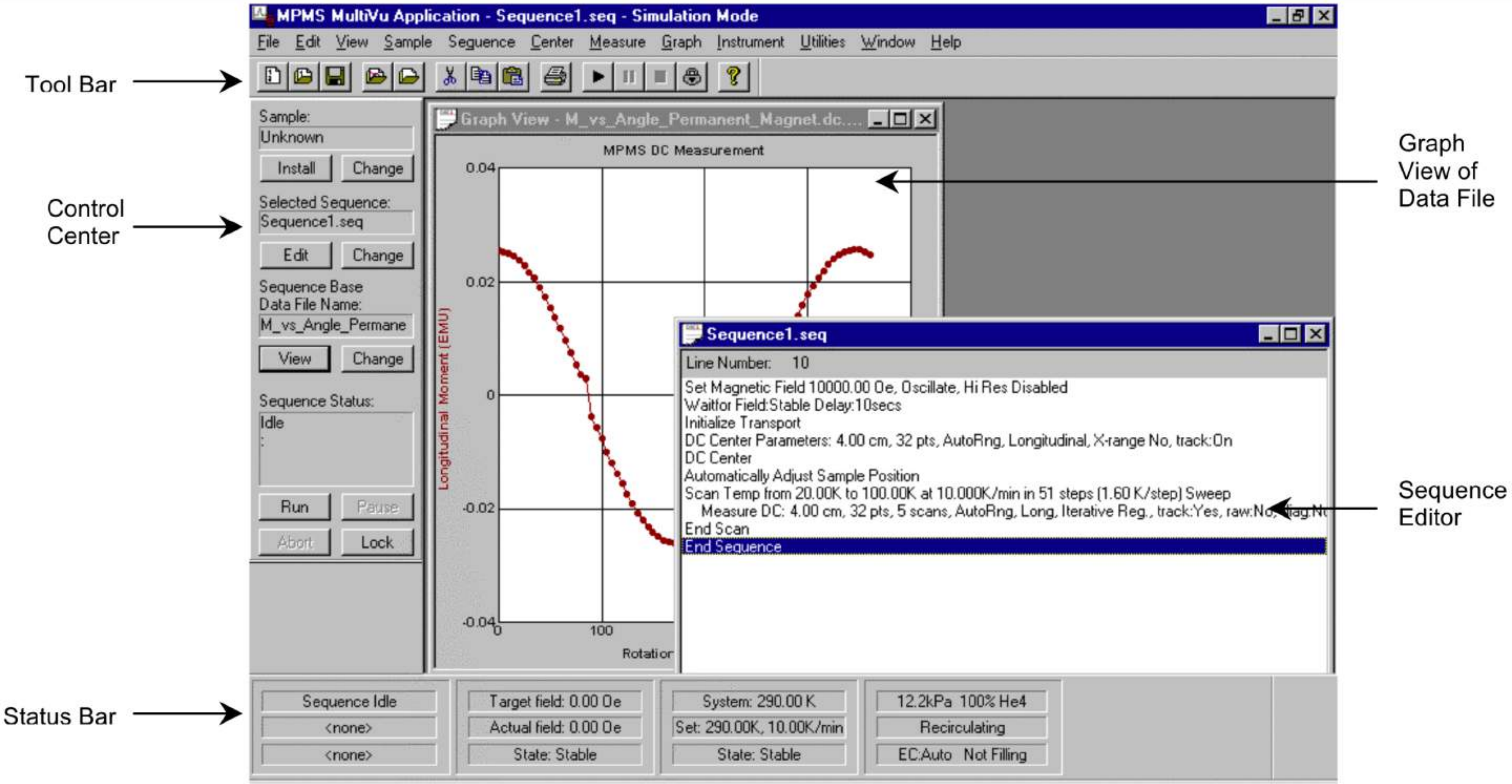
polythene bag

ceramic knife

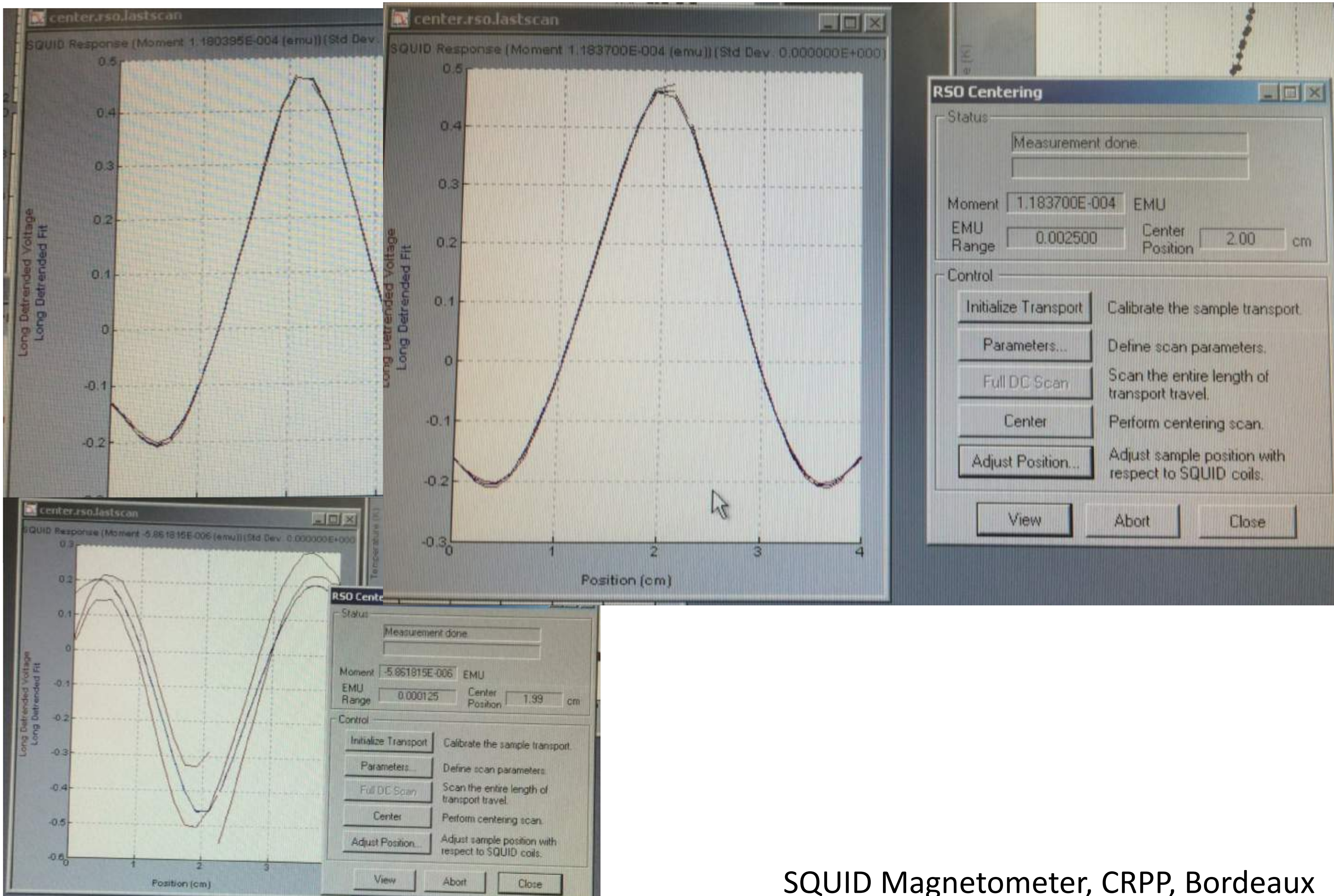
ceramic tweezer

Ceramic scissors

Centering of Sample

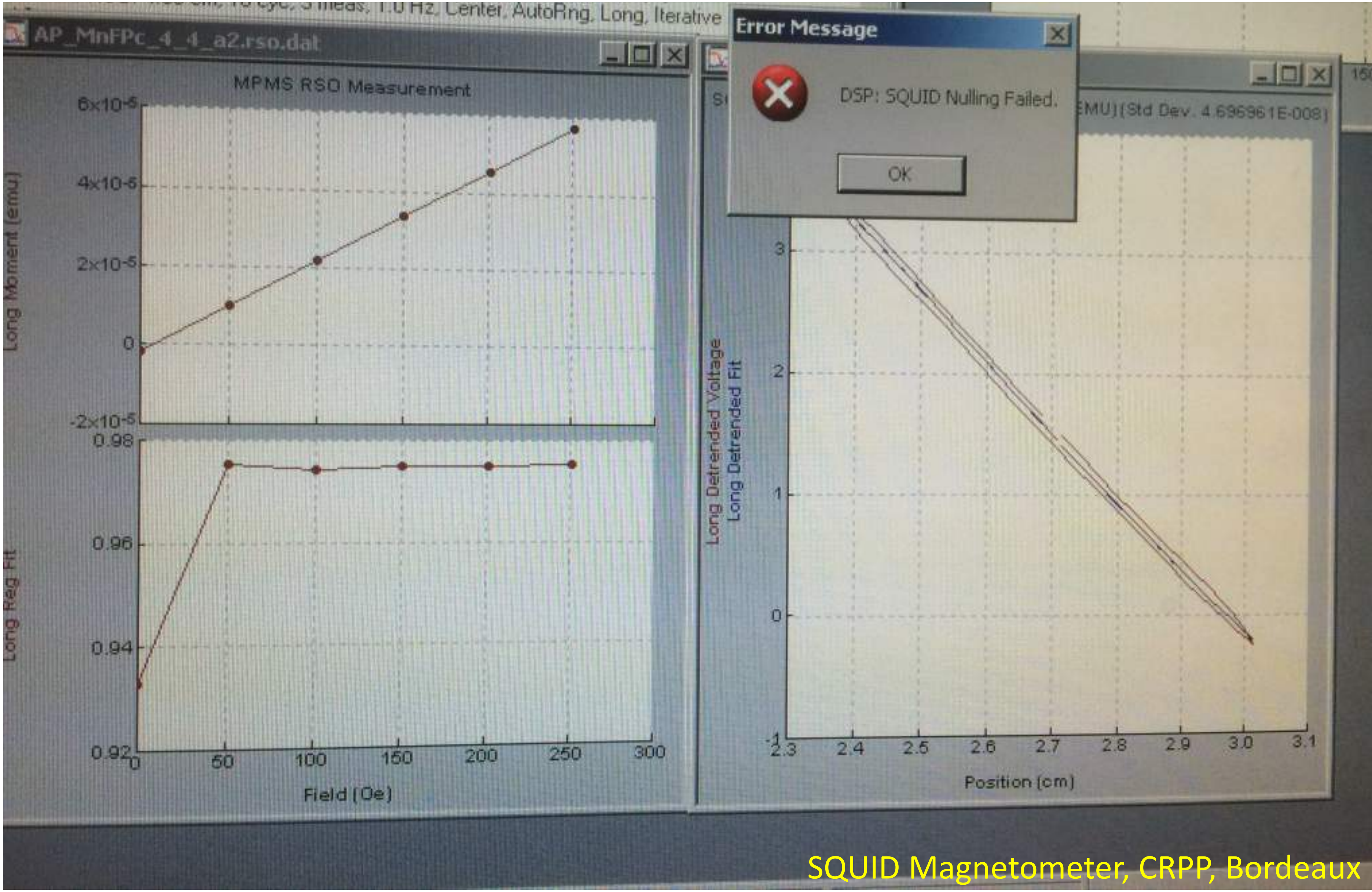


Centering of Sample

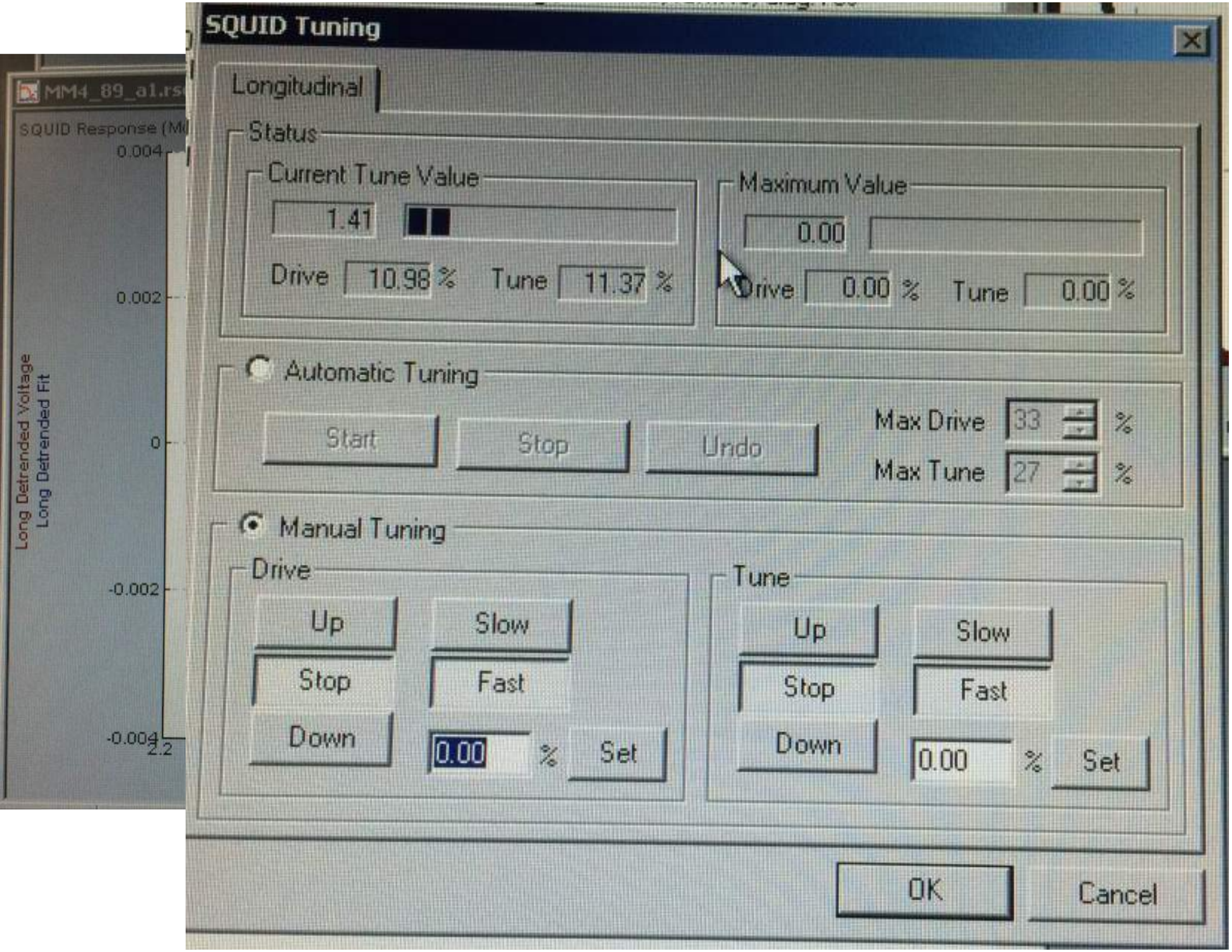


SQUID Magnetometer, CRPP, Bordeaux

Problem due to loss of SQUID tuning



Restoring SQUID tuning



SQUID Magnetometer, CRPP, Bordeaux

Good Magnetic Data

Obviously, you need good measurements!!!

What are the possible sources of errors when you measure magnetic properties?

There are five traditional source of errors which one can finds in the scientific articles and most of the magneto-chemists have made one of these mistakes at least once

- **Ferromagnetic impurity**
- **Loss of solvent molecules**
- **Orientation of the microcrystals under magnetic field**
- **Saturation effect**
- **Diamagnetic correction**

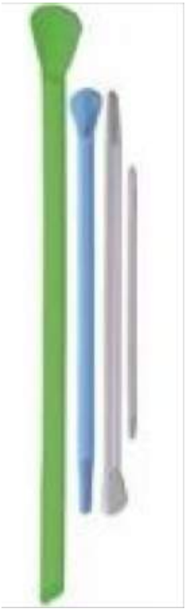
Slide Courtesy Dr. Hab. Yves Journaux

Ferromagnetic impurity

The enemy of the magneto-chemist

The metallic spatula !!!!

good tools



Your sample is polluted with a ferromagnetic impurity !!!!

Slide Courtesy Dr. Hab. Yves Journaux

Presence of a ferromagnetic impurity (magnet)

$$B = \mu_0 [\, H + M \,] \quad \textit{with} \;\; M = \chi \,.\, H$$

$$\chi = M / H \textit{ without ferromagnetic impurity}$$

At low field, the magnetic susceptibility χ does not depend on the magnetic field

with Ferromagnetic impurity

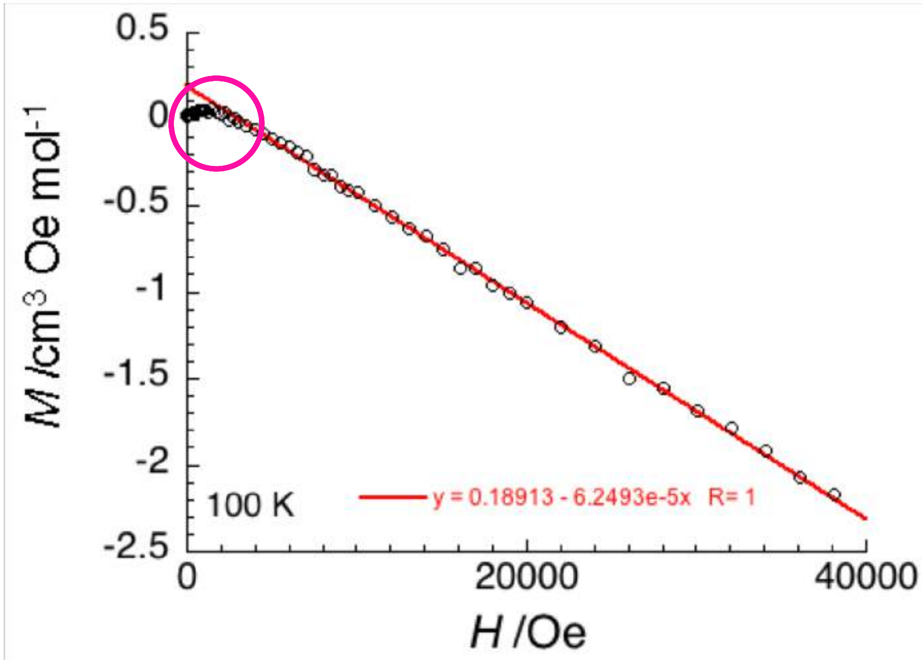
$$M_{measured} = \chi_{true} . H + M_{impurity}$$

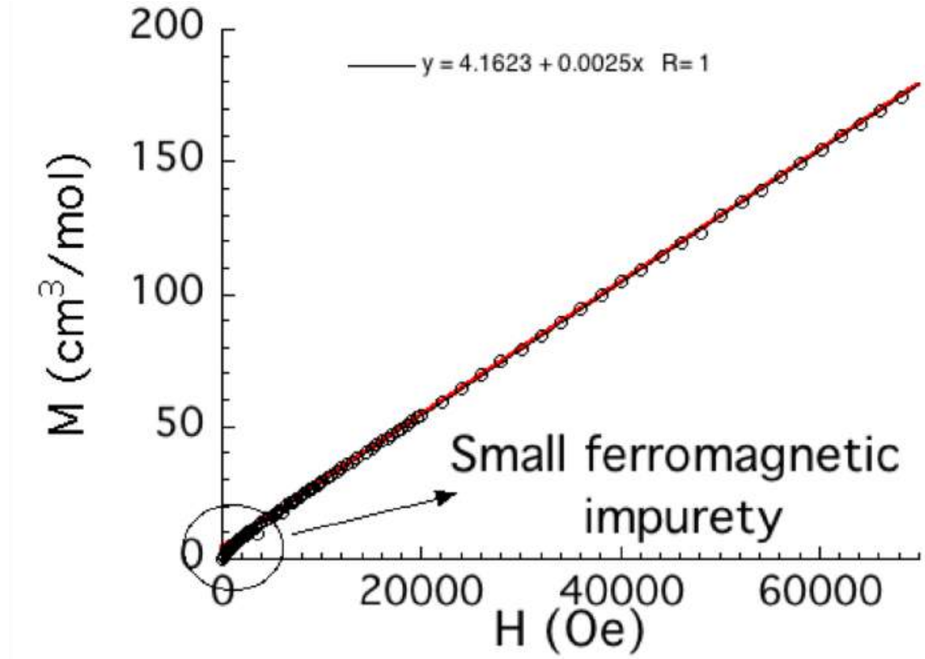
$$\chi_{measured} = \chi_{true} + M_{impurity} / H$$

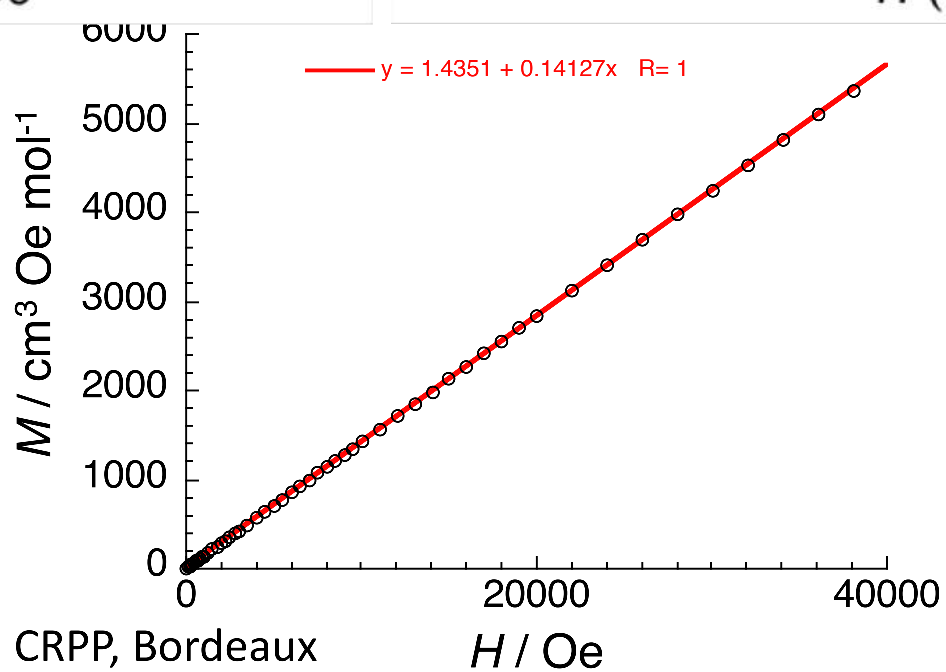
with a ferromagnetic impurity magnetic susceptibility χ depends on the magnetic field

Slide Courtesy Dr. Hab. Yves Journaux

The first thing to do, is to check the field-dependent magnetization at 100 K



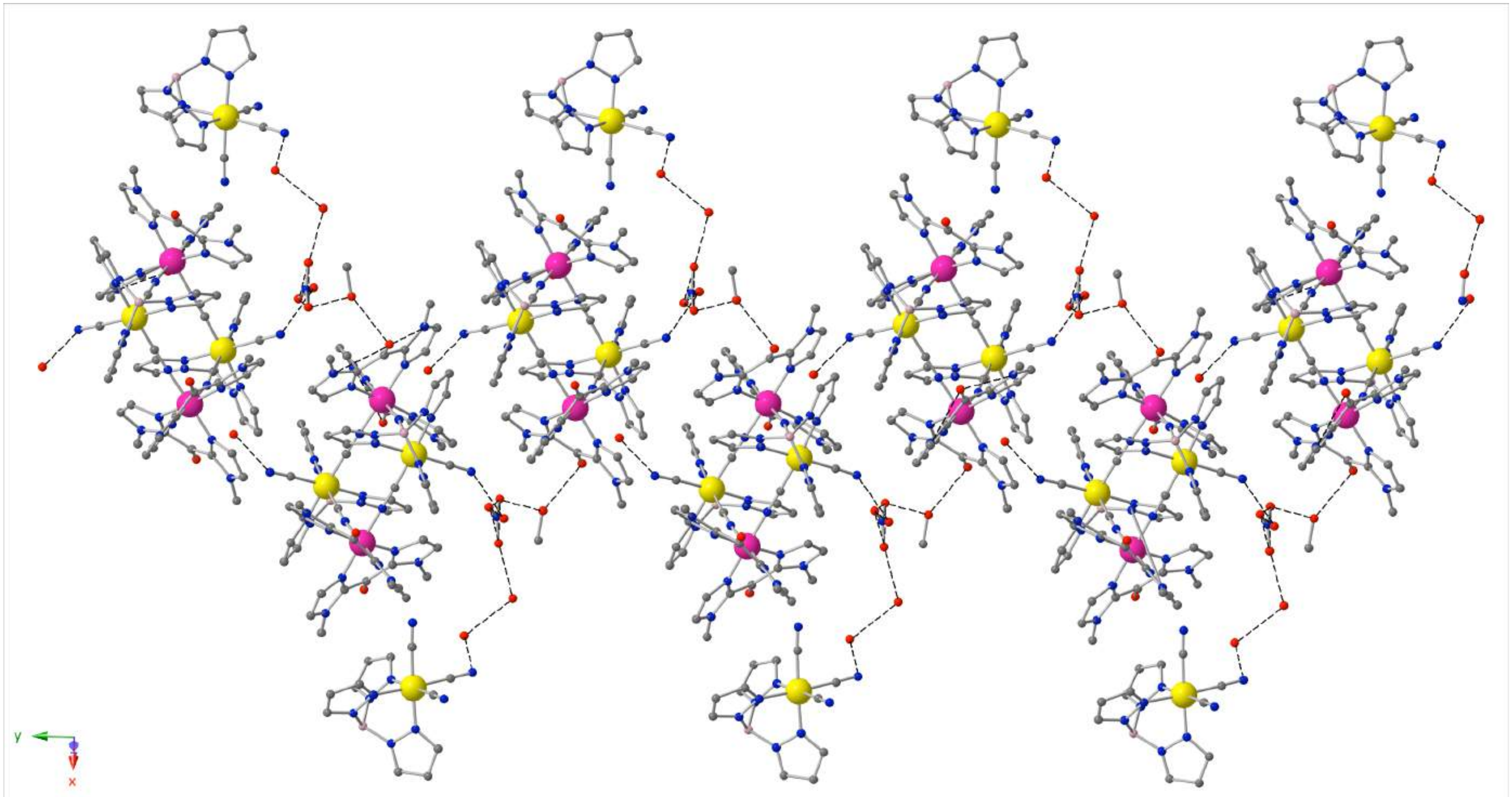




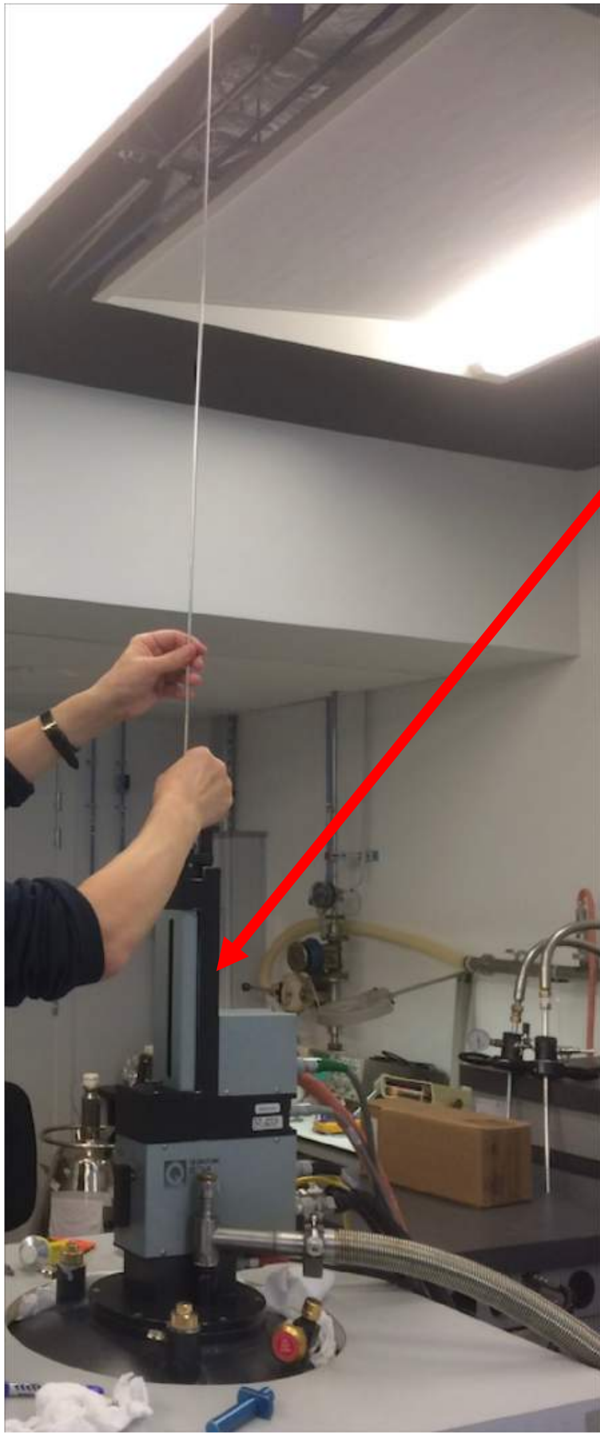
SQUID Magnetometer data, CRPP, Bordeaux

Loss of Solvent Molecules

Presence of the solvent molecules in the crystal structure



Molecular compounds are fragile



Sample Loading and Purging

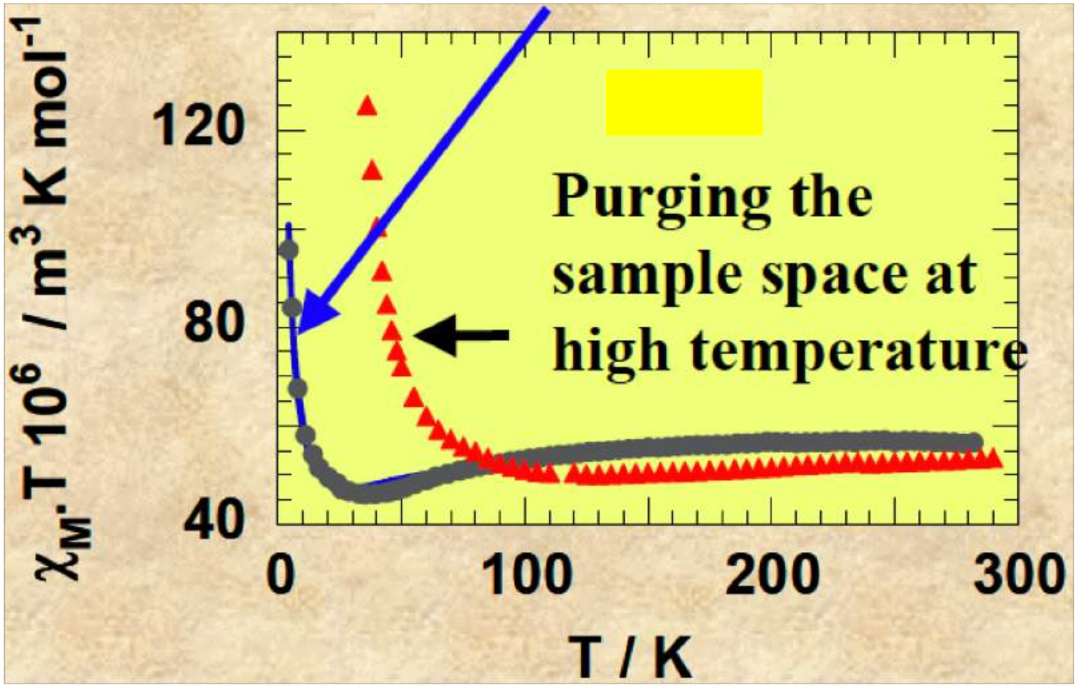
When you introduce your sample in the SQUID. You put it in the sample loading chamber.

"The standard sample loading technique is the presence of a vacuum atmosphere inside the sample loading space. When the system is purged, the sample space goes through a series of pump/purge cycles using the FLUSH valve to pump out the sample space and the VENT valve to back fill with helium gas."

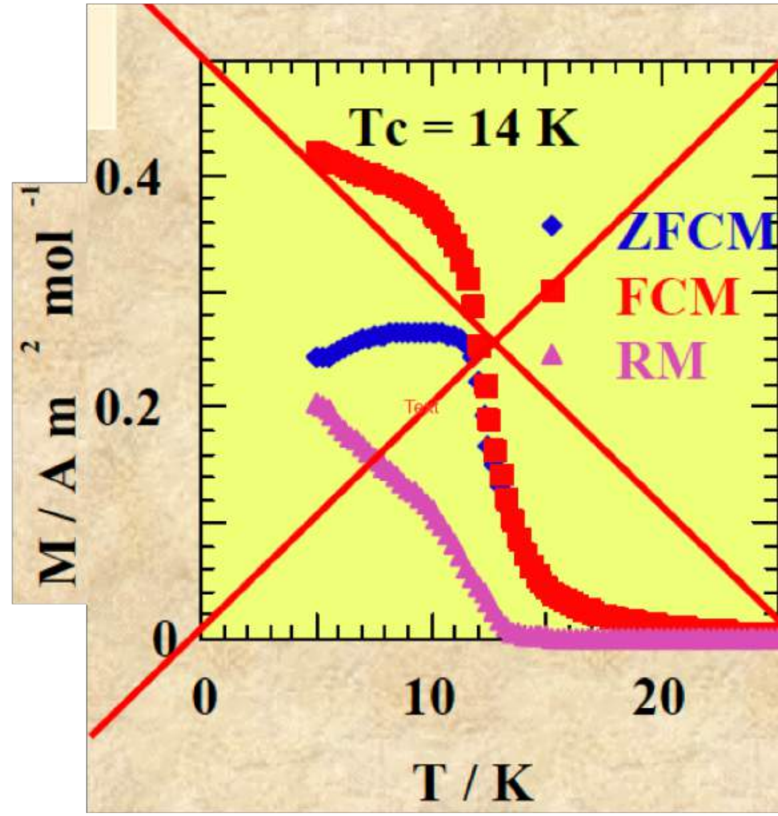
For molecular compounds, there is great risk to loose the crystallization solvent molecules!!!

Loss of Solvent Molecules

Purging the sample space at low temperature



With crystallization solvent molecules this sample exhibit an antiferromagnetic ordering at low temperature



Without crystallization solvent molecules sample shows a ferromagnetic ordering at 14 K

Slide Courtesy Dr. Hab. Yves Journaux

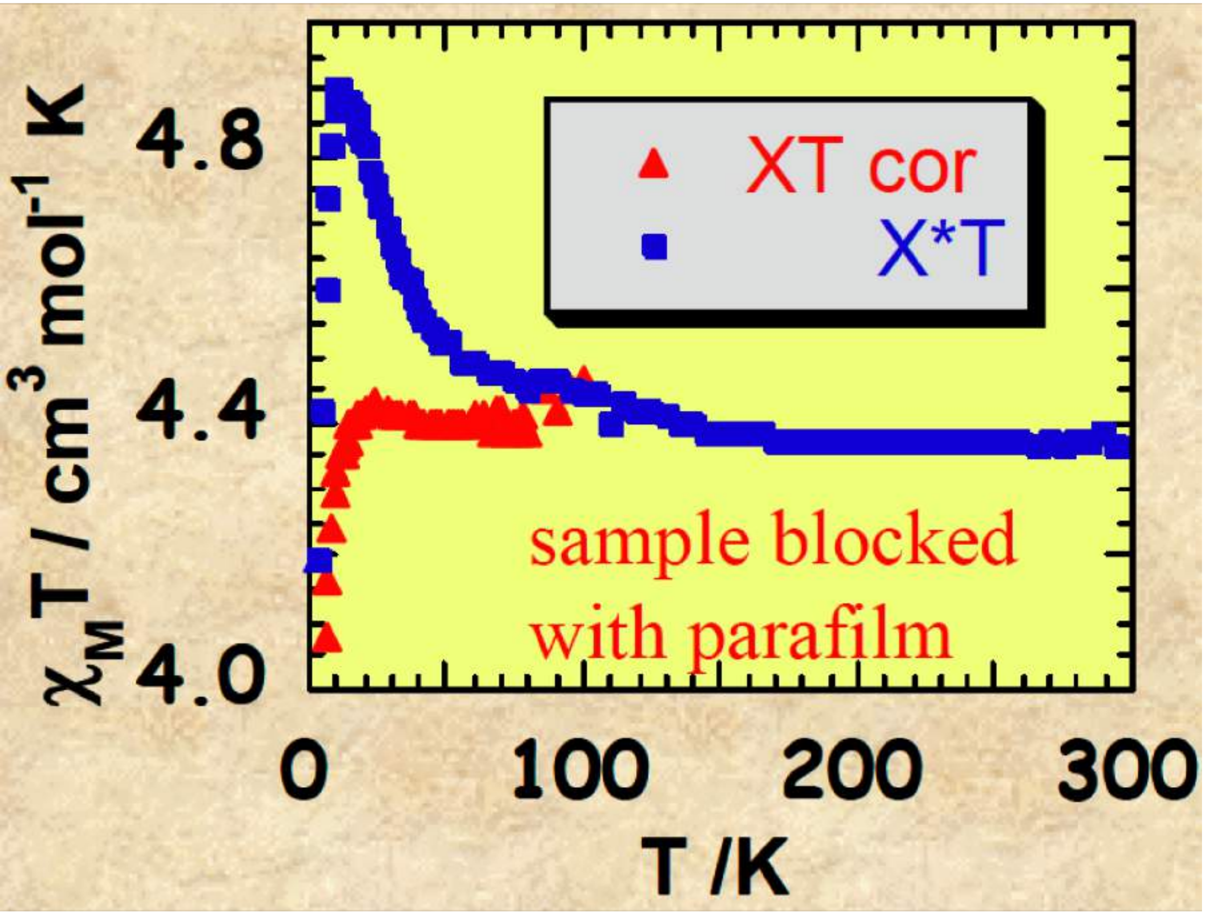
The crystallization solvent molecules control the intermolecular interaction

In most cases the loss of crystallization solvent molecules lead to inter-molecular antiferromagnetic interaction and could mask the interesting magnetic properties like slow relaxation of magnetization in case of Single Molecule Magnets

To be sure about the magnetic data, it is a good practice to perform a TGA (thermogravimetry) or DTA (Differential Thermal Analysis) experiment before measuring the sample in the SQUID magnetometer, in order to see the possible solvent loss around room temperature

Orientation of the microcrystals under magnetic field

~~**Intermolecular ferromagnetic interaction ?**~~



No ! An artefact

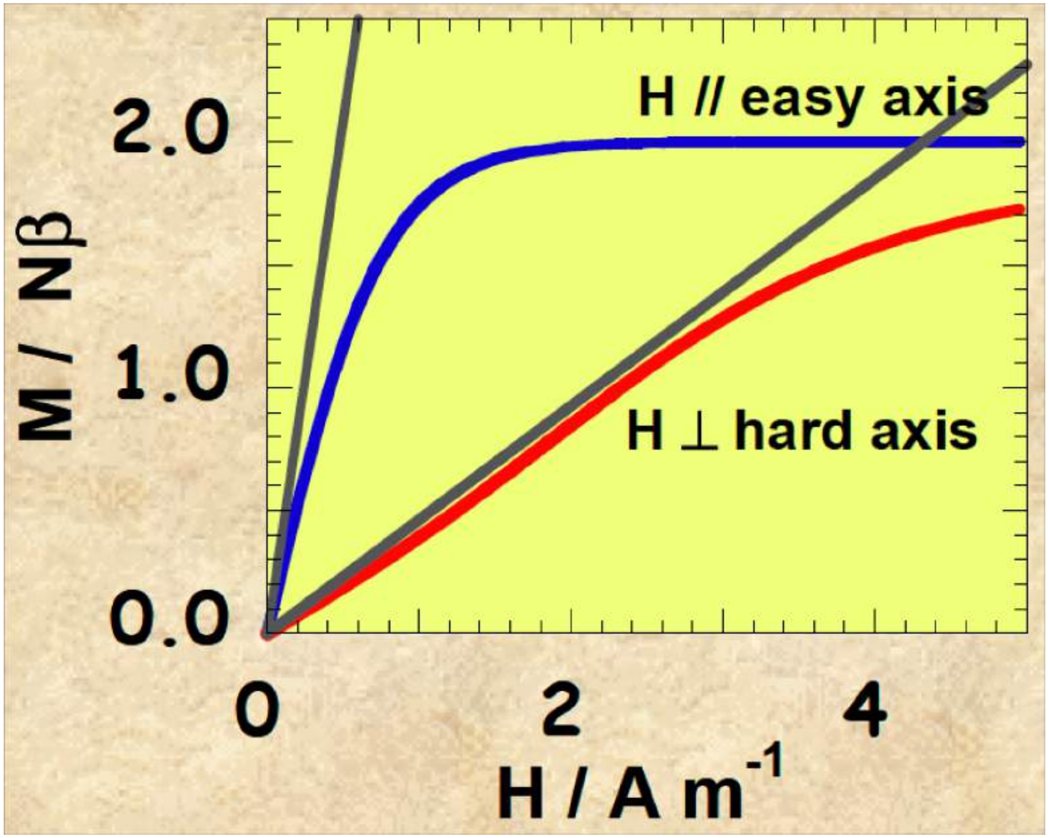
The micro crystals are oriented by the magnetic field. Now the sample is no longer being randomly oriented. A majority of micro crystals have their easy axis // to the magnetic field

Slide Courtesy Dr. Hab. Yves Journaux

Orientation of the microcrystals under magnetic field

$E = -M \cdot H = -\chi \cdot H^2$ to minimize its energy, the crystal will orient itself in order to have the largest χ value

$\chi = M / H$



$\chi_{//} >> \chi_{\perp}$

To avoid the orientation of the microcrystal

You have to block the microcrystals!!!

Slide Courtesy Dr. Hab. Yves Journaux

To block the crystals, several solutions are possible

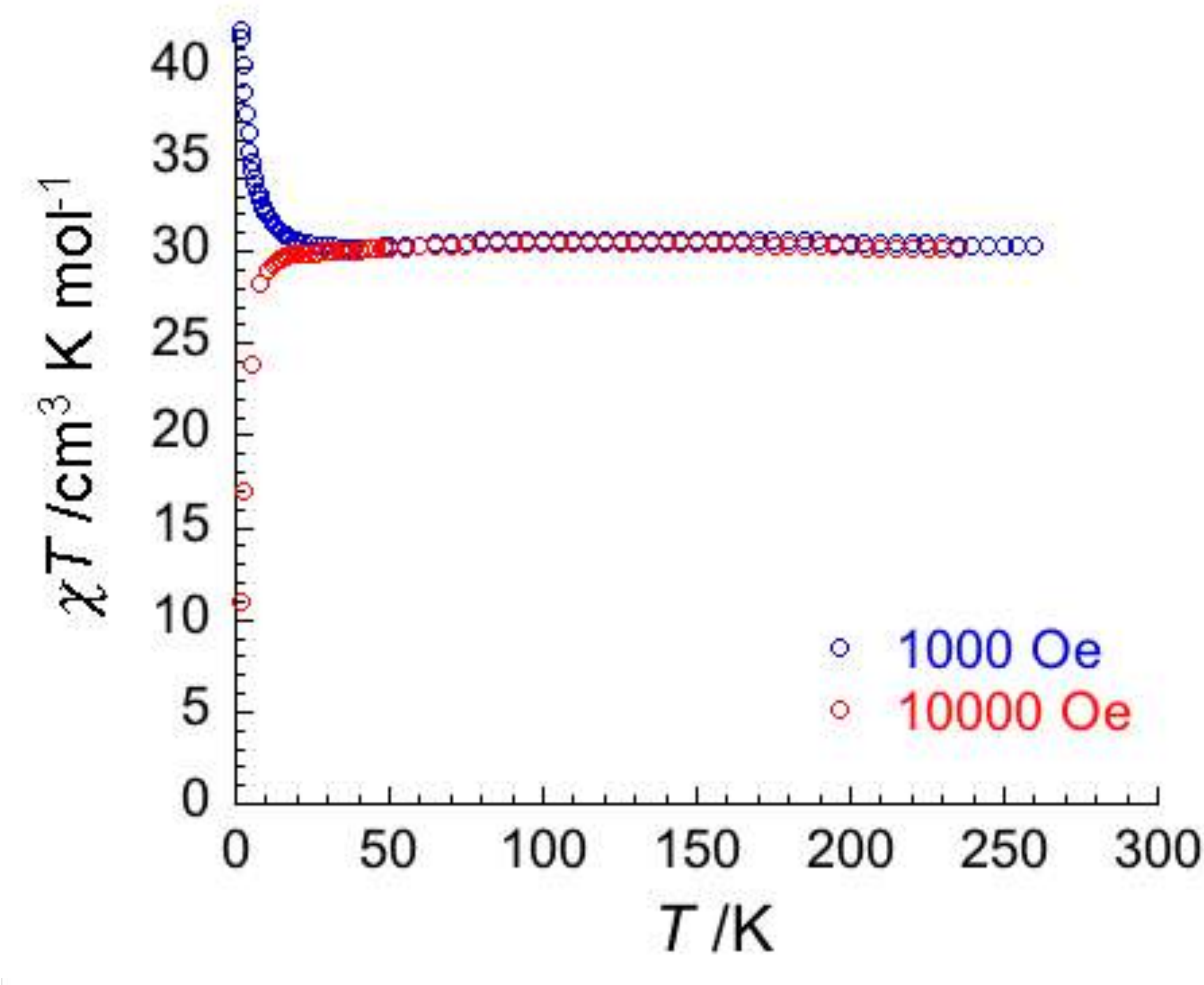
- -Parafilm
- -Araldite
- -Viscous liquid

But with this kind of solution it is difficult to correct the diamagnetic contribution of these supplementary materials

easy solution but not very safe

Slide Courtesy Dr. Hab. Yves Journaux

Blocking the microcrystals using Viscous liquid



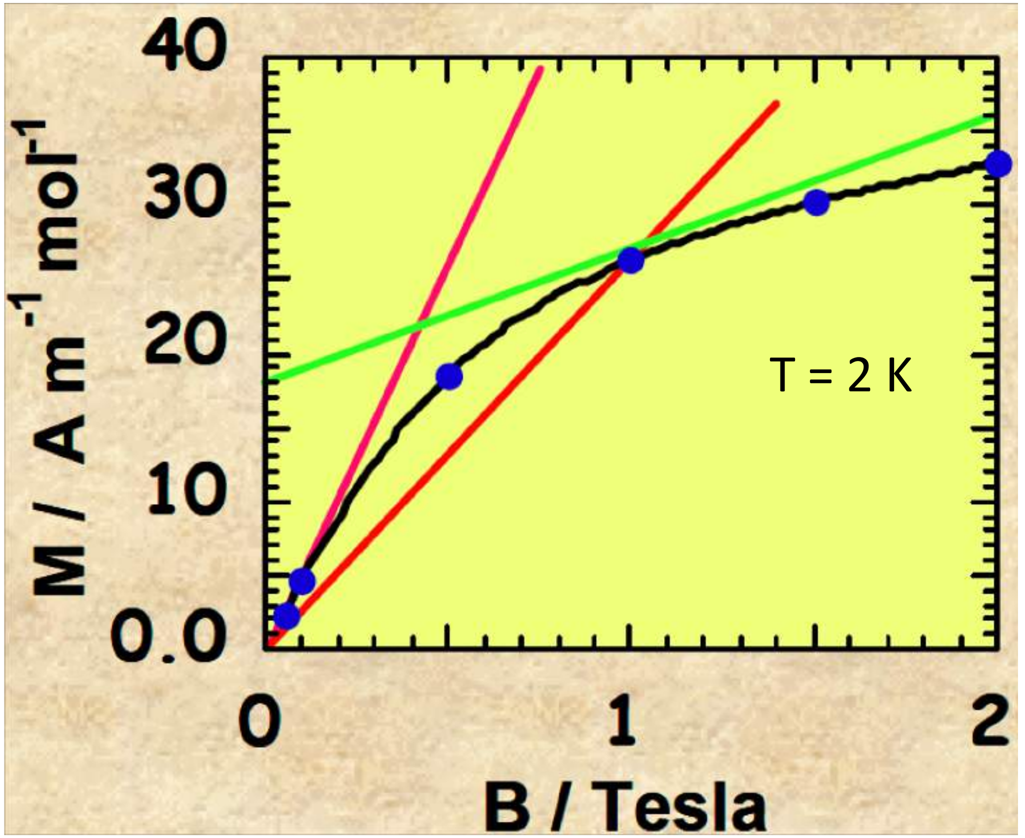
SQUID Magnetometer data, CRPP, Bordeaux

Saturation Effect

In a SQUID magnetometer (DC measurement), the susceptibility is obtained by $\chi_M = M_M / B$

χ_M is calculated as the slope of the **red line** (secant line) which has nothing to do with the real value of χ_M .

χ_M at 1 T is given by the slope of **the green line** (tangent line)



However, we are interested in the value of χ_M at B=0, which is the slope of the **pink line** (linear part of the M=f(B) curve)

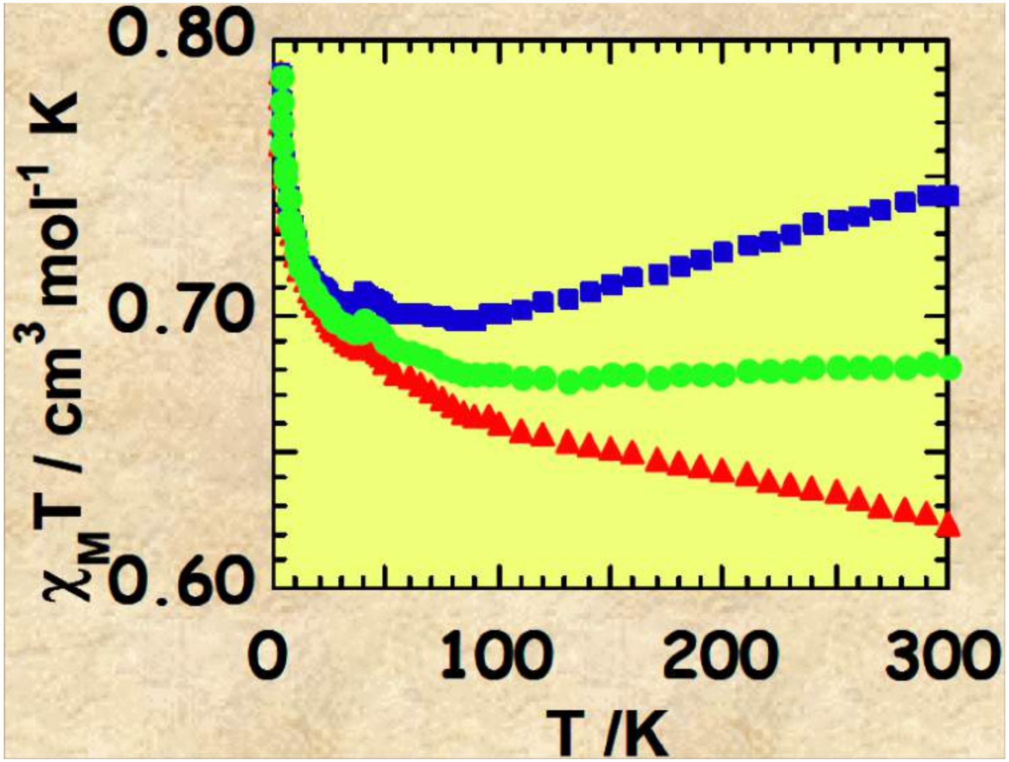
At low temperature, measurements have to be done at low field

Slide Courtesy Dr. Hab. Yves Journaux

Diamagnetic corrections

Crude data must be corrected for

-Diamagnetism of the sample holder
-diamagnetism of the sample
-TIP contribution



▲ $\chi_M T$ uncorrected
■ $\chi_M T$ overcorrected
● $\chi_M T$ corrected

for a weakly coupled system a bad diamagnetic correction could lead to an apparent ferro or ferrimagnetic interaction

Slide Courtesy Dr. Hab. Yves Journaux

Diamagnetic corrections

To find the right correction for the diamagnetism

You have to have a good law χ_{dia}=f(T,H) for the diamagnetism of the sample holder
We use χ_{nac}= A(H) T + B(H)/T +C(H)/T^2

For the sample

The ideal solution is to have the measurements for an isomorphic compound containing non-magnetic metal ions like Zn(II)

Calculate the diamagnetism of the sample using Pascal's constants,

A good approximation is given by
χ_M ***dia*** $\approx$ **{*M_{mol}*/2 }*10^{-6}**

Slide Courtesy Dr. Hab. Yves Journaux

Diamagnetic corrections

Actually you do not need to correct the data for the diamagnetism of the sample.
In fact, it would be better to add a Constant term to the theoretical law

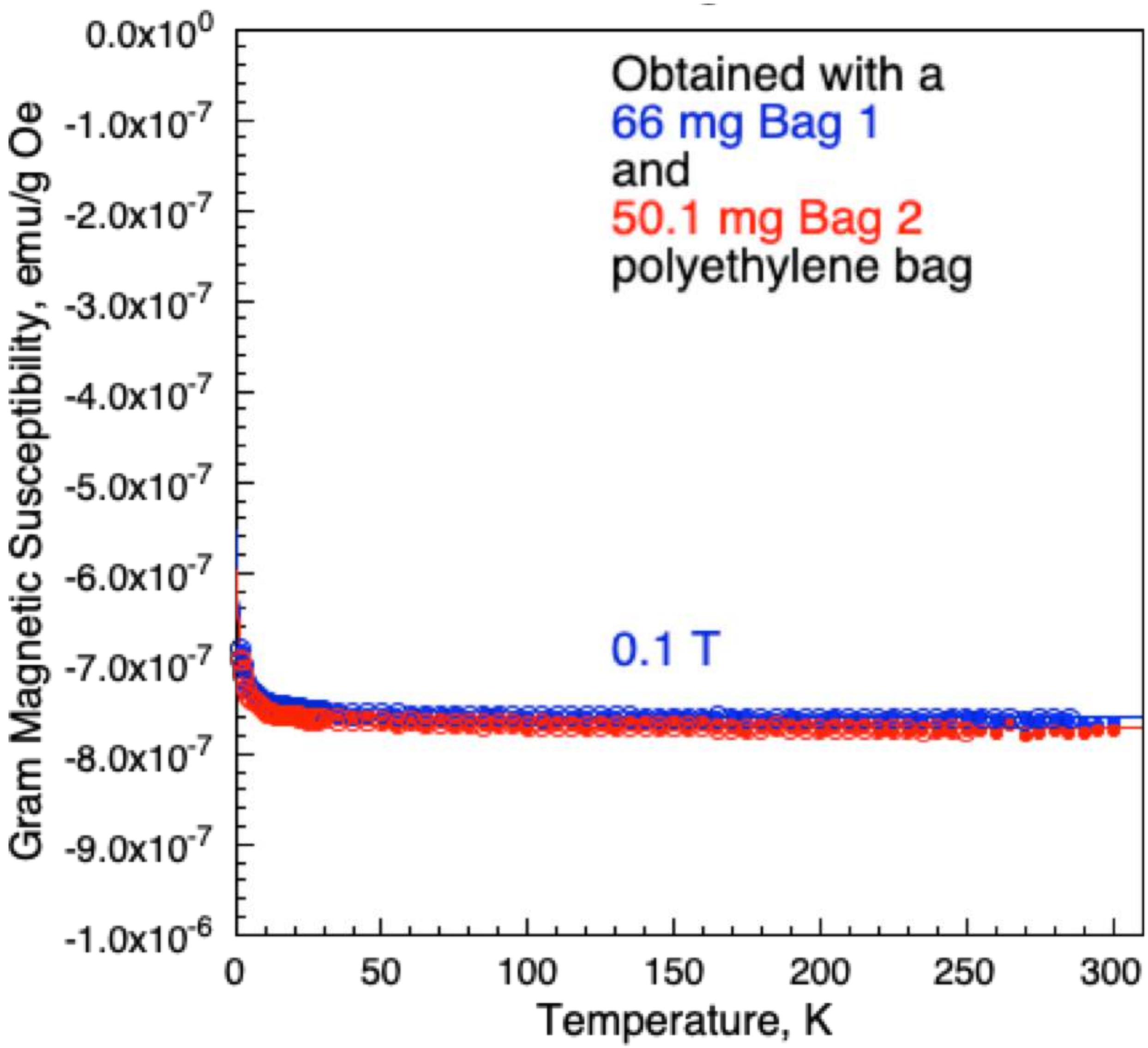
$$\chi_M = \boldsymbol{f(J_i, D_i, g_i, T)} + \boldsymbol{C_{dia}.10^{-6}}$$

and check afterwards if the C_{dia} value is reasonable

The C_{dia} term contains both the diamagnetic and the TIP contributions
TIP : temperature independent paramagnetism

Slide Courtesy Dr. Hab. Yves Journaux

Diamagnetic corrections of the bag



SQUID Magnetometer data, KIT, Germany

SQUID data treatment

SK.M1_149_Xd.dc

	Time C0	Comment C1	Field (Oe) C2	Tempe...re C3	Long ...(emu) C4	Long S...d Dev C5	Long A...rithm C6	Long Reg Fit C7
0	1.5382e+09		500.00	109.95	8.3764e-05	0.0000	3.0000	0.99495
1	1.5382e+09		500.00	107.86	8.5043e-05	0.0000	3.0000	0.99562
2	1.5382e+09		500.00	105.81	8.5477e-05	0.0000	3.0000	0.99490
3	1.5382e+09		500.00	103.75	8.5817e-05	0.0000	3.0000	0.99428
4	1.5382e+09		500.00	101.78	8.7192e-05	0.0000	3.0000	0.99569
5	1.5382e+09		500.00	99.728	8.8529e-05	0.0000	3.0000	0.99155
6	1.5382e+09		500.00	97.785	8.9166e-05	0.0000	3.0000	0.99580
7	1.5382e+09		500.00	95.771	9.0567e-05	0.0000	3.0000	0.99598
8	1.5382e+09		500.00	93.733	9.1144e-05	0.0000	3.0000	0.99414
9	1.5382e+09		500.00	91.711	9.2576e-05	0.0000	3.0000	0.99573
10	1.5382e+09		500.00	89.708	9.3603e-05	0.0000	3.0000	0.99340
11	1.5382e+09		500.00	87.758	9.5090e-05	0.0000	3.0000	0.99344
12	1.5382e+09		500.00	85.745	9.7302e-05	0.0000	3.0000	0.99545
13	1.5382e+09		500.00	83.769	9.7134e-05	0.0000	3.0000	0.99725
14	1.5382e+09		500.00	81.748	9.8978e-05	0.0000	3.0000	0.99735
15	1.5382e+09		500.00	79.711	0.00010036	0.0000	3.0000	0.99609
16	1.5382e+09		500.00	77.743	0.00010071	0.0000	3.0000	0.99290
17	1.5382e+09		500.00	75.707	0.00010270	0.0000	3.0000	0.99514
18	1.5382e+09		500.00	73.750	0.00010500	0.0000	3.0000	0.99540
19	1.5382e+09		500.00	71.784	0.00010630	0.0000	3.0000	0.99664
20	1.5382e+09		500.00	69.740	0.00010805	0.0000	3.0000	0.99716
21	1.5382e+09		500.00	67.733	0.00011048	0.0000	3.0000	0.99751
22	1.5382e+09		500.00	65.733	0.00011099	0.0000	3.0000	0.99557

Magnetic moment vs Temperature

SQUID Magnetometer data, UPMC, Paris-6

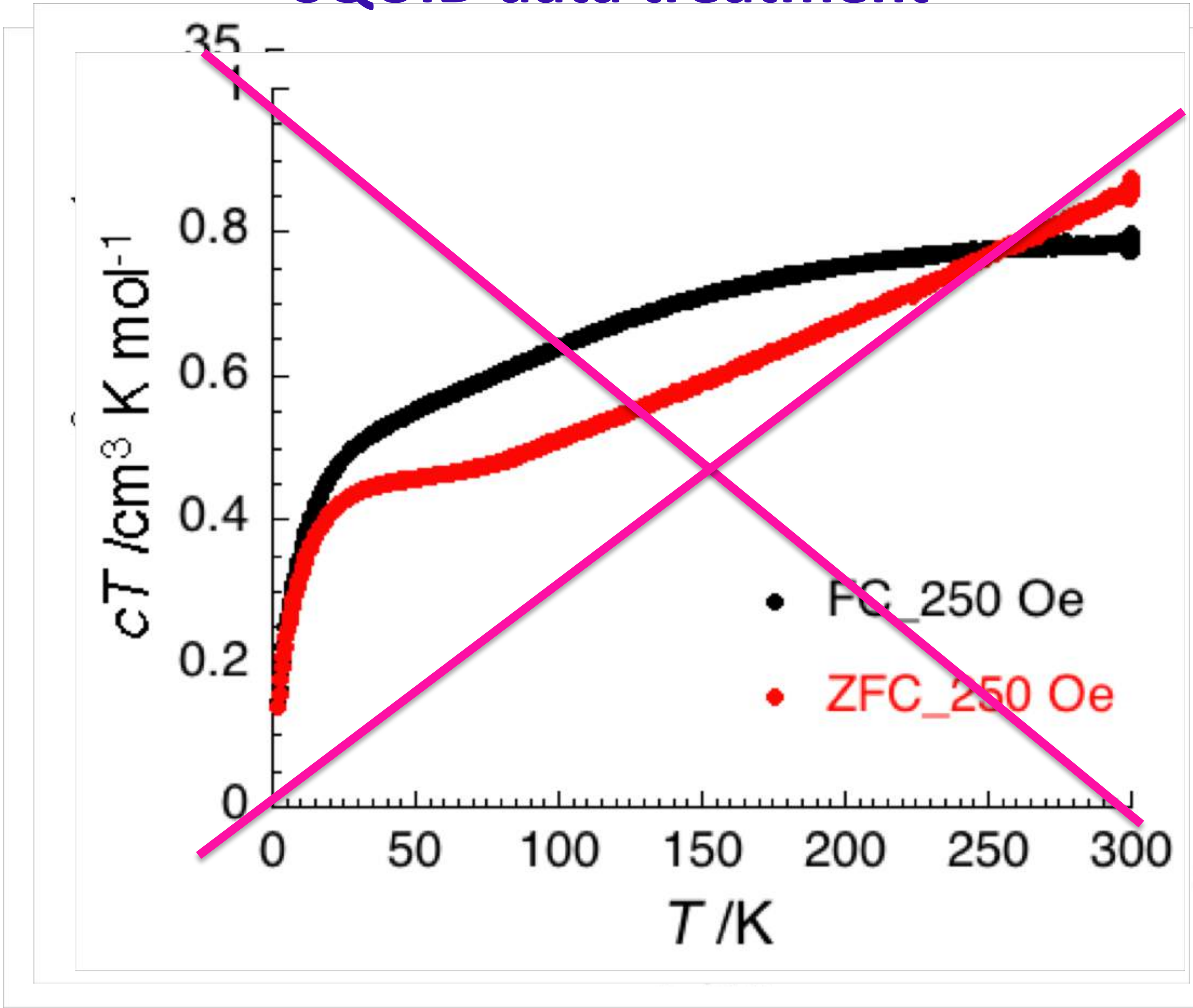
SQUID data treatment

	Comment C0	Time S... C1	Tempe...re C2	Magne...d C3	Range C4	Pressu...(Torr) C5	Measure C6	Measu...umber C7	Motor ...p. (C) C8	Temp. C9	Field S...code) C10	Chamb...code) C11	Chamb...p (K) C12	Redire... State C13	Rotati... (deg) C14	Rotator state C15
0		3.7494e+09	249.91	2499.6	1.0000	6.0766	-1.0000e+08	1.0000	29.326	1.0000	1.0000	1.0000	249.91	0.0000	249.91	9.9492e-44
1		3.7494e+09	250.11	2499.6	1.0000	6.0767	-1.0000e+08	1.0000	28.837	2.0000	1.0000	1.0000	250.20	0.0000	250.09	9.9492e-44
2		3.7494e+09	254.18	2499.6	1.0000	6.0795	-1.0000e+08	1.0000	28.837	2.0000	1.0000	1.0000	254.33	0.0000	254.14	9.9492e-44
3		3.7494e+09	258.12	2499.6	1.0000	6.0838	-1.0000e+08	1.0000	28.837	2.0000	1.0000	1.0000	258.28	0.0000	258.07	9.9492e-44
4		3.7494e+09	262.04	2499.6	1.0000	6.0893	-1.0000e+08	1.0000	28.837	2.0000	1.0000	1.0000	262.19	0.0000	261.99	9.9492e-44
5		3.7494e+09	265.97	2499.6	1.0000	6.0973	-1.0000e+08	1.0000	28.837	2.0000	1.0000	1.0000	266.12	0.0000	265.93	9.9492e-44
6		3.7494e+09	269.91	2499.6	1.0000	6.1063	-1.0000e+08	1.0000	28.837	2.0000	1.0000	1.0000	270.04	0.0000	269.90	9.9492e-44
7		3.7494e+09	273.94	2499.6	1.0000	6.1181	-1.0000e+08	1.0000	28.837	2.0000	1.0000	1.0000	274.11	0.0000	273.93	9.9492e-44
8		3.7494e+09	277.87	2499.6	1.0000	6.1309	-1.0000e+08	1.0000	28.837	2.0000	1.0000	1.0000	278.04	0.0000	277.81	9.9492e-44
9		3.7494e+09	281.76	2499.6	1.0000	6.1465	-1.0000e+08	1.0000	28.837	2.0000	1.0000	1.0000	281.91	0.0000	281.71	9.9492e-44
10		3.7494e+09	285.72	2499.6	1.0000	6.1664	-1.0000e+08	1.0000	28.837	2.0000	1.0000	1.0000	285.85	0.0000	285.71	9.9492e-44
11		3.7494e+09	289.71	2499.6	1.0000	6.1957	-1.0000e+08	1.0000	28.837	2.0000	1.0000	1.0000	289.85	0.0000	289.68	9.9492e-44
12		3.7494e+09	293.69	2499.6	1.0000	6.2319	-1.0000e+08	1.0000	28.837	2.0000	1.0000	1.0000	293.87	0.0000	293.64	9.9492e-44
13		3.7494e+09	297.60	2499.6	1.0000	6.2749	-1.0000e+08	1.0000	28.837	2.0000	1.0000	1.0000	297.76	0.0000	297.55	9.9492e-44
14		3.7494e+09	301.54	2499.6	1.0000	6.3271	-1.0000e+08	1.0000	28.837	2.0000	1.0000	1.0000	301.68	0.0000	301.52	9.9492e-44
15		3.7494e+09	305.54	2499.6	1.0000	6.3844	-1.0000e+08	1.0000	28.837	2.0000	1.0000	1.0000	305.70	0.0000	305.50	9.9492e-44
16		3.7494e+09	309.44	2499.6	1.0000	6.4464	-1.0000e+08	1.0000	29.326	2.0000	1.0000	1.0000	309.60	0.0000	309.39	9.9492e-44
17		3.7494e+09	313.35	2499.6	1.0000	6.5135	-1.0000e+08	1.0000	29.326	2.0000	1.0000	1.0000	313.51	0.0000	313.30	9.9492e-44
18		3.7494e+09	317.31	2499.6	1.0000	6.5846	-1.0000e+08	1.0000	29.326	2.0000	1.0000	1.0000	317.48	0.0000	317.25	9.9492e-44
19		3.7494e+09	321.23	2499.6	1.0000	6.6616	-1.0000e+08	1.0000	29.326	2.0000	1.0000	1.0000	321.35	0.0000	321.21	9.9492e-44
20		3.7494e+09	325.23	2499.6	1.0000	6.7317	-1.0000e+08	1.0000	28.837	2.0000	1.0000	1.0000	325.38	0.0000	325.18	9.9492e-44
21		3.7494e+09	329.14	2499.6	1.0000	6.8027	-1.0000e+08	1.0000	28.837	2.0000	1.0000	1.0000	329.30	0.0000	329.08	9.9492e-44
22																

Magnetic moment vs Temperature Data from VSM

SQUID-VSM data, IISc, Bangalore

SQUID data treatment



Magnetic susceptibility vs Temperature

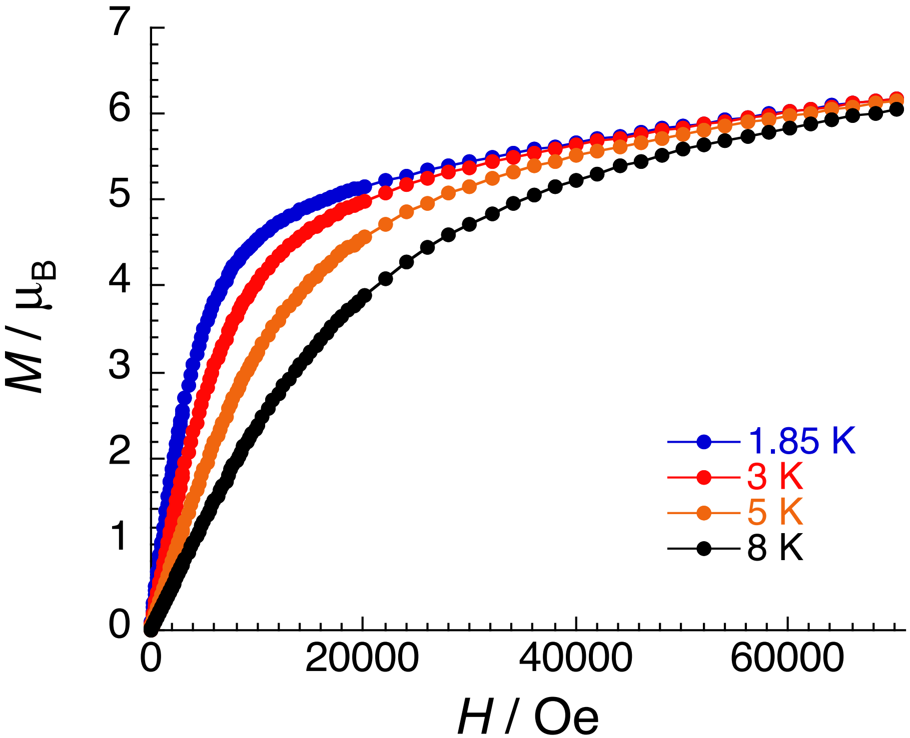
SQUID data treatment

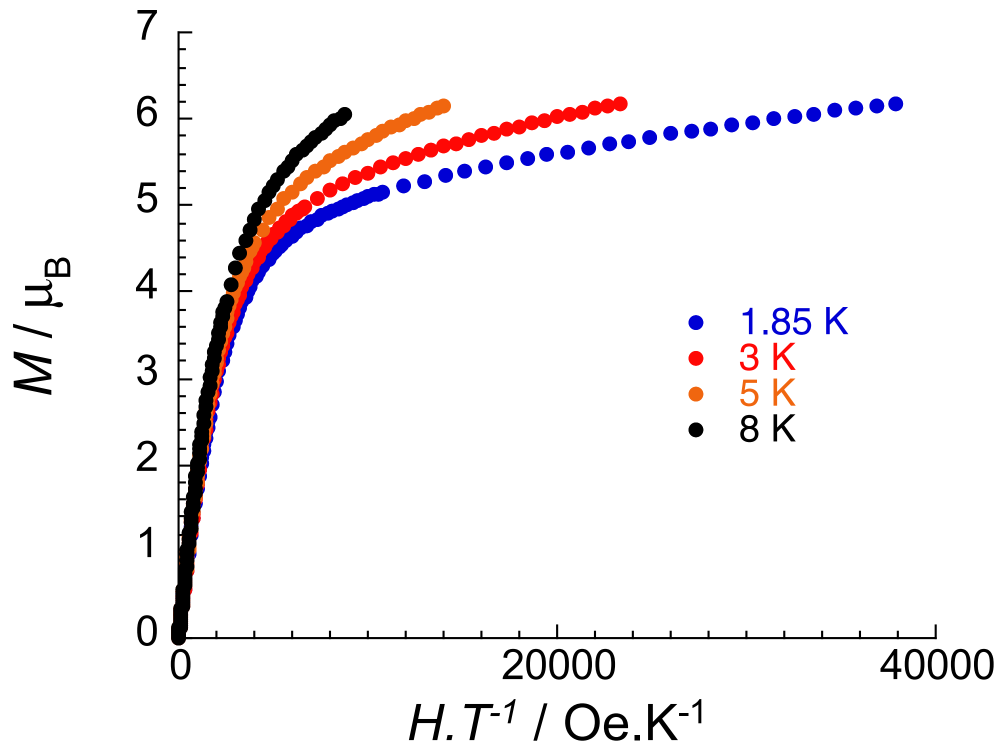
FeTpCovimBF4DRIED_a13.rso

	Time C0	Comment C1	Field (Oe) C2	Tempe...re C3	Long ...(emu) C4	Long S...d Dev C5	Long ...t (cm) C6	Long O...d C7	Long A...rithm C8	Long Reg Fit C9	Long R...actor C10
0	1.4825e+09		0.62804	100.04	-3.6648e-06	6.1532e-08	0.0000	0.0000	2.0000	0.96614	1.8250
1	1.4825e+09		49.660	100.03	1.3416e-05	1.1775e-07	0.0000	0.0000	2.0000	0.97973	1.8250
2	1.4825e+09		99.798	100.02	3.0147e-05	8.8269e-08	0.0000	0.0000	2.0000	0.97670	1.8250
3	1.4825e+09		150.06	100.02	4.7152e-05	9.9945e-10	0.0000	0.0000	2.0000	0.97720	1.8250
4	1.4825e+09		199.98	100.01	6.4091e-05	8.6343e-08	0.0000	0.0000	2.0000	0.97755	1.8250
5	1.4825e+09		250.23	100.01	8.1053e-05	3.8547e-08	0.0000	0.0000	2.0000	0.97743	1.8250
6	1.4825e+09		300.25	100.00	9.7872e-05	2.5973e-08	0.0000	0.0000	2.0000	0.97775	1.8250
7	1.4825e+09		400.57	100.00	0.00013183	5.5144e-08	0.0000	0.0000	2.0000	0.97764	1.8250
8	1.4825e+09		500.71	100.00	0.00016550	1.0957e-07	0.0000	0.0000	2.0000	0.97777	1.8250
9	1.4825e+09		600.97	100.00	0.00019943	8.1564e-08	0.0000	0.0000	2.0000	0.97773	1.8250
10	1.4825e+09		701.28	99.998	0.00023311	1.0955e-07	0.0000	0.0000	2.0000	0.97781	1.8250
11	1.4825e+09		801.36	99.999	0.00026686	1.2128e-07	0.0000	0.0000	2.0000	0.97781	1.8250
12	1.4825e+09		901.56	99.997	0.00030052	1.5613e-07	0.0000	0.0000	2.0000	0.97791	1.8250
13	1.4825e+09		1002.0	99.999	0.00033426	1.9030e-07	0.0000	0.0000	2.0000	0.97793	1.8250
14											

Magnetic moment vs field

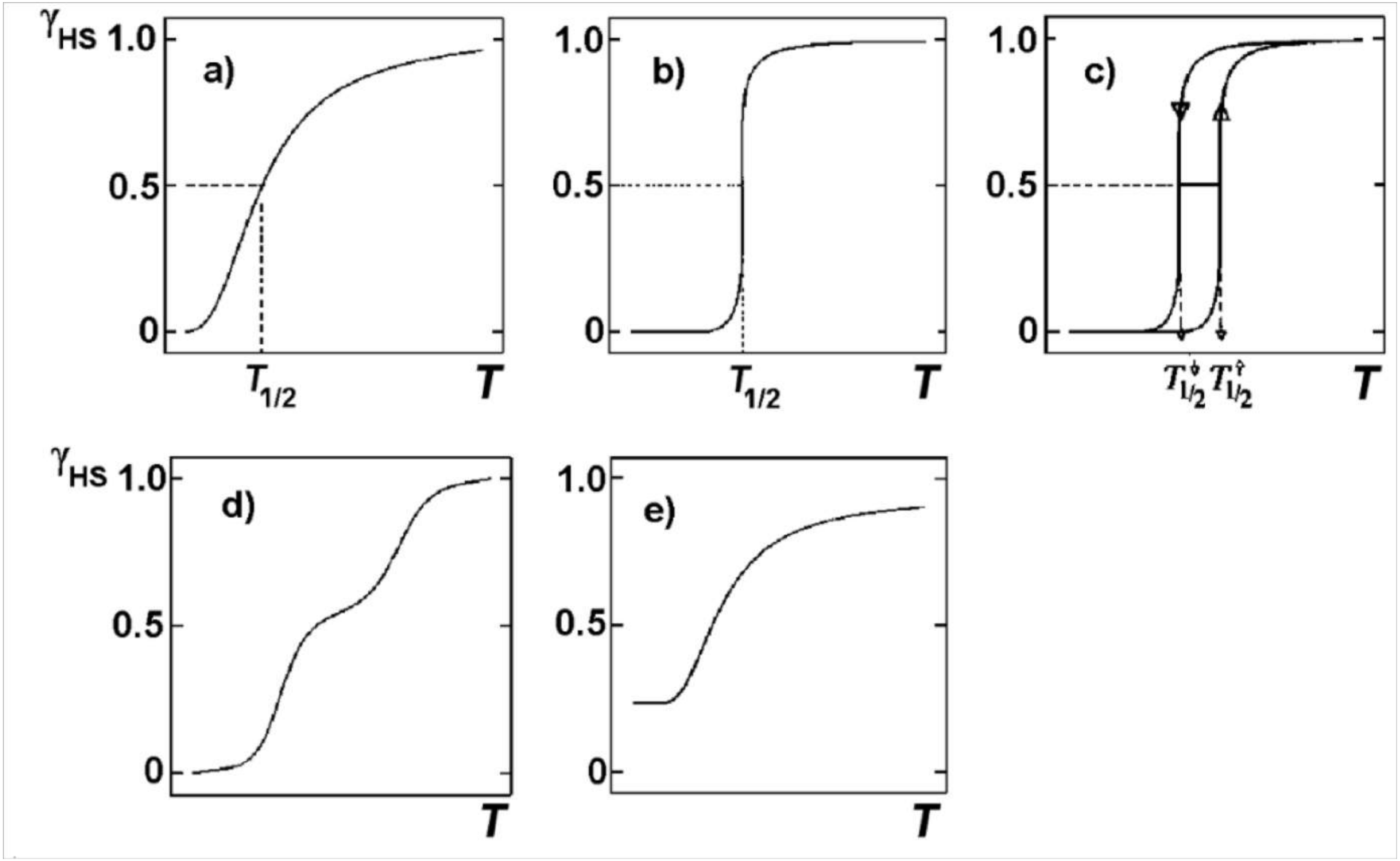
SQUID data treatment





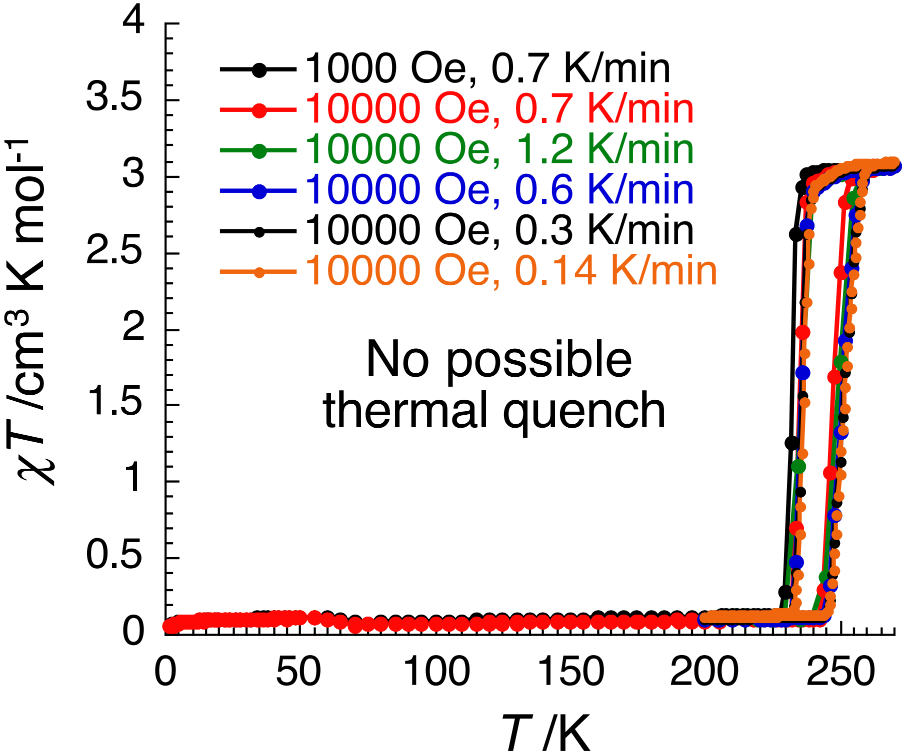
Magnetization vs vs field

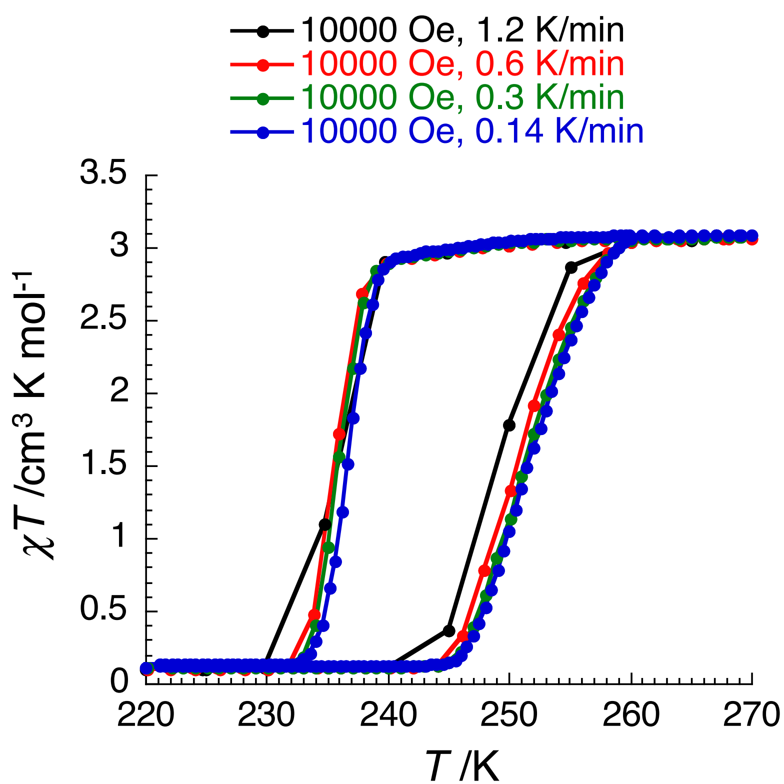
Spin Crossover or Spin-transition



Atkins P. W. Physical chemistry. **1994** 221.
Slichter C. P. J. Chem. Phys. **1972**, *56,* 2142.

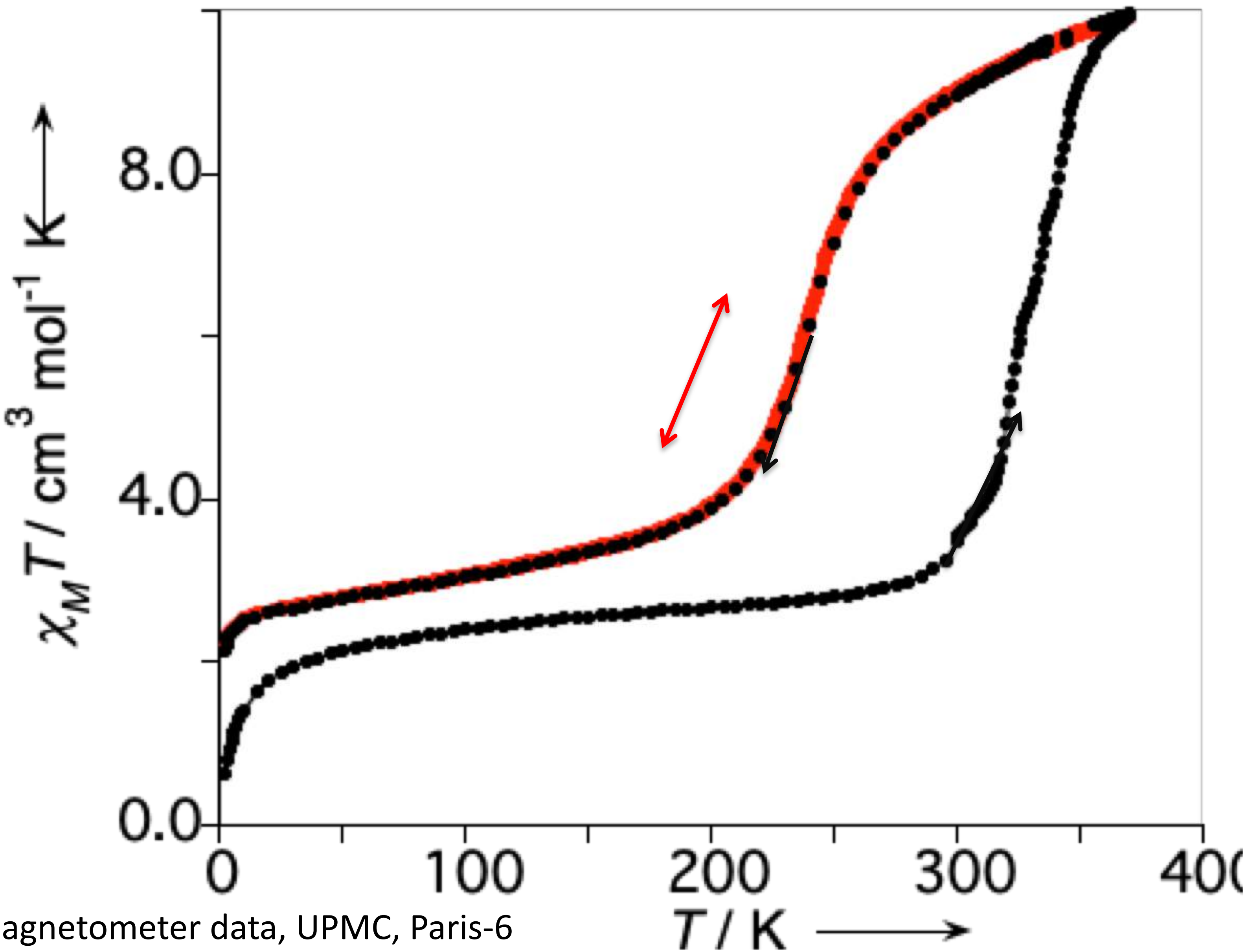
Spin Crossover or Spin Transition
Electron-Transfer-Coupled Spin Transition





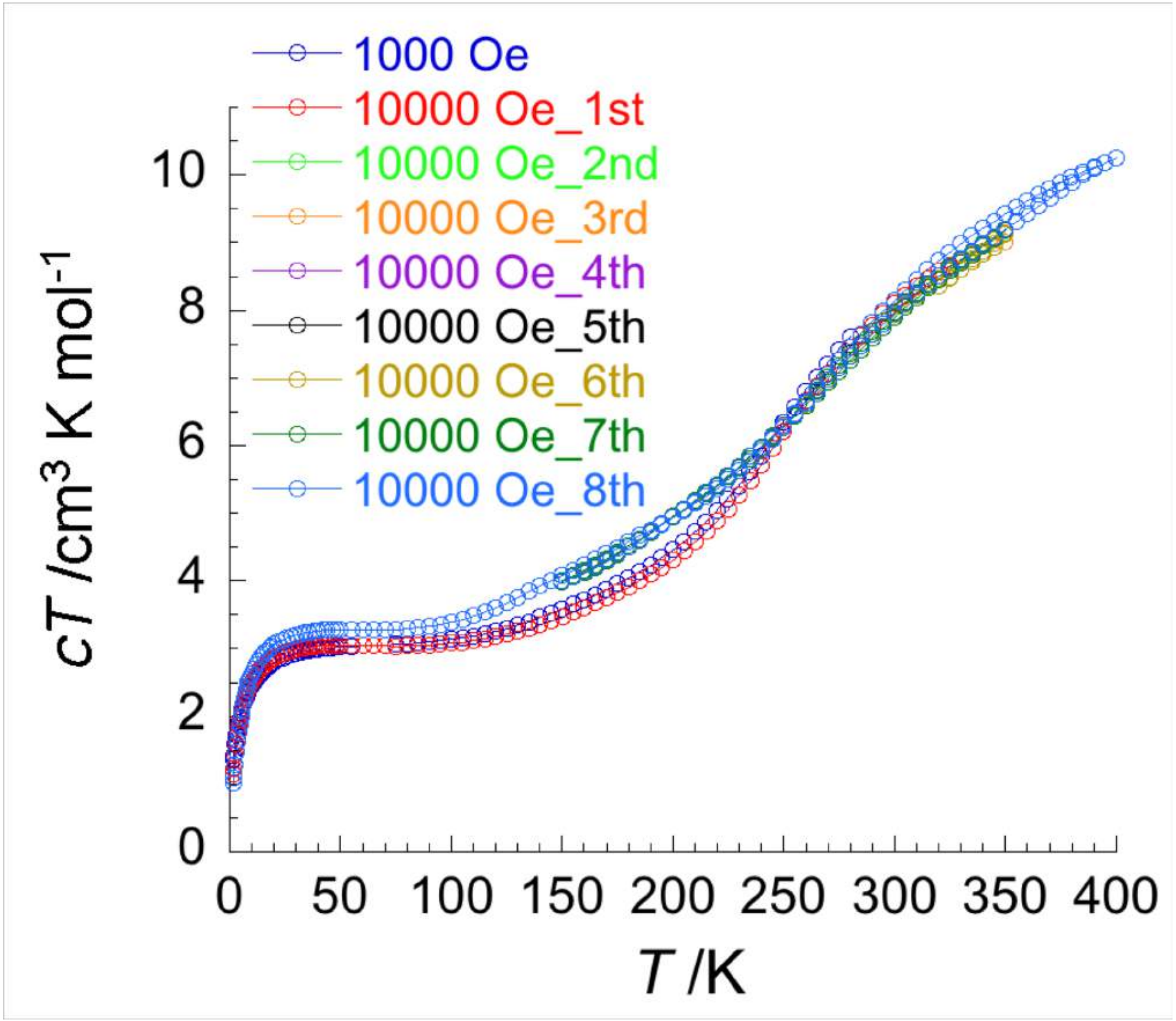
SQUID Magnetometer data analysis, CRPP, Bordeaux

Spin Crossover or Spin Transition
Electron-Transfer-Coupled Spin Transition



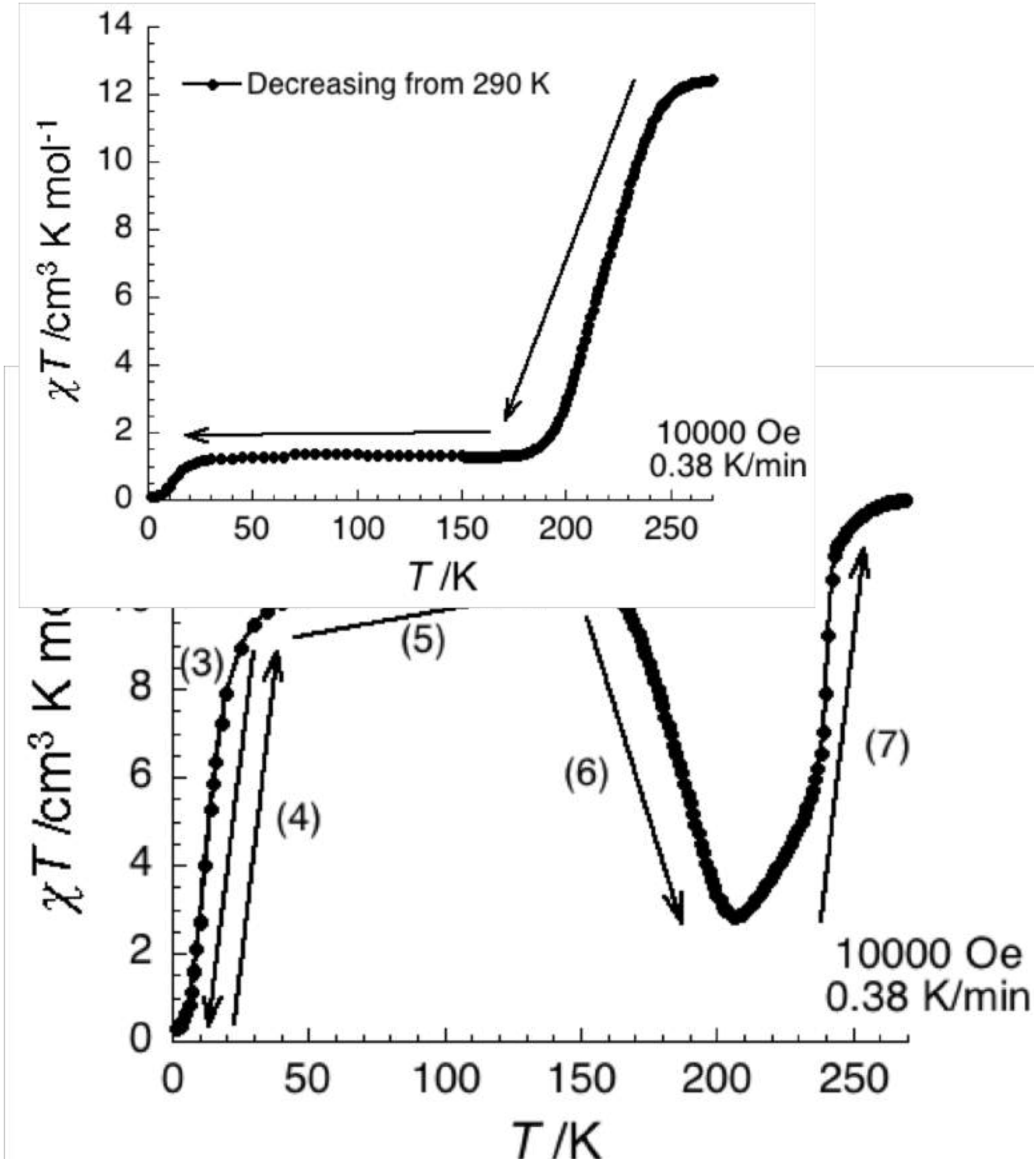
SQUID Magnetometer data, UPMC, Paris-6

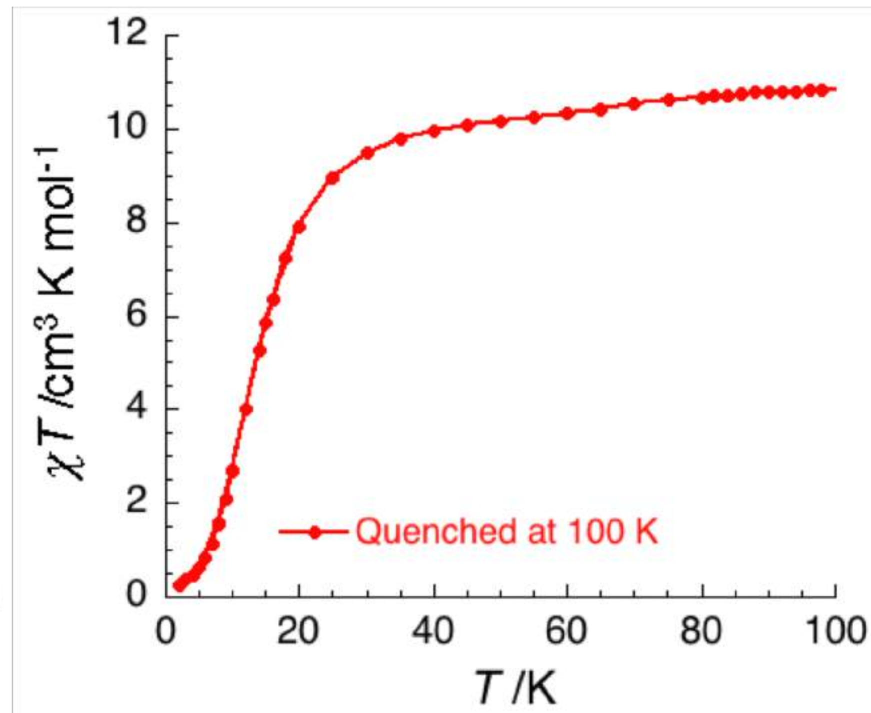
Spin Crossover or Spin Transition
Electron-Transfer-Coupled Spin Transition



SQUID Magnetometer data analysis, CRPP, Bordeaux

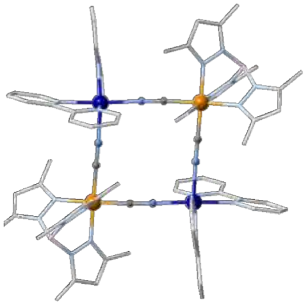
Magnetic Measurements: Thermal Quenching

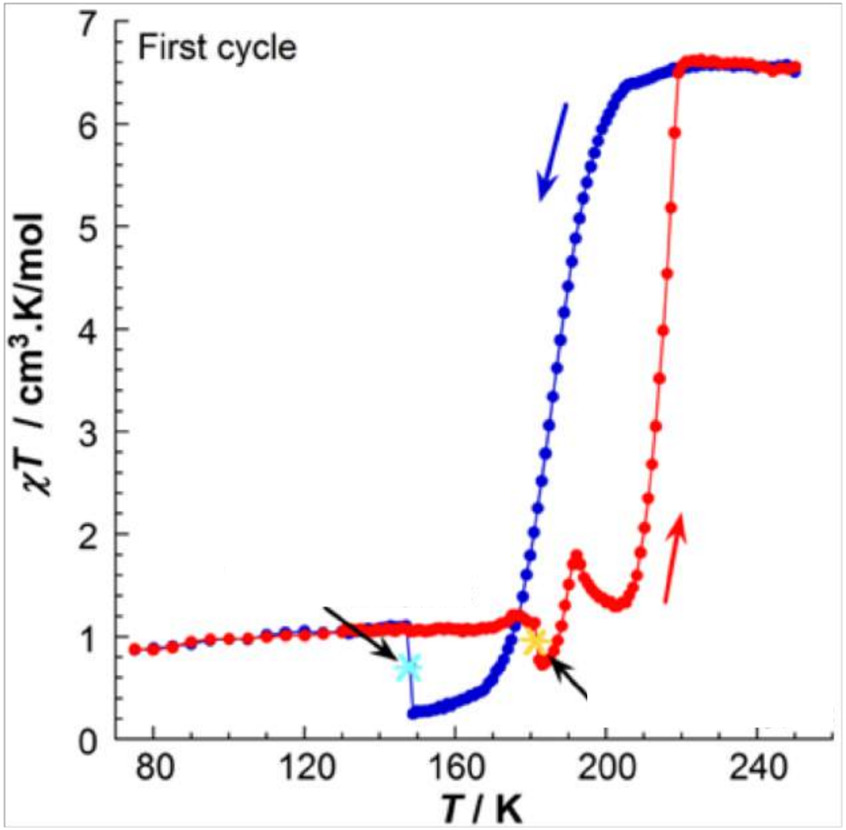


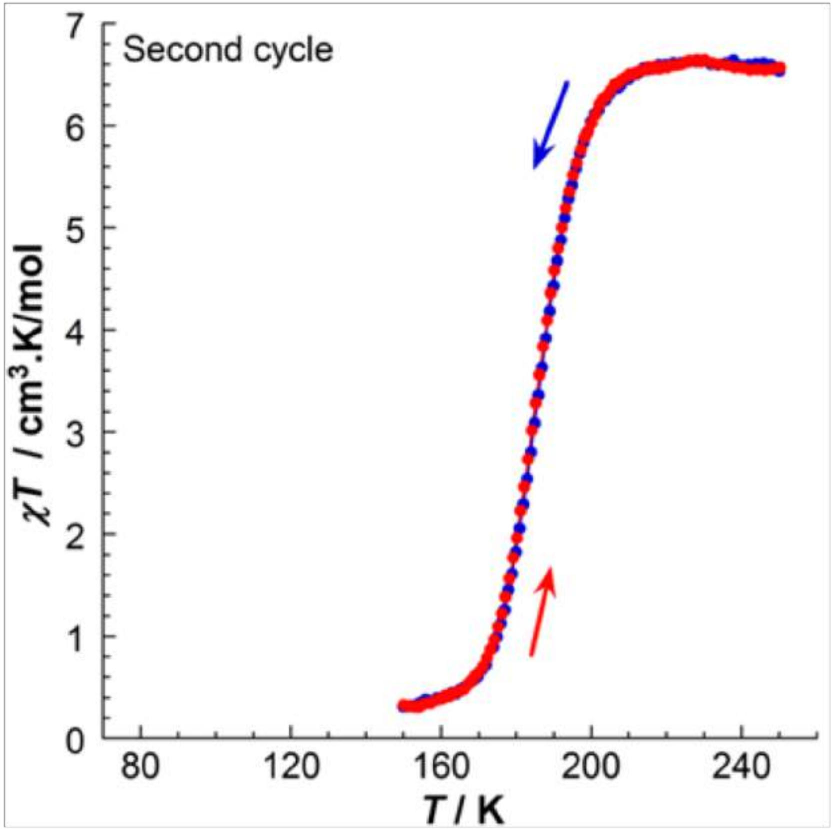


SQUID Magnetometer data, CRPP, Bordeaux

Magnetic measurement in solution

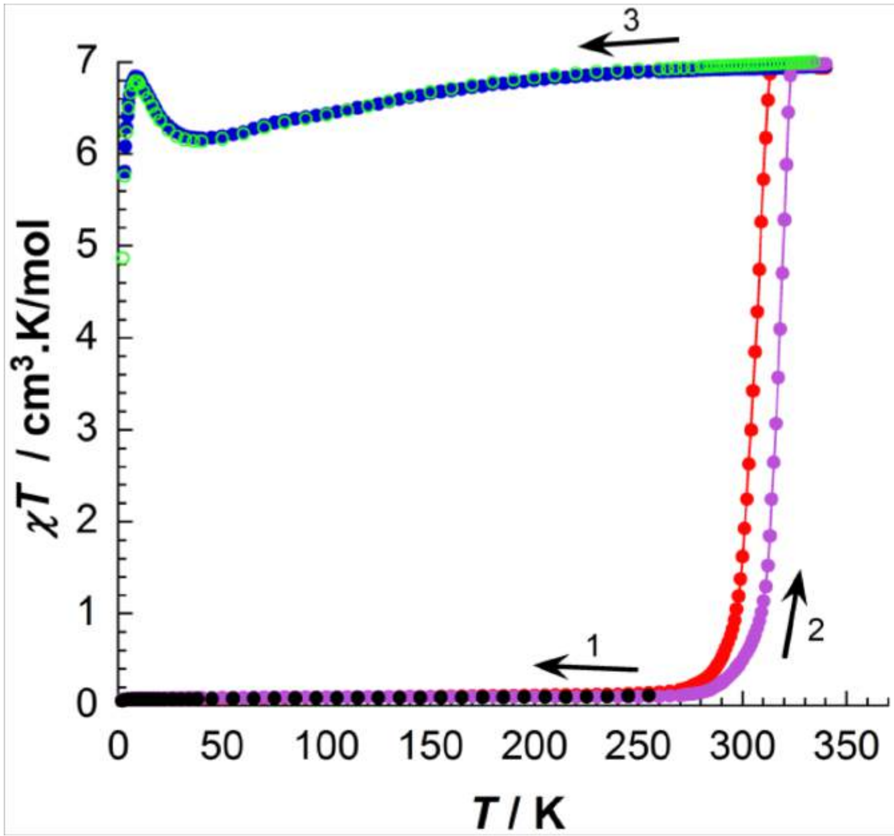


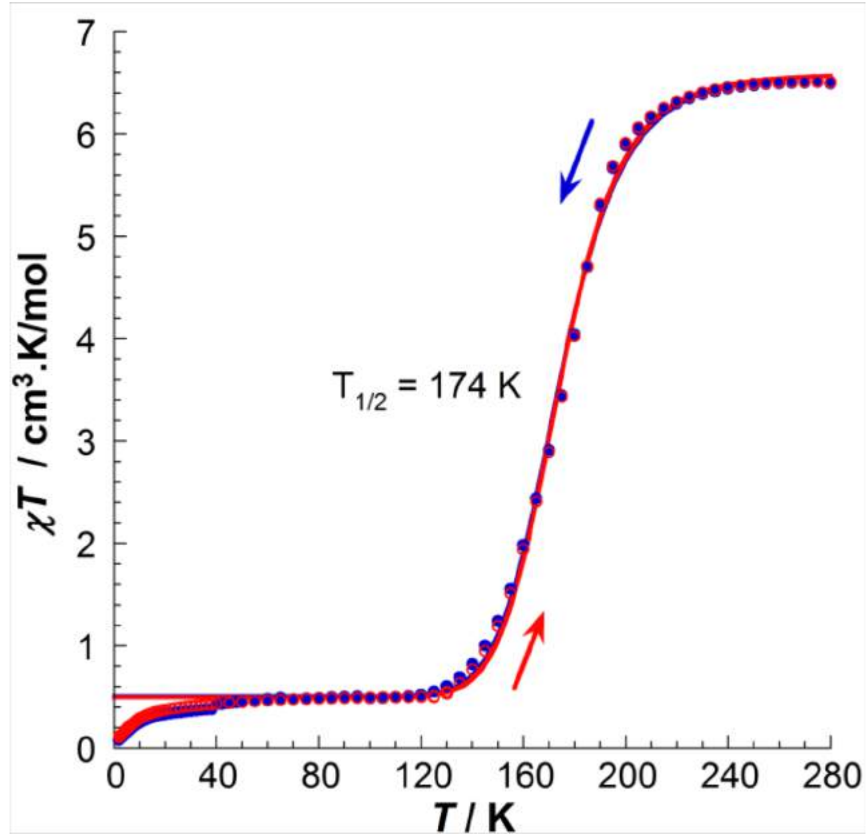




SQUID Magnetometer data, CRPP, Bordeaux

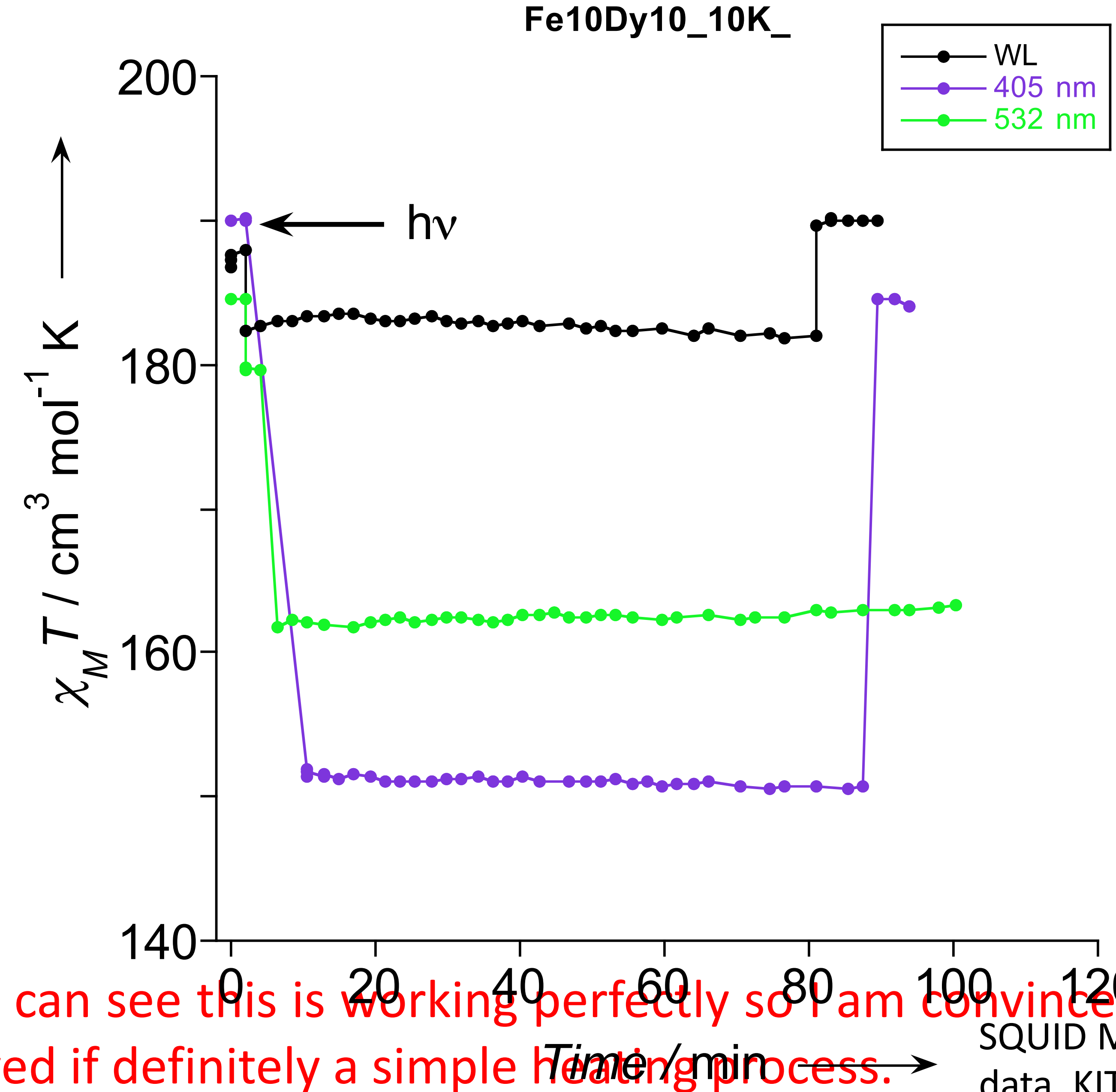
Magnetic measurement: crystals kept in the mother liquor





SQUID Magnetometer data, CRPP, Bordeaux

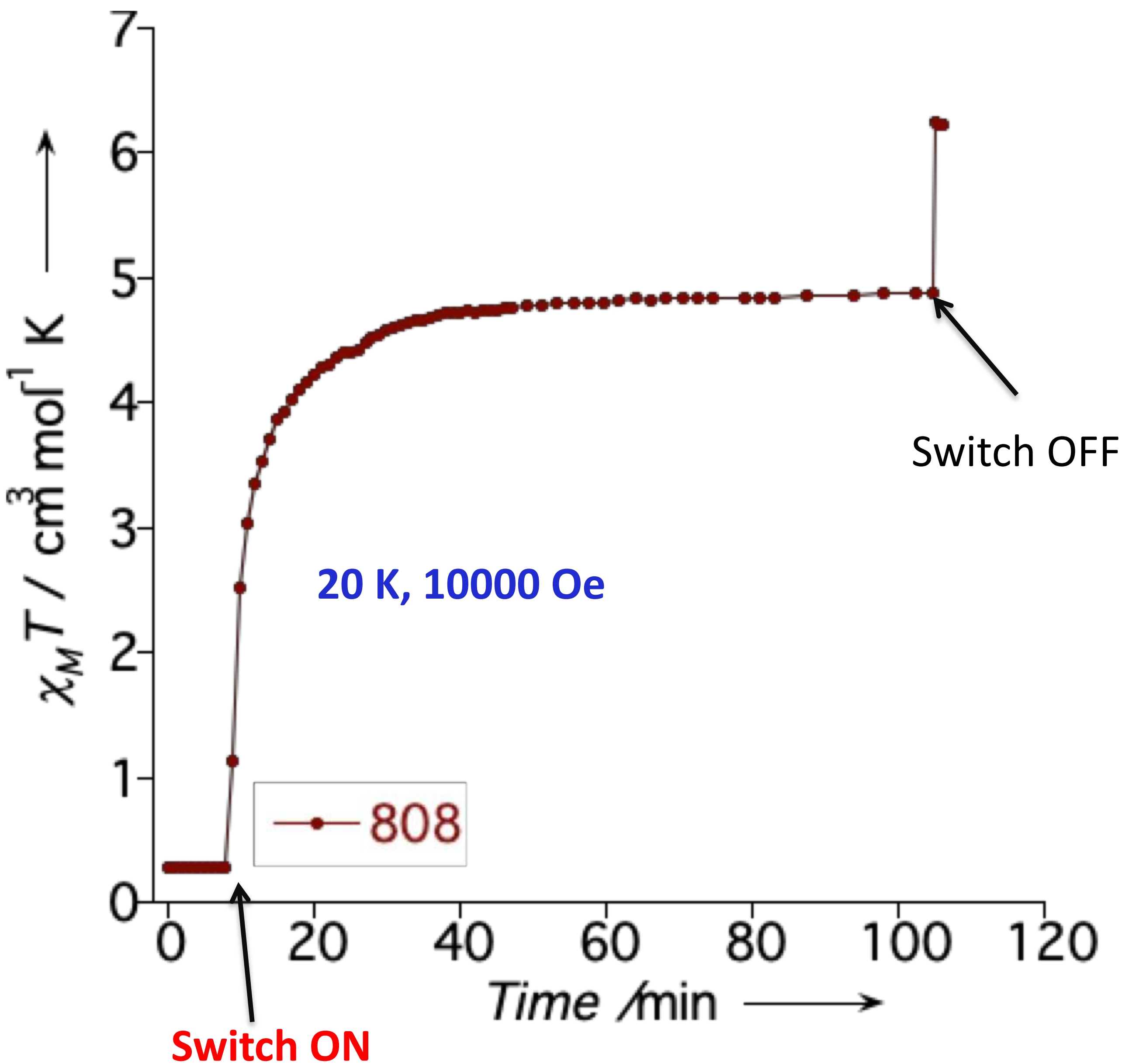
1st Measurement: Irradiation vs Time



As you can see this is working perfectly so I am convinced that what is observed if definitely a simple heating process.

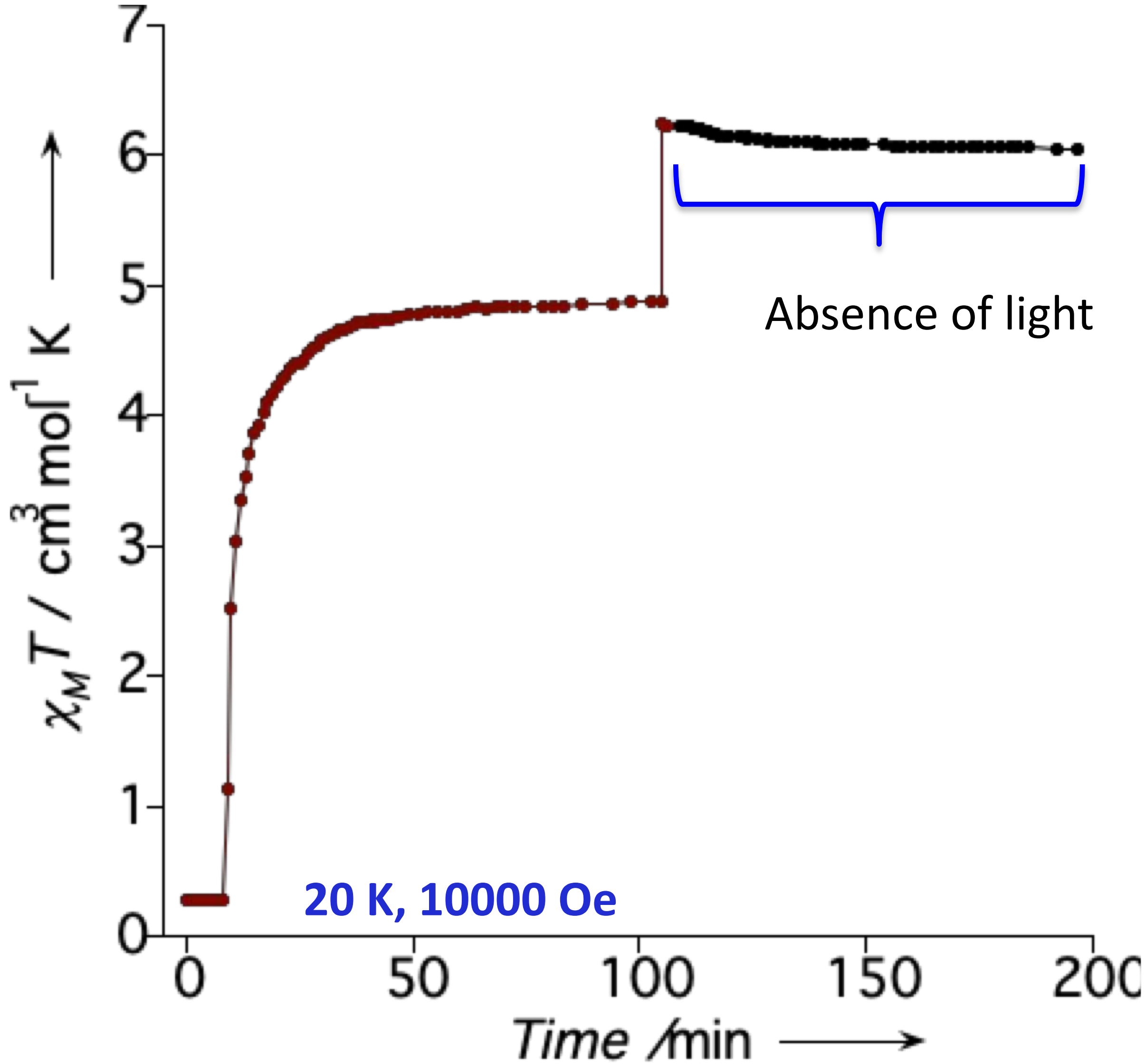
SQUID Magnetometer data, KIT, Germany

1st measurement: kinetic of the irradiation



Abhishake Mondal_Thesis, 2013, UPMC-Paris-6

2nd measurement:
Relaxation of the photoinduced metastable state



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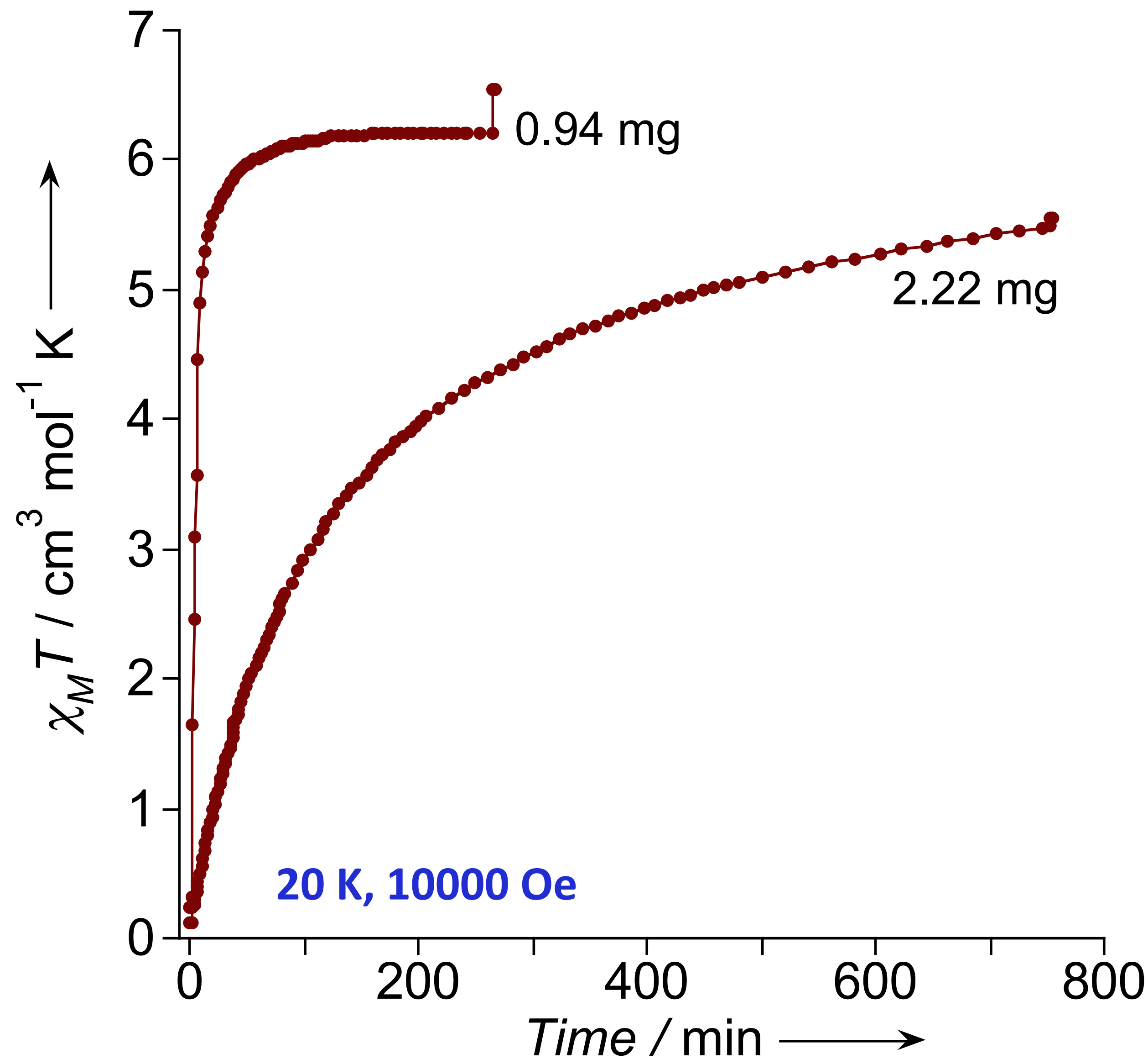
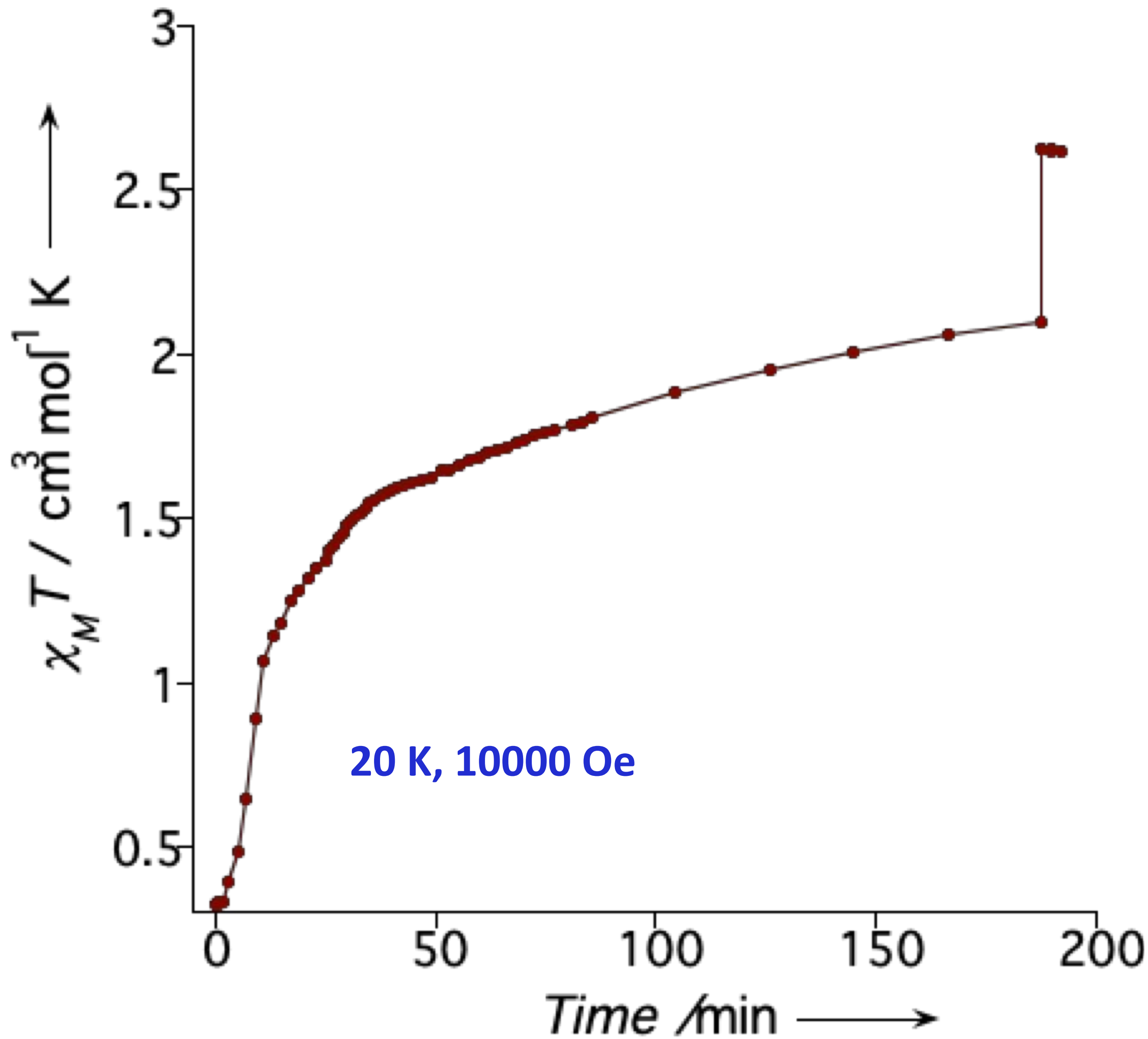
Depending upon the sample weight



Abhishake Mondal_Thesis, 2013, UPMC-Paris-6

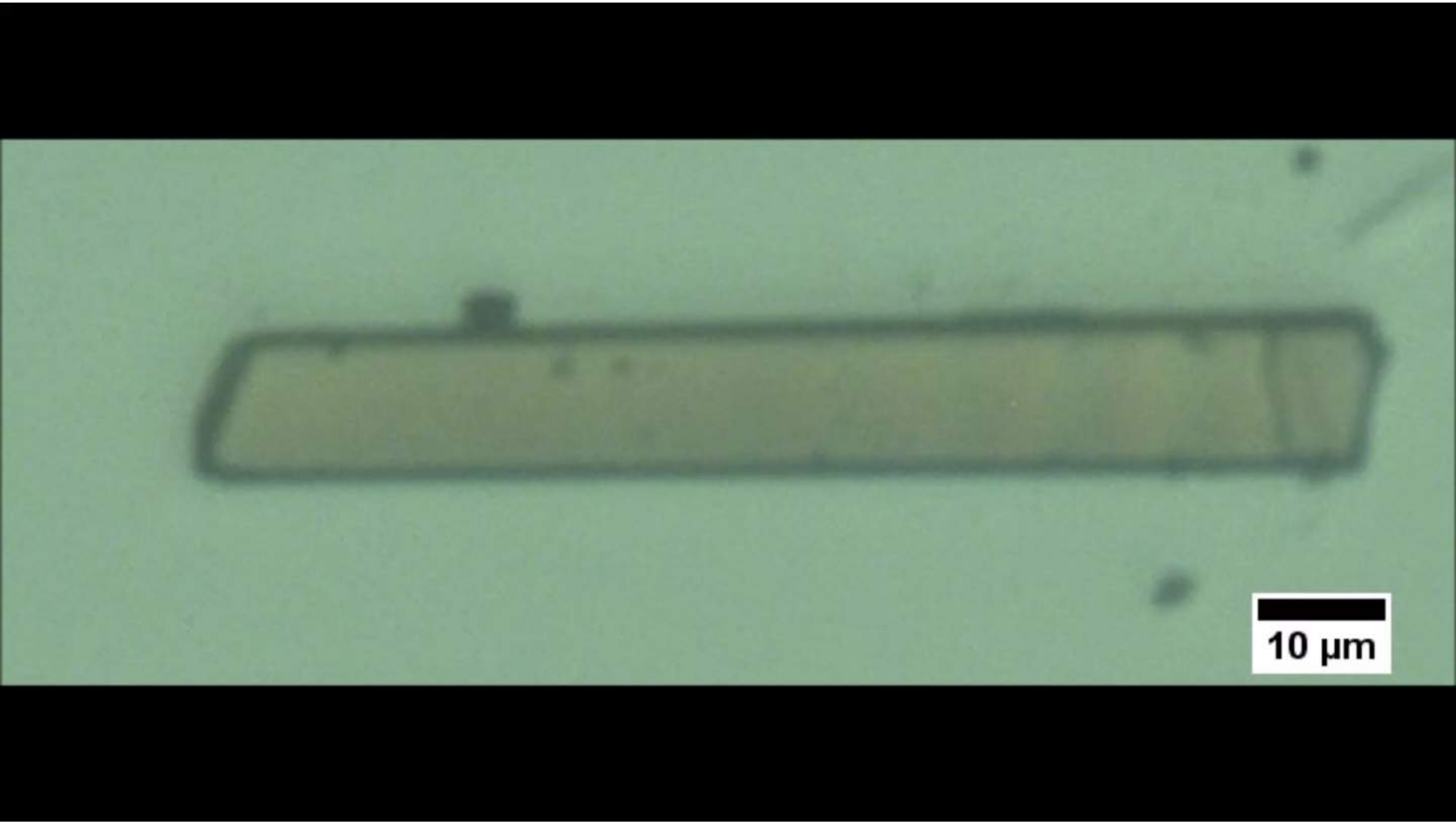
Photomagnetic measurement on a single crystal



size: 1.5 x 1.5 x 1 mm^3, wt: 0.5 mg

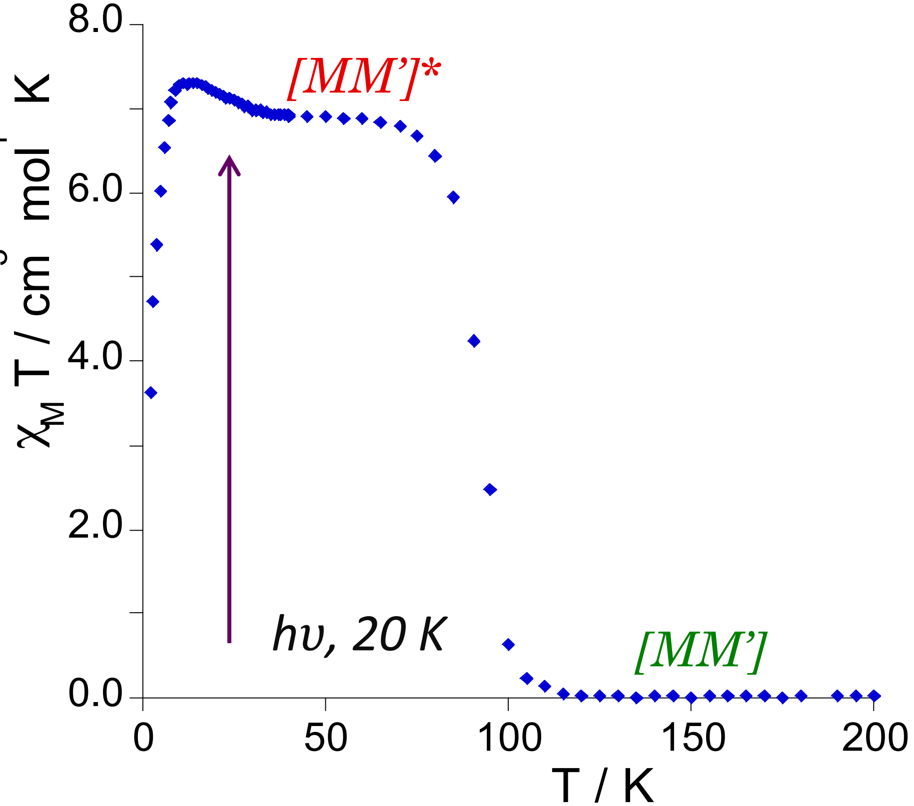
Abhishake Mondal_Thesis, 2013, UPMC-Paris-6

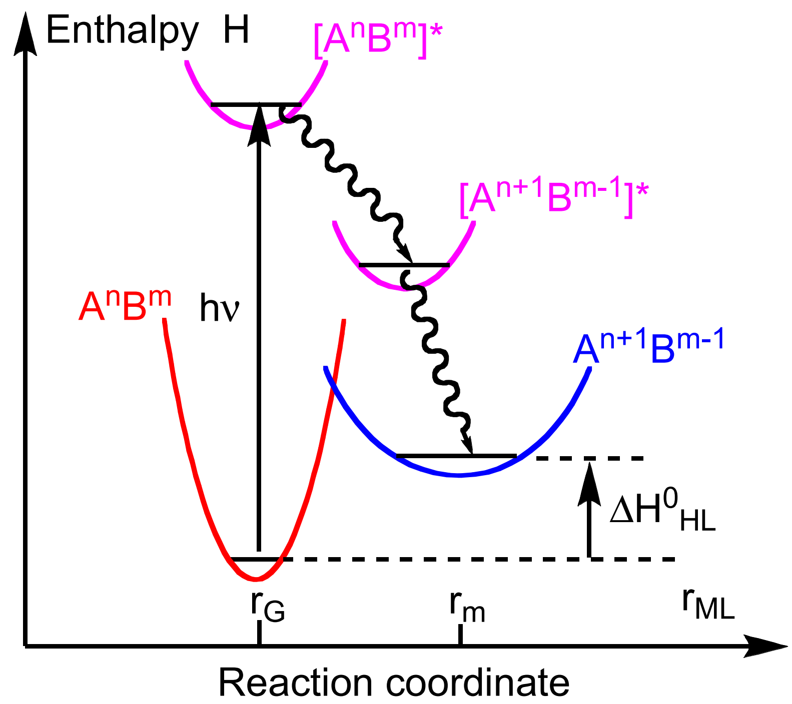
Photomagnetic measurement on a single crystal



Heating after irradiation: 0.5 K/min

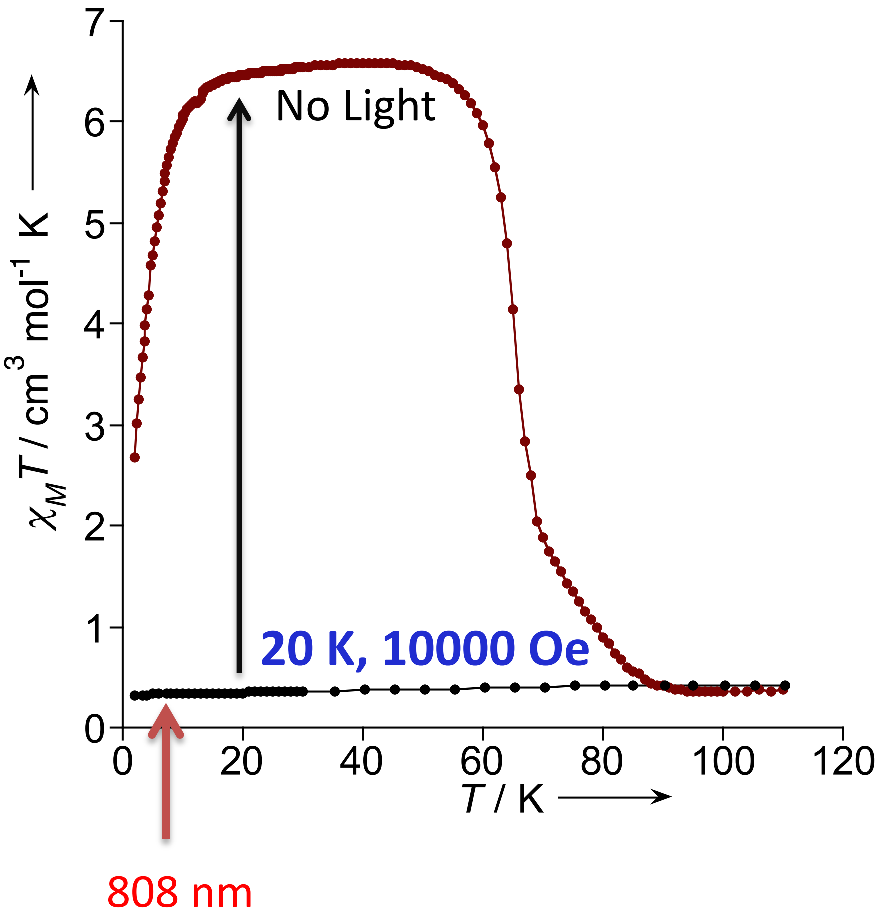
[MM']* <=> [MM']

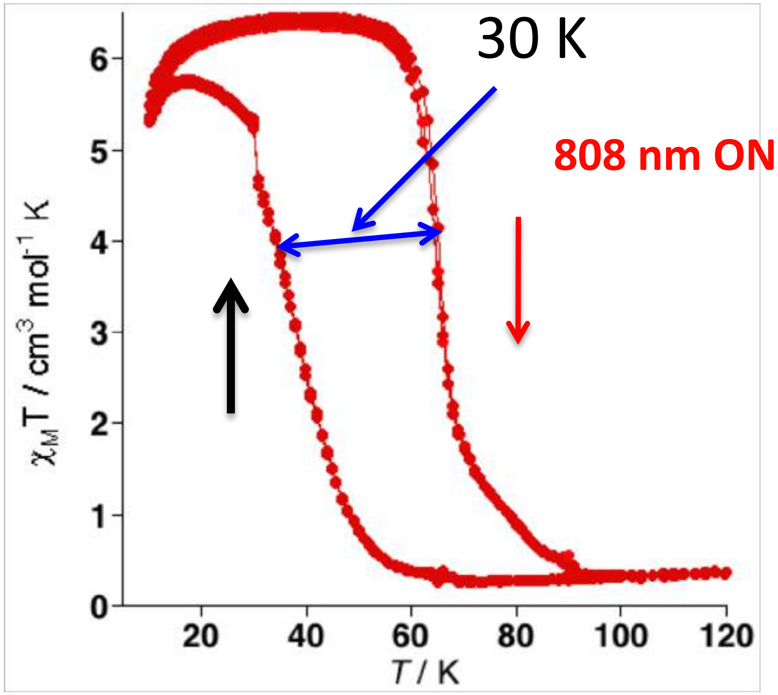




SQUID Magnetometer data analysis, UPMC, Paris-6

Light induced thermal hysteresis effects



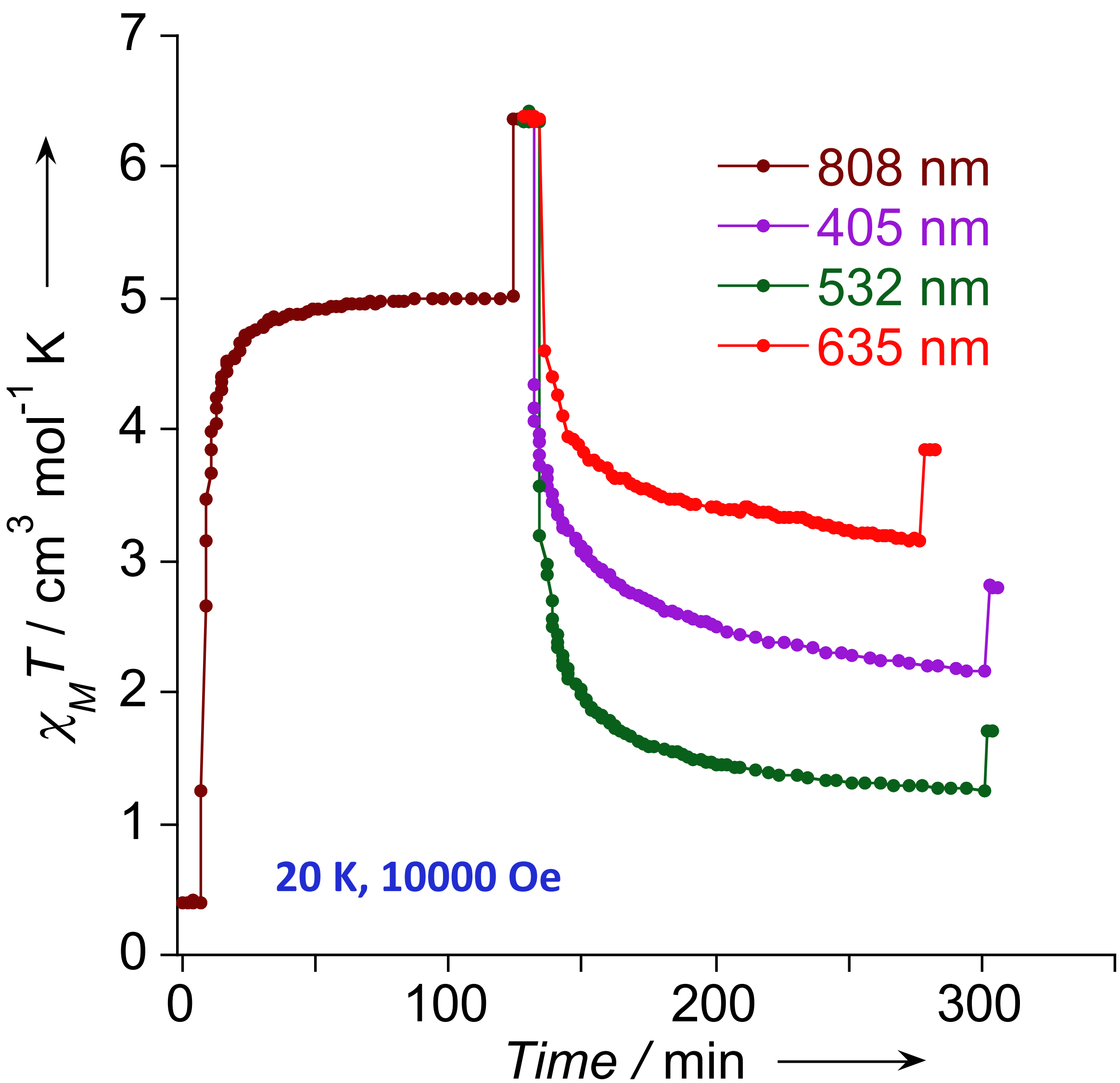


LITH effect

Abhishake Mondal_Thesis, 2013, UPMC-Paris-6

Inorg. Chem. **1998,** *37,* 4432

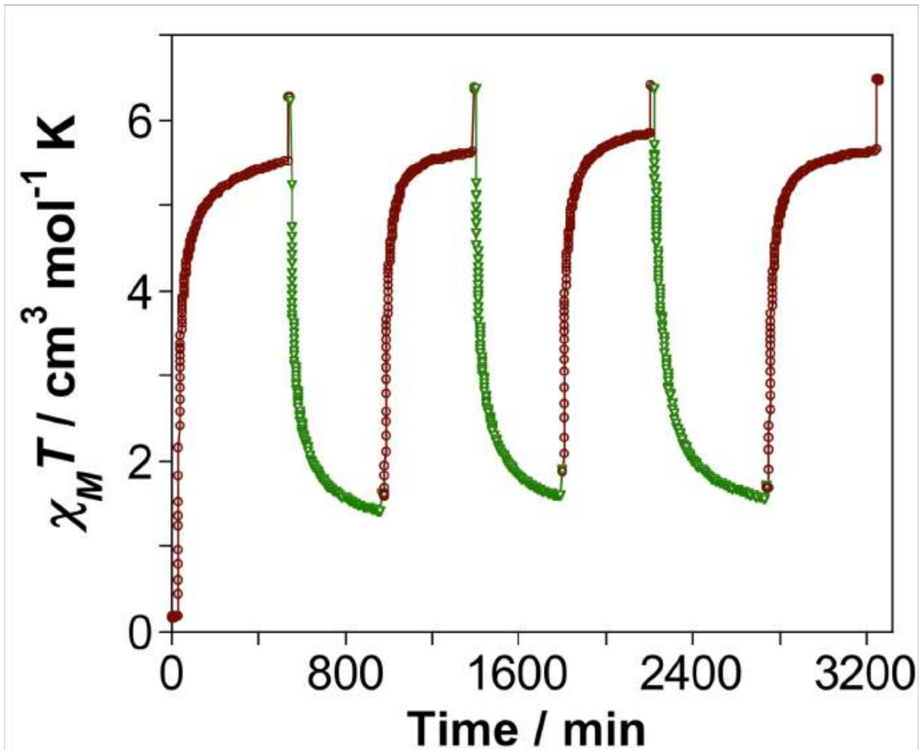
Reverse Photomagnetism: OFF Mode

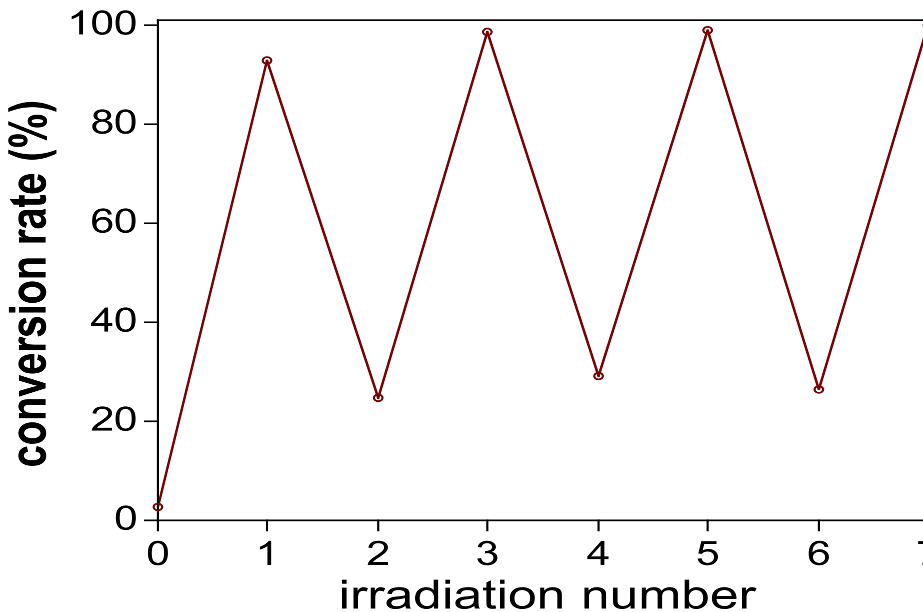


Abhishake Mondal_Thesis, 2013, UPMC-Paris-6

On/off repeatable photo(magnetic) switch

$\{Fe^{III}{}_2\text{-}Co^{II}{}_2\} \Leftrightarrow \{Fe^{II}{}_2\text{-}Co^{III}{}_2\}$





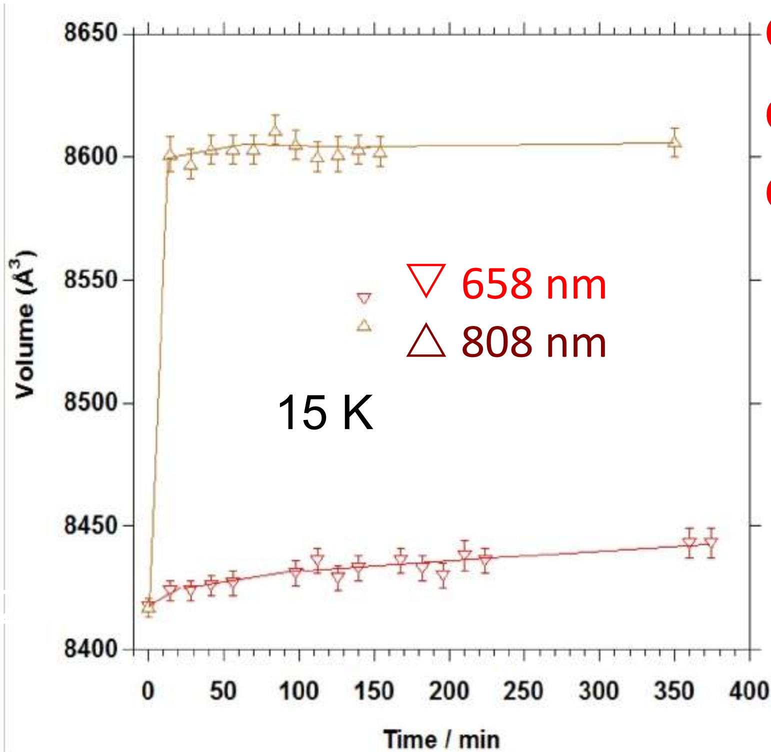
J. Am. Chem. Soc. **2013**, *135*, 1653

Abhishake Mondal_Thesis, 2013, UPMC-Paris-6

Other Measurement Techniques: Single-Crystal X-ray diffraction

On/off photo-switch : in a single crystal

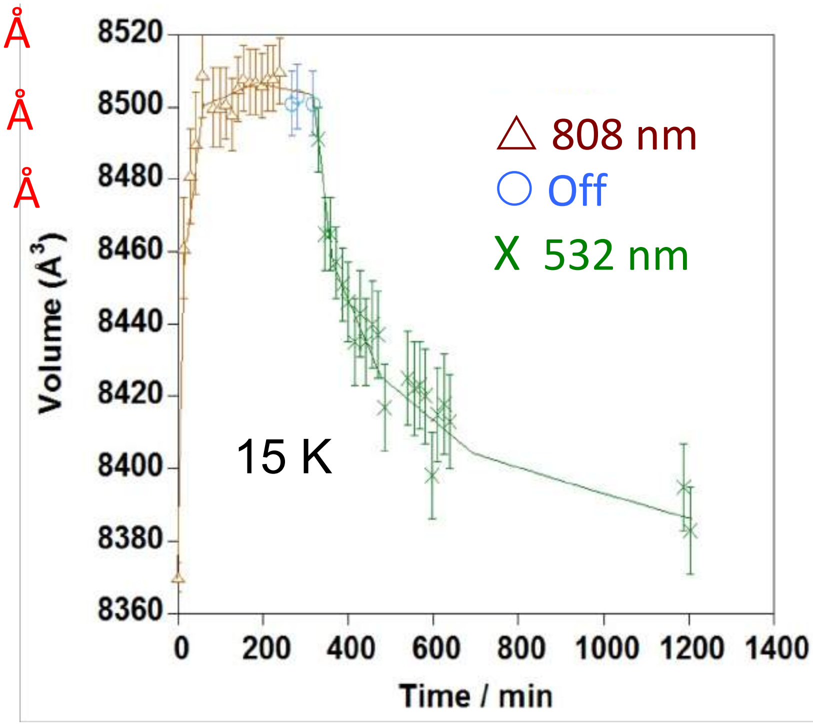
$\{Fe^{III}_2\text{-}Co^{II}_2\} \Leftrightarrow \{Fe^{III}_2\text{-}Co^{II}_2\}$



Co^{III}_{LS}-N = 1.9 Å

Co^{II}_{LS}-N = 2.0 Å

Co^{II}_{HS}-N = 2.1 Å



Δ Co-N ≈ 0.2 Å

ON mode

Using Single crystal

Co-N= 1.91 Å (200 K)

Co-N= 2.10 Å (808 nm)

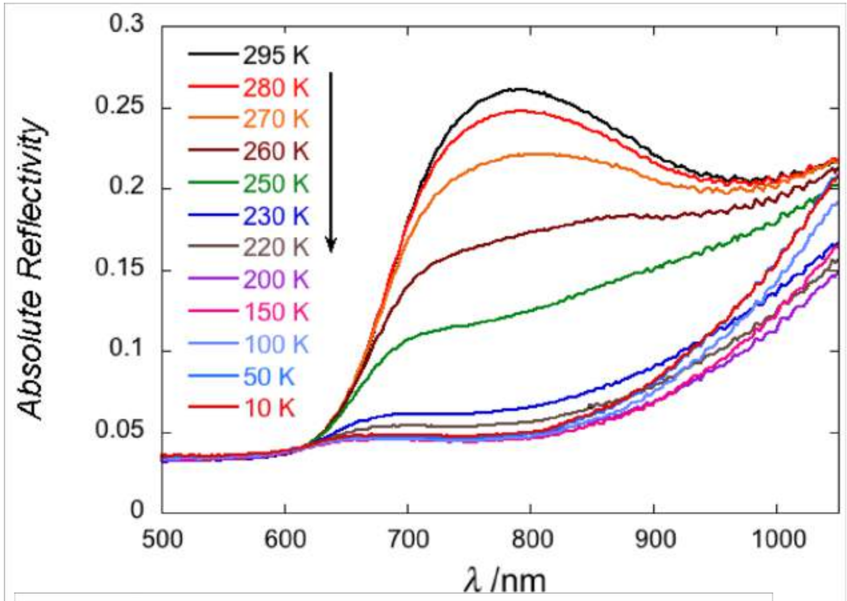
Co-N= 1.95 Å (532 nm)

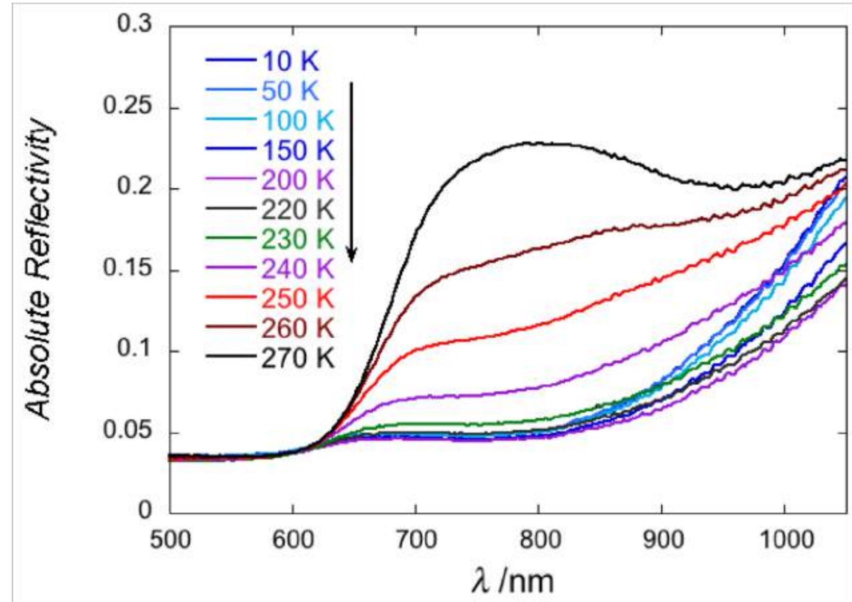
Δ Co-N ≈ 0.15 Å

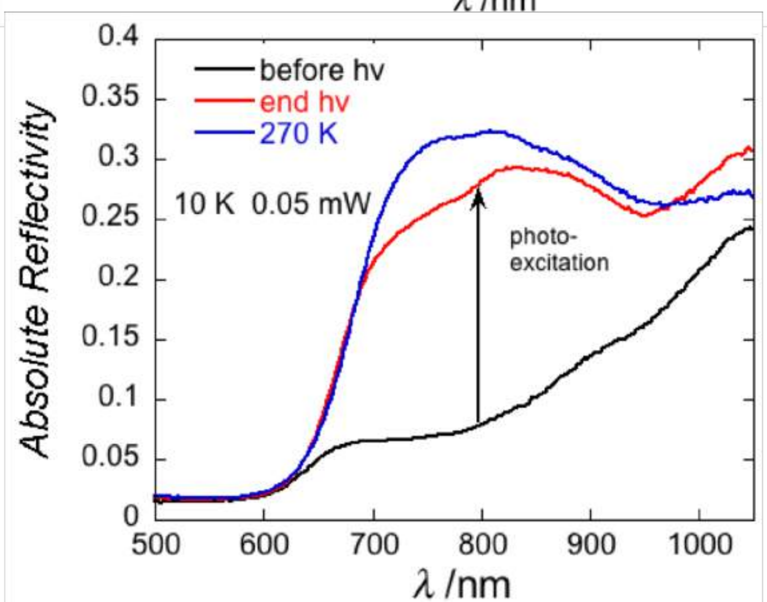
OFF mode

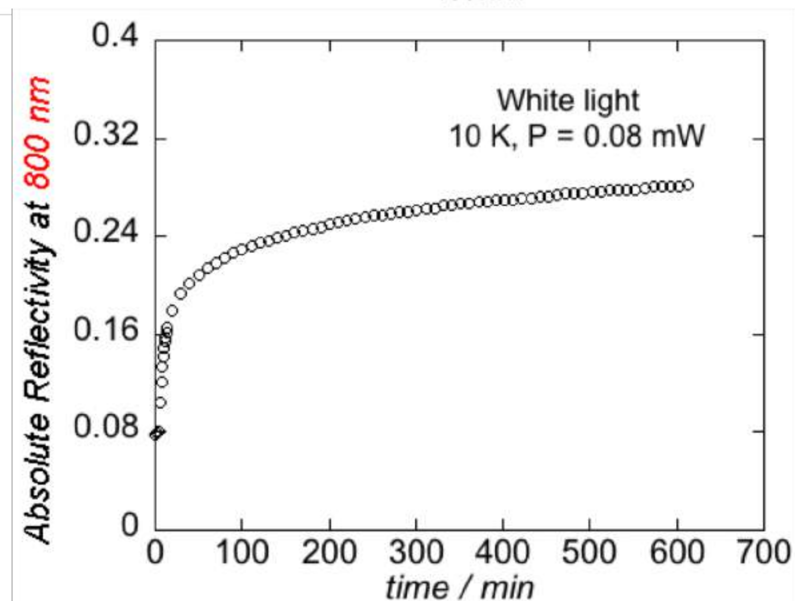
Abhishake Mondal_Thesis, 2013, UPMC-Paris-6

Other Measurement Techniques: Reflectivity measurements









Reflectivity data analysis, CRPP, Bordeaux

AC susceptibility measurement using SQUID and PPMS

$$\chi = dM/dH$$

$$B = B_0 + B_1 \cos(t)$$

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

Superconducting Quantum Interference Device (SQUID)

Physical Properties Measurement System (PPMS)

Real part

$$\chi' = \chi\cos(\varphi)$$

Reflects sensitivity of the material to H applied

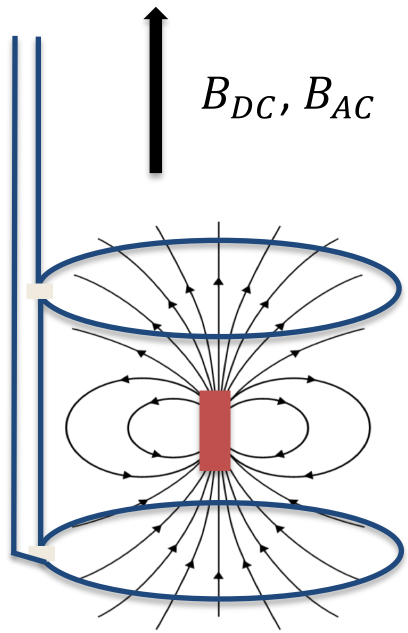
Imaginary part

$$\chi'' = \chi\sin(\varphi)$$

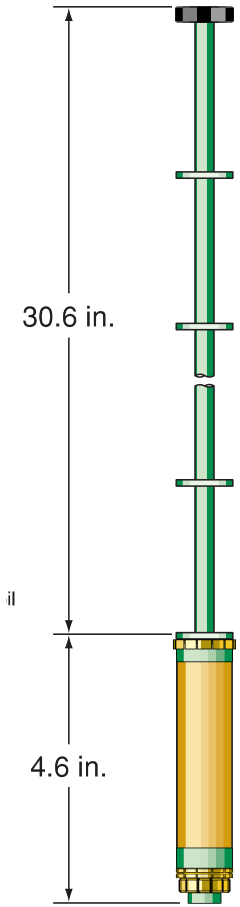
Reflects dissipation, energy lost, absorption of energy

SQUID Magnetometer and PPMS Susceptometer, CRPP, Bordeaux

AC Susceptibility

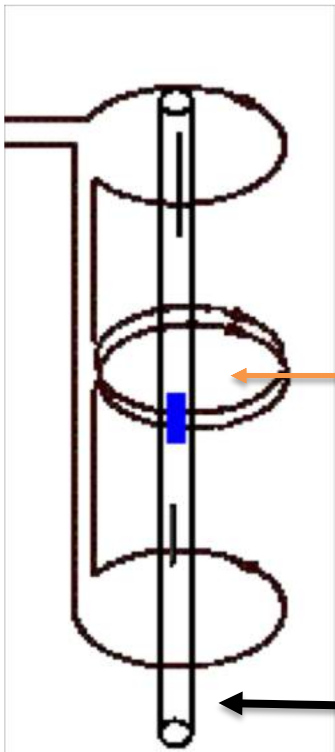


Gradiometer
Detection coils



Slide courtesy Dr. Hab. Rodolphe Clérac

AC measurement on SQUID – two points measurements



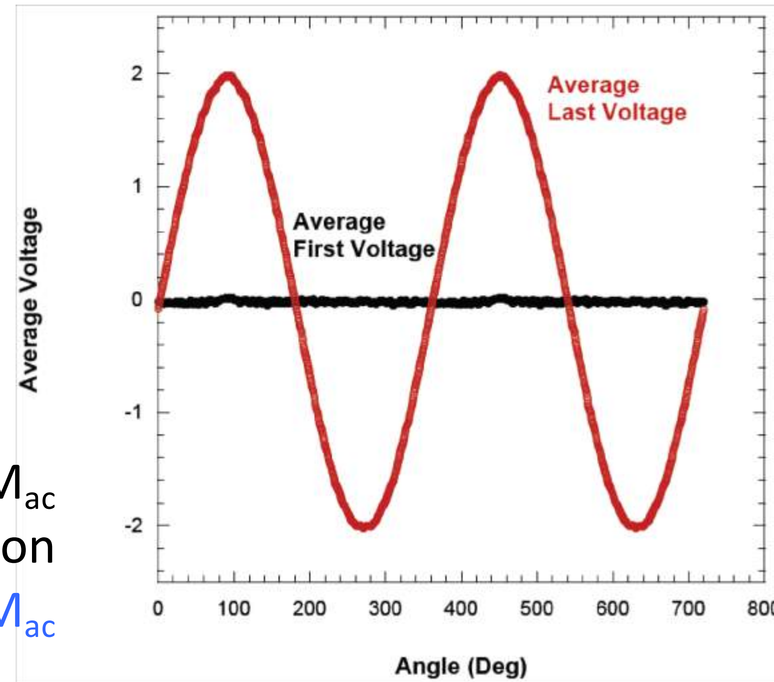
At P1, detection of driver AC, M_{ac} and noises at bottom; synthesis and application of nulling signal.

P2

At P2, detection of driver AC, M_{ac} and noises at center; application of nulling signal synthetized. M_{ac} enhanced 3 times

P1

AC signal extraction



Two properties measured in AC mode M_{ac} and phase shift, φ

M' (in phase)= M_{ac} Cos (φ)

M ''(out of phase)= M_{ac} Sin (φ)

X'= X Cos (φ) and X''= X Sin (φ)

Slide Courtesy Dr. Yangling Li

AC susceptibility measurement using SQUID

AM Ni2_a1.ac

	Time C0	Comment C1	Field (Oe) C2	Tempe...re C3	m' (emu) C4	m' Sca...d Dev C5	m" (emu) C6	m" Sc...d Dev C7	Amplit...(emu) C8	Amplit...d Dev C9	Phase (deg) C10	Phase ...d Dev C11	Regression Fit C12	Drive ...e (Oe) C13	Wave ...y (Hz) C14	Steps ... Cycle C15	Blocks C16	Scans...ement C17	Clock ...uency C18	Amplifier Gain C19	AC Filte C20
0	1.4529e+09		0.0000	15.005	6.0202e-06	4.9617e-08	-5.6042e-08	1.1511e-08	6.0204e-06	4.9507e-08	-0.53336	0.11394	0.96086	3.0000	199.89	938.00	2.0000	2.0000	4.0000	1.0000	0.0000
1	1.4529e+09		0.0000	14.497	6.2862e-06	4.3870e-08	2.6738e-08	8.2096e-08	6.2862e-06	4.3520e-08	0.24370	0.74996	0.82088	3.0000	199.89	938.00	2.0000	2.0000	4.0000	1.0000	0.0000
2	1.4529e+09		0.0000	14.000	6.5657e-06	5.7577e-08	-9.6766e-08	4.4435e-08	6.5664e-06	5.8225e-08	-0.84436	0.38030	0.87671	3.0000	199.89	938.00	2.0000	2.0000	4.0000	1.0000	0.0000
3	1.4529e+09		0.0000	13.500	6.9017e-06	4.0601e-08	6.1174e-09	8.8077e-09	6.9017e-06	4.0593e-08	0.050785	0.073420	0.88425	3.0000	199.89	938.00	2.0000	2.0000	4.0000	1.0000	0.0000
4	1.4529e+09		0.0000	13.000	7.1537e-06	6.7430e-08	-1.3525e-08	9.6713e-08	7.1537e-06	6.7611e-08	-0.10834	0.77360	0.88918	3.0000	199.89	938.00	2.0000	2.0000	4.0000	1.0000	0.0000
5	1.4529e+09		0.0000	12.501	7.6384e-06	1.5678e-07	-7.0424e-08	9.4412e-08	7.6388e-06	1.5764e-07	-0.52823	0.69749	0.89001	3.0000	199.89	938.00	2.0000	2.0000	4.0000	1.0000	0.0000
6	1.4529e+09		0.0000	11.999	8.1850e-06	3.4296e-08	4.1590e-08	1.4156e-07	8.1851e-06	3.3585e-08	0.29113	0.99209	0.90189	3.0000	199.89	938.00	2.0000	2.0000	4.0000	1.0000	0.0000
7	1.4529e+09		0.0000	11.500	8.5420e-06	6.7623e-09	-3.5339e-09	9.3255e-08	8.5420e-06	6.7334e-09	-0.023712	0.62551	0.91803	3.0000	199.89	938.00	2.0000	2.0000	4.0000	1.0000	0.0000
8	1.4529e+09		0.0000	11.001	9.0324e-06	3.6253e-08	-7.7692e-08	2.9697e-08	9.0328e-06	3.5996e-08	-0.49280	0.19033	0.91836	3.0000	199.89	938.00	2.0000	2.0000	4.0000	1.0000	0.0000
9	1.4529e+09		0.0000	10.498	9.7175e-06	1.7631e-07	-3.4693e-08	1.1369e-08	9.7176e-06	1.7635e-07	-0.20456	0.063319	0.93118	3.0000	199.89	938.00	2.0000	2.0000	4.0000	1.0000	0.0000
10	1.4529e+09		0.0000	9.9999	1.0359e-05	1.2565e-07	-5.4337e-08	2.2464e-08	1.0359e-05	1.2577e-07	-0.30054	0.12061	0.93563	3.0000	199.89	938.00	2.0000	2.0000	4.0000	1.0000	0.0000
11	1.4529e+09		0.0000	9.4976	1.1055e-05	5.7623e-10	5.5024e-08	1.0417e-09	1.1055e-05	5.8137e-10	0.28518	0.0053843	0.94495	3.0000	199.89	938.00	2.0000	2.0000	4.0000	1.0000	0.0000
12	1.4529e+09		0.0000	8.9990	1.1892e-05	1.3152e-07	8.8929e-08	1.5605e-07	1.1892e-05	1.3034e-07	0.42846	0.75658	0.95350	3.0000	199.89	938.00	2.0000	2.0000	4.0000	1.0000	0.0000
13	1.4529e+09		0.0000	8.4986	1.2731e-05	2.2075e-08	-6.9146e-08	2.9716e-09	1.2731e-05	2.2059e-08	-0.31119	0.013919	0.95998	3.0000	199.89	938.00	2.0000	2.0000	4.0000	1.0000	0.0000
14	1.4529e+09		0.0000	8.0000	1.3905e-05	3.7013e-08	1.3327e-08	3.0660e-08	1.3905e-05	3.6983e-08	0.054916	0.12649	0.96488	3.0000	199.89	938.00	2.0000	2.0000	4.0000	1.0000	0.0000
15	1.4529e+09		0.0000	7.4986	1.5091e-05	7.5102e-09	2.8443e-08	3.4359e-08	1.5091e-05	7.5746e-09	0.10799	0.13040	0.96917	3.0000	199.89	938.00	2.0000	2.0000	4.0000	1.0000	0.0000
16	1.4529e+09		0.0000	6.9993	1.6262e-05	9.1913e-09	-8.1038e-08	1.0382e-07	1.6263e-05	9.7112e-09	-0.28552	0.36559	0.97407	3.0000	199.89	938.00	2.0000	2.0000	4.0000	1.0000	0.0000
17	1.4529e+09		0.0000	6.4996	1.7902e-05	1.7768e-07	2.2250e-08	1.3317e-07	1.7902e-05	1.7785e-07	0.071212	0.42552	0.97906	3.0000	199.89	938.00	2.0000	2.0000	4.0000	1.0000	0.0000
18	1.4529e+09		0.0000	5.9998	1.9571e-05	3.2814e-08	-1.3570e-07	1.0927e-07	1.9571e-05	3.3571e-08	-0.39725	0.31922	0.98248	3.0000	199.89	938.00	2.0000	2.0000	4.0000	1.0000	0.0000
19	1.4529e+09		0.0000	5.4995	2.1474e-05	8.1841e-08	1.3219e-07	1.5059e-08	2.1474e-05	8.1747e-08	0.35270	0.041523	0.98396	3.0000	199.89	938.00	2.0000	2.0000	4.0000	1.0000	0.0000
20	1.4529e+09		0.0000	4.9995	2.4011e-05	1.8977e-07	6.0200e-08	3.2245e-08	2.4012e-05	1.8969e-07	0.14365	0.078080	0.98847	3.0000	199.89	938.00	2.0000	2.0000	4.0000	1.0000	0.0000
21	1.4529e+09		0.0000	4.4988	2.6836e-05	1.3486e-07	-9.8183e-08	4.2770e-08	2.6836e-05	1.3470e-07	-0.20963	0.092381	0.99012	3.0000	199.89	938.00	2.0000	2.0000	4.0000	1.0000	0.0000
22	1.4529e+09		0.0000	3.9970	3.0495e-05	8.1109e-09	7.1537e-08	7.1203e-10	3.0495e-05	8.1083e-09	0.13441	0.0013735	0.99191	3.0000	199.89	938.00	2.0000	2.0000	4.0000	1.0000	0.0000
23	1.4529e+09		0.0000	3.4980	3.4866e-05	1.2332e-07	4.6583e-07	9.3668e-09	3.4869e-05	1.2343e-07	0.76545	0.012683	0.99447	3.0000	199.89	938.00	2.0000	2.0000	4.0000	1.0000	0.0000
24	1.4529e+09		0.0000	2.9989	4.0105e-05	6.2557e-08	2.5631e-06	2.5030e-08	4.0187e-05	6.0833e-08	3.6567	0.041302	0.99571	3.0000	199.89	938.00	2.0000	2.0000	4.0000	1.0000	0.0000
25	1.4529e+09		0.0000	2.5001	4.0716e-05	3.9950e-09	7.8396e-06	7.6535e-08	4.1464e-05	1.0545e-08	10.899	0.10489	0.99633	3.0000	199.89	938.00	2.0000	2.0000	4.0000	1.0000	0.0000
26	1.4529e+09		0.0000	2.0000	3.7205e-05	1.1046e-08	7.1586e-06	9.0378e-08	3.7888e-05	2.7921e-08	10.891	0.13106	0.99574	3.0000	199.89	938.00	2.0000	2.0000	4.0000	1.0000	0.0000

PPMS data treatment

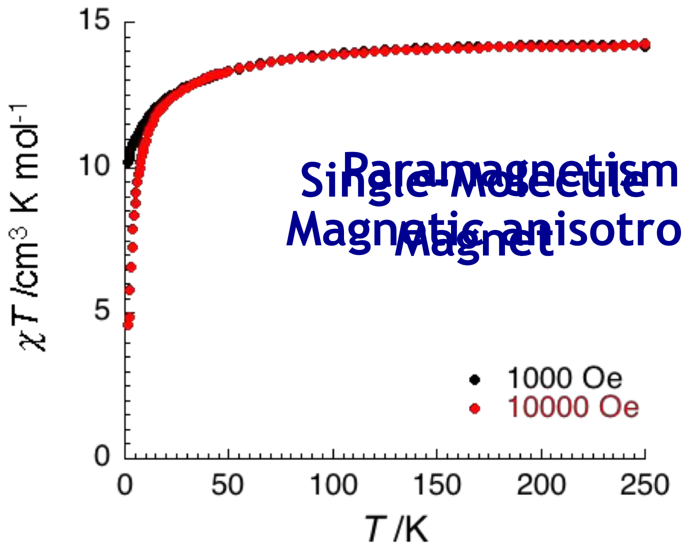
AM Ni2_a1

	Comment C0	Time S... C1	Tempe...re C2	Magne...d C3	Frequ...y (Hz) C4	Ampli...e (Oe) C5	M-DC (emu) C6	M-Std....(emu) C7	M' (emu) C8	M'' (emu) C9
0		3.2937e+07	15.004	0.037000	1000.0	9.9994		0.082311		
1		3.2937e+07	15.013	0.037000	10.000	6.0013		3.1272e-07	1.3181e-05	9.7036e-07
2		3.2937e+07	15.014	0.037000	30.000	6.0013		2.7670e-07	1.4040e-05	-1.2801e-07
3		3.2937e+07	15.012	0.037000	60.000	6.0012		7.7553e-08	1.4004e-05	-9.7183e-09
4		3.2937e+07	15.009	0.037000	100.00	6.0012		4.9844e-08	1.4019e-05	-1.3385e-07
5		3.2937e+07	15.008	0.037000	150.00	6.0011		2.1754e-08	1.3610e-05	-1.8560e-07
6		3.2937e+07	15.007	0.037000	200.00	6.0010		1.9351e-08	1.4035e-05	2.1641e-08
7		3.2938e+07	15.007	0.037000	300.00	6.0007		2.2447e-08	1.4010e-05	-1.8482e-09
8		3.2938e+07	15.006	0.037000	400.00	6.0002		1.0912e-08	1.3943e-05	5.3320e-08
9		3.2938e+07	15.006	0.037000	600.00	5.9989		1.2257e-08	1.3975e-05	1.3184e-08
10		3.2938e+07	15.005	0.037000	800.00	6.0012		6.0471e-09	1.3972e-05	1.9419e-08
11		3.2938e+07	15.006	0.037000	1000.0	5.9988		6.6535e-09	1.3941e-05	5.6084e-08
12		3.2938e+07	15.004	0.037000	1200.0	2.9979		1.0892e-08	6.9508e-06	5.4902e-08
13		3.2938e+07	15.004	0.037000	1500.0	2.9994		8.2410e-09	6.9698e-06	1.6602e-08
14		3.2938e+07	15.004	0.037000	2000.0	3.0019		6.7756e-09	6.9631e-06	2.4793e-08
15		3.2938e+07	15.005	0.037000	3000.0	3.0020		6.4149e-09	6.9491e-06	3.3770e-08
16		3.2938e+07	15.004	0.037000	4000.0	2.9999		4.4454e-09	6.9273e-06	2.5859e-08
17		3.2938e+07	15.003	0.037000	5000.0	0.99989		4.1146e-09	2.3069e-06	3.3642e-09
18		3.2938e+07	15.003	0.037000	6000.0	1.0005		5.0114e-09	2.3109e-06	-7.7236e-09
19		3.2938e+07	15.003	0.037000	8000.0	1.0000		1.4844e-09	2.3058e-06	-7.5598e-09
20		3.2939e+07	15.001	0.037000	10000	1.0004		1.9217e-09	2.3018e-06	-1.5635e-08
21		3.2939e+07	14.007	0.037000	10.000	6.0013		4.9950e-07	1.5471e-05	-6.9448e-07
22		3.2939e+07	14.008	0.037000	30.000	6.0013		3.5684e-07	1.5318e-05	-2.3782e-08
23		3.2939e+07	14.009	0.037000	60.000	6.0012		8.8672e-08	1.5384e-05	4.2570e-08
24		3.2939e+07	14.010	0.037000	100.00	6.0012		2.3721e-08	1.5306e-05	6.0380e-08
25		3.2939e+07	14.010	0.037000	150.00	6.0011		2.0029e-08	1.5364e-05	2.9322e-08
26		3.2939e+07	14.009	0.037000	200.00	6.0010		2.1429e-08	1.5379e-05	1.6630e-08
27		3.2939e+07	14.009	0.037000	300.00	6.0007		2.7606e-08	1.5363e-05	1.3833e-08
28		3.2939e+07	14.009	0.037000	400.00	6.0002		1.6951e-08	1.5356e-05	1.1159e-08
29		3.2940e+07	14.009	0.037000	600.00	5.9989		1.6185e-08	1.5334e-05	2.9843e-08

	Moment (emu) C10	Phase (deg) C11	Calcoil' (emu) C12	Calcoil'' (emu) C13	Calcoil (emu) C14	CC Ph... (deg) C15	Count C16	Gain C17	Measure Type C18	Elapsed (sec) C19	Sampl...r (c C20
0								125.00	1.0000	0.0000	-0.29313
1	1.3217e-05	4.2104	1.4928e-08	2.2305e-11	1.4928e-08	0.085611	3200.0	5.0000	5.0000	13.497	-0.29313
2	1.4040e-05	-0.52240	1.4922e-08	5.9940e-12	1.4922e-08	0.023016	4800.0	5.0000	5.0000	13.497	-0.29313
3	1.4004e-05	-0.039761	1.4929e-08	1.3918e-13	1.4929e-08	0.00053414	4800.0	5.0000	5.0000	13.497	-0.29313
4	1.4020e-05	-0.54703	1.4932e-08	-1.1339e-11	1.4932e-08	-0.043510	4000.0	5.0000	5.0000	13.497	-0.29313
5	1.3612e-05	-0.78127	1.4925e-08	-3.2536e-11	1.4925e-08	-0.12490	6000.0	5.0000	5.0000	13.497	-0.29313
6	1.4035e-05	0.088350	1.4925e-08	-4.7864e-11	1.4925e-08	-0.18375	4000.0	5.0000	5.0000	13.497	-0.29313
7	1.4010e-05	-0.0075583	1.4925e-08	-7.9101e-11	1.4925e-08	-0.30367	6000.0	5.0000	5.0000	13.497	-0.29313
8	1.3943e-05	0.21911	1.4926e-08	-1.0872e-10	1.4927e-08	-0.41734	4000.0	5.0000	5.0000	13.497	-0.29313
9	1.3975e-05	0.054053	1.4935e-08	-1.7010e-10	1.4936e-08	-0.65255	6000.0	5.0000	5.0000	13.497	-0.29313
10	1.3972e-05	0.079636	1.4941e-08	-2.3193e-10	1.4943e-08	-0.88933	2666.0	5.0000	5.0000	13.497	-0.29313
11	1.3941e-05	0.23049	1.4946e-08	-2.9487e-10	1.4949e-08	-1.1302	3333.0	5.0000	5.0000	13.497	-0.29313
12	6.9510e-06	0.45255	1.4924e-08	-3.6791e-10	1.4928e-08	-1.4122	4000.0	5.0000	5.0000	13.497	-0.29313
13	6.9698e-06	0.13648	1.4924e-08	-4.6425e-10	1.4931e-08	-1.7818	5000.0	5.0000	5.0000	13.497	-0.29313
14	6.9631e-06	0.20401	1.4919e-08	-6.2470e-10	1.4932e-08	-2.3977	4000.0	5.0000	5.0000	13.497	-0.29313
15	6.9492e-06	0.27843	1.4906e-08	-9.4562e-10	1.4936e-08	-3.6300	6000.0	5.0000	5.0000	13.497	-0.29313
16	6.9273e-06	0.21388	1.4886e-08	-1.2641e-09	1.4940e-08	-4.8536	5714.0	5.0000	5.0000	13.497	-0.29313
17	2.3069e-06	0.083555	1.4863e-08	-1.5869e-09	1.4948e-08	-6.0940	4545.0	5.0000	5.0000	13.497	-0.29313
18	2.3109e-06	-0.19150	1.4837e-08	-1.9044e-09	1.4959e-08	-7.3142	5454.0	5.0000	5.0000	13.497	-0.29313
19	2.3058e-06	-0.18785	1.4781e-08	-2.5261e-09	1.4995e-08	-9.6982	6153.0	5.0000	5.0000	13.497	-0.29313
20	2.3019e-06	-0.38917	1.4711e-08	-3.1691e-09	1.5049e-08	-12.157	5882.0	5.0000	5.0000	13.497	-0.29313
21	1.5487e-05	-2.5702	1.4903e-08	1.5635e-11	1.4903e-08	0.060110	3200.0	5.0000	5.0000	13.497	-0.29313
22	1.5318e-05	-0.088957	1.4921e-08	8.2645e-12	1.4921e-08	0.031735	4800.0	5.0000	5.0000	13.497	-0.29313
23	1.5384e-05	0.15854	1.4931e-08	-7.2444e-13	1.4931e-08	-0.0027800	4800.0	5.0000	5.0000	13.497	-0.29313
24	1.5306e-05	0.22603	1.4932e-08	-1.1422e-11	1.4932e-08	-0.043828	4000.0	5.0000	5.0000	13.497	-0.29313
25	1.5364e-05	0.10935	1.4924e-08	-3.2084e-11	1.4924e-08	-0.12318	6000.0	5.0000	5.0000	13.497	-0.29313
26	1.5379e-05	0.061957	1.4925e-08	-4.7626e-11	1.4926e-08	-0.18282	4000.0	5.0000	5.0000	13.497	-0.29313
27	1.5363e-05	0.051591	1.4925e-08	-7.9114e-11	1.4925e-08	-0.30371	6000.0	5.0000	5.0000	13.497	-0.29313
28	1.5356e-05	0.041635	1.4927e-08	-1.0874e-10	1.4927e-08	-0.41736	4000.0	5.0000	5.0000	13.497	-0.29313
29	1.5334e-05	0.11151	1.4935e-08	-1.7009e-10	1.4936e-08	-0.65246	6000.0	5.0000	5.0000	13.497	-0.29313

PPMS Susceptometer AC data, CRPP, Bordeaux

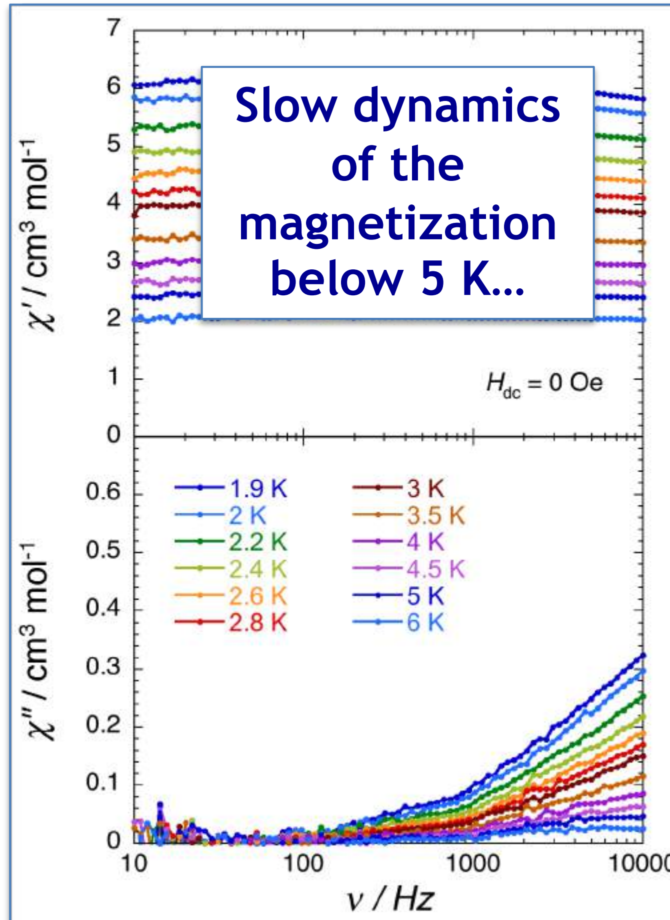
AC susceptibility measurement



Paramagnetism

Single-Molecule Magnet

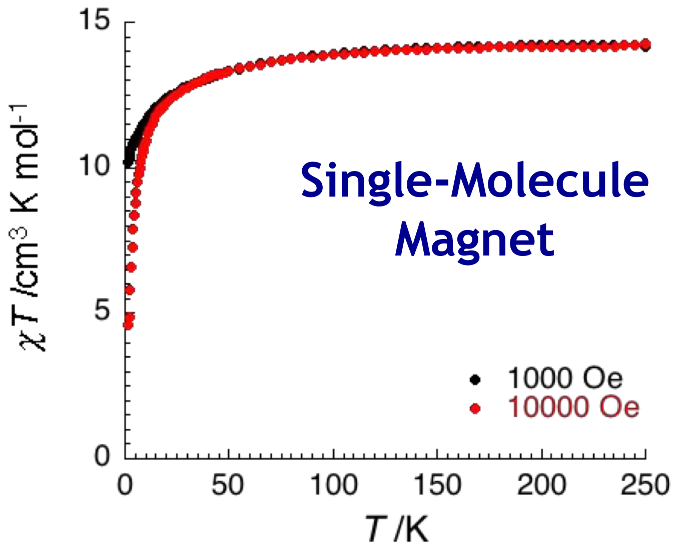
Magnetic anisotropy

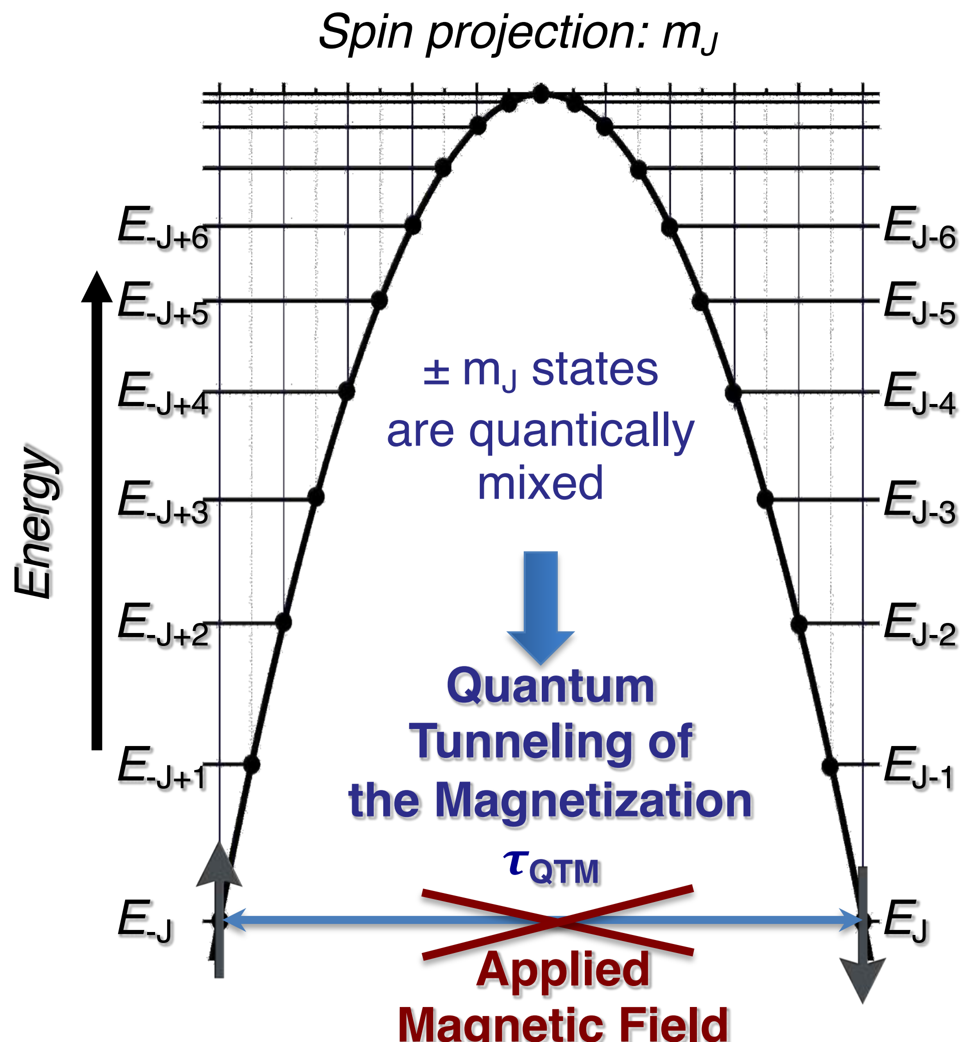


Slow dynamics of the magnetization below 5 K…

Slide courtesy Dr. Hab. Rodolphe Clérac

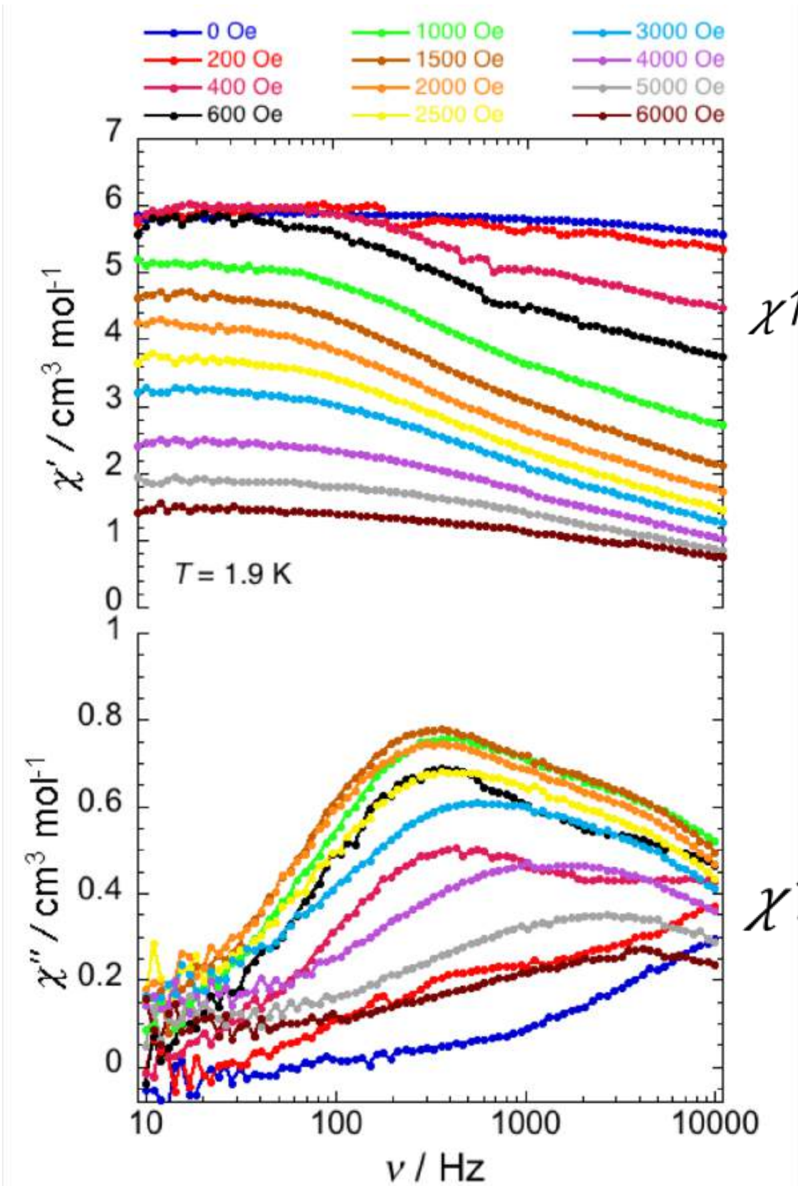
AC susceptibility measurement





Slide courtesy Dr. Hab. Rodolphe Clérac

AC susceptibility measurement

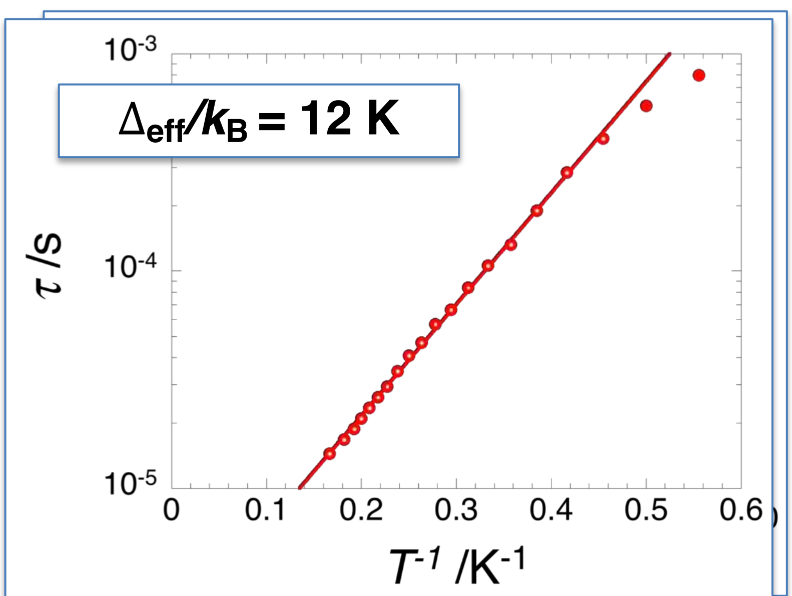


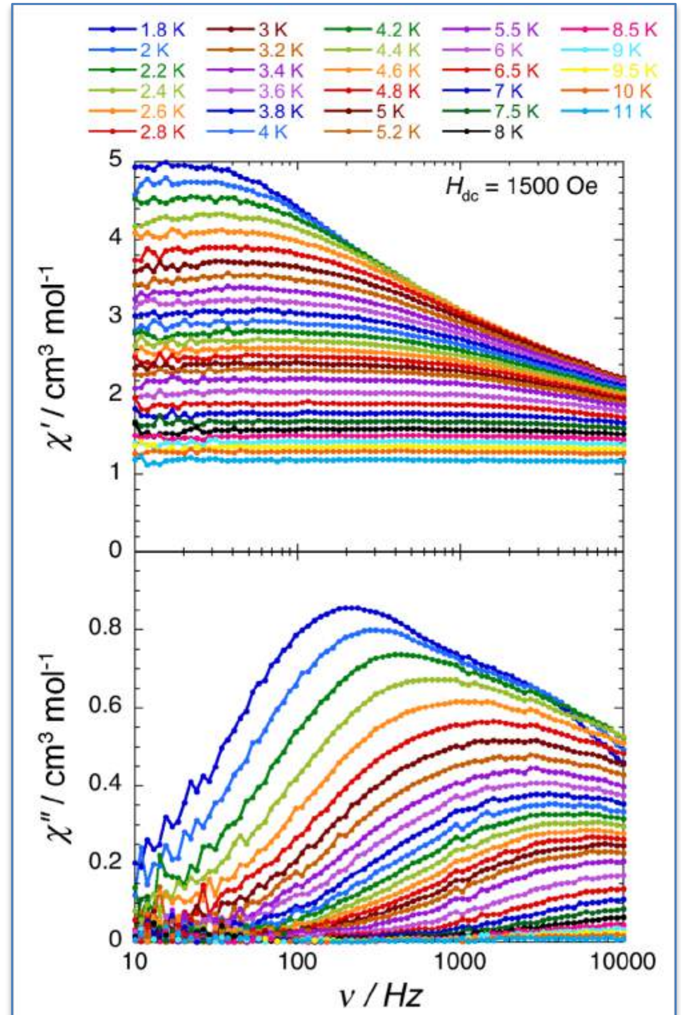
Fit with generalized Debye model for each temperature

$$\chi' = \mathbf{f}(\boldsymbol{\tau}, \alpha, \Delta\chi')$$

$$\chi'' = \mathbf{g}(\boldsymbol{\tau}, \alpha, \Delta\chi')$$

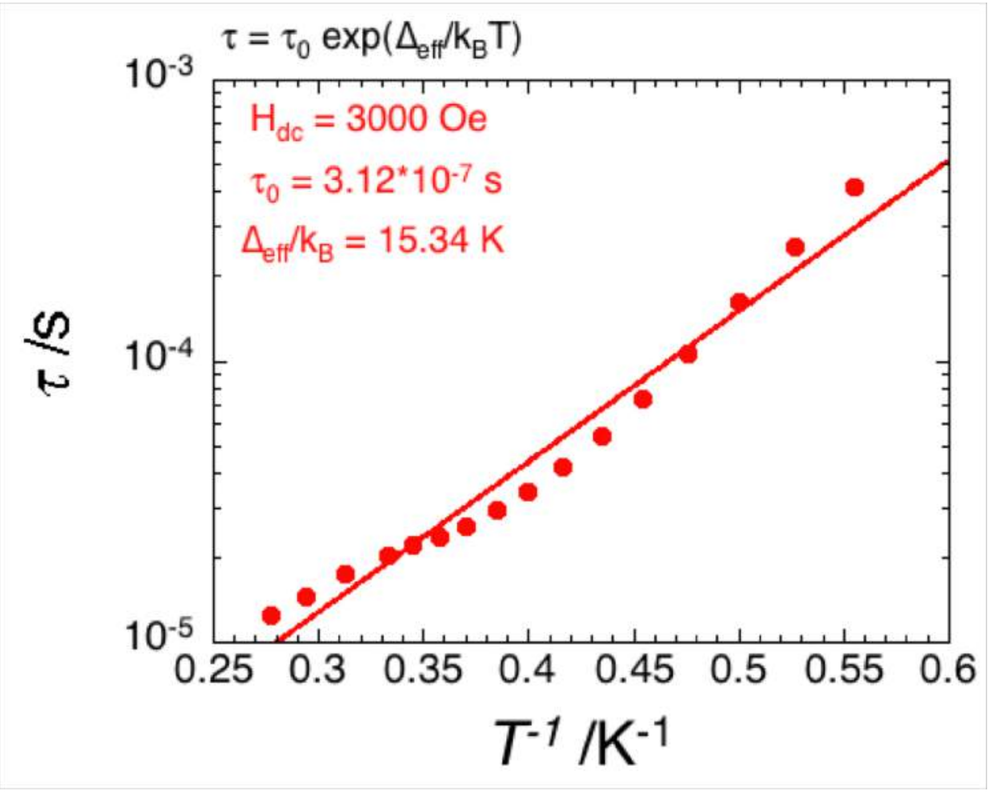
AC susceptibility measurement





Slide courtesy Dr. Hab. Rodolphe Clérac

AC susceptibility measurement



The magnetization dynamics follows an Arrhenius behavior

$$\tau(T) = \tau_0 exp\left(\frac{\Delta_A}{k_B T}\right) = \tau_0 exp\left(\frac{|D|S^2}{k_B T}\right)$$

$$\tau(T,H)^{-1} = AH^4T + CT^n + \tau_0^{-1}\exp[-\Delta_{eff}/(k_B T)]$$

direct Raman Orbach

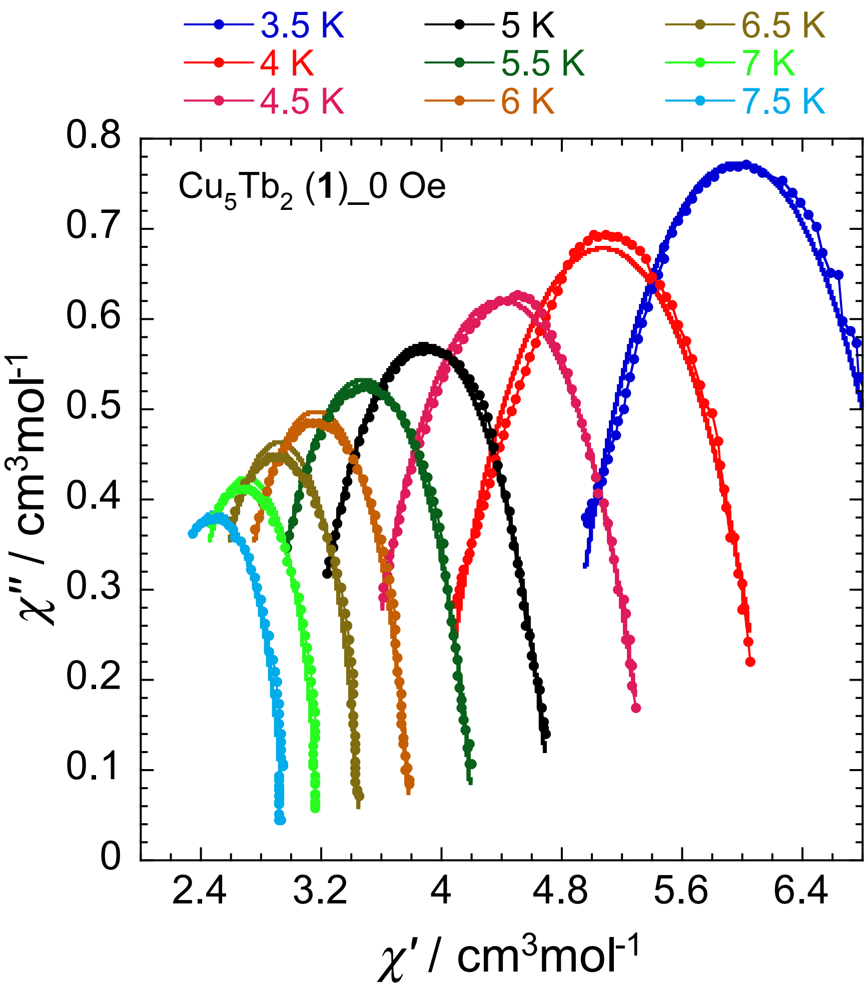
$$\chi' = \frac{(\chi_{isoT} - \chi_{adia})\left((2\pi)^{1-\alpha}\sin\left(\frac{\pi\alpha}{2}\right)(\nu\tau)^{1-\alpha} + 1\right)}{(2\pi)^{2-2\alpha}(\nu\tau)^{2-2\alpha} + 2^{2-\alpha}\pi^{1-\alpha}\sin\left(\frac{\pi\alpha}{2}\right)(\nu\tau)^{1-\alpha} + 1} + \chi_{adia}$$

$$\chi'' = \frac{(2\pi)^{1-\alpha}\cos\left(\frac{\pi\alpha}{2}\right)(\nu\tau)^{1-\alpha}(\chi_{isoT} - \chi_{adia})}{(2\pi)^{2-2\alpha}(\nu\tau)^{2-2\alpha} + 2^{2-\alpha}\pi^{1-\alpha}\sin\left(\frac{\pi\alpha}{2}\right)(\nu\tau)^{1-\alpha} + 1}$$

Fitting all data with generalized Debye model for each temperature

AC susceptibility measurement

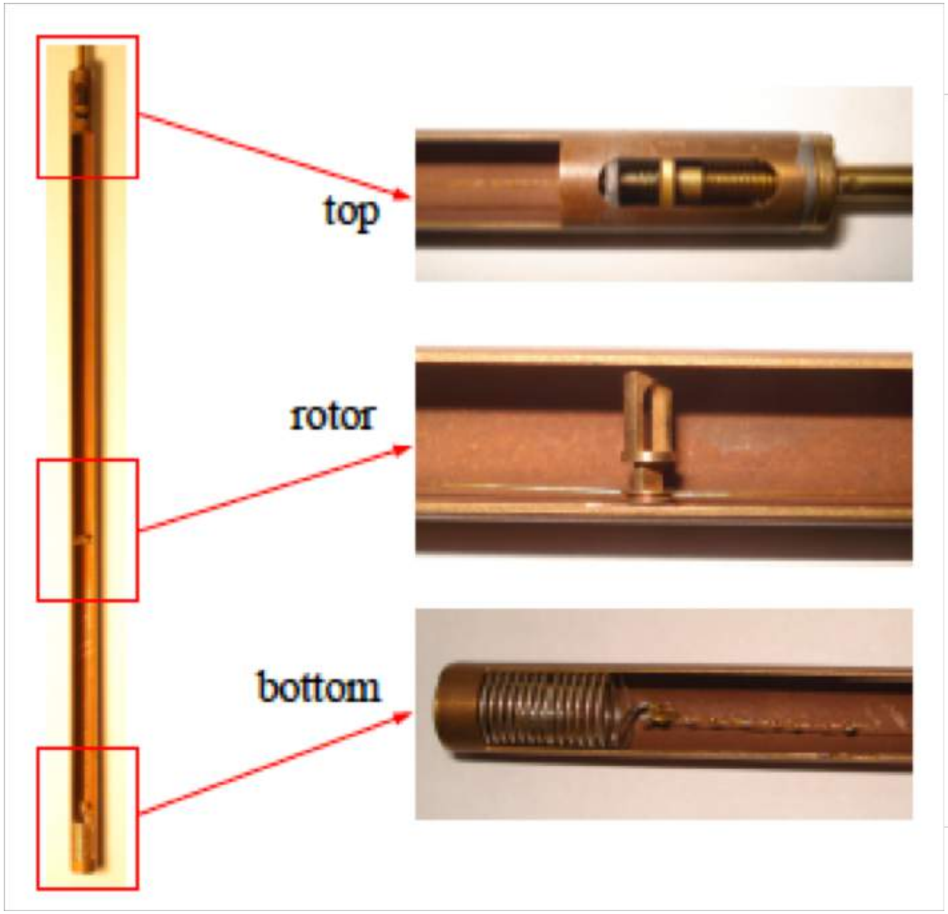
Cole-Cole fittings

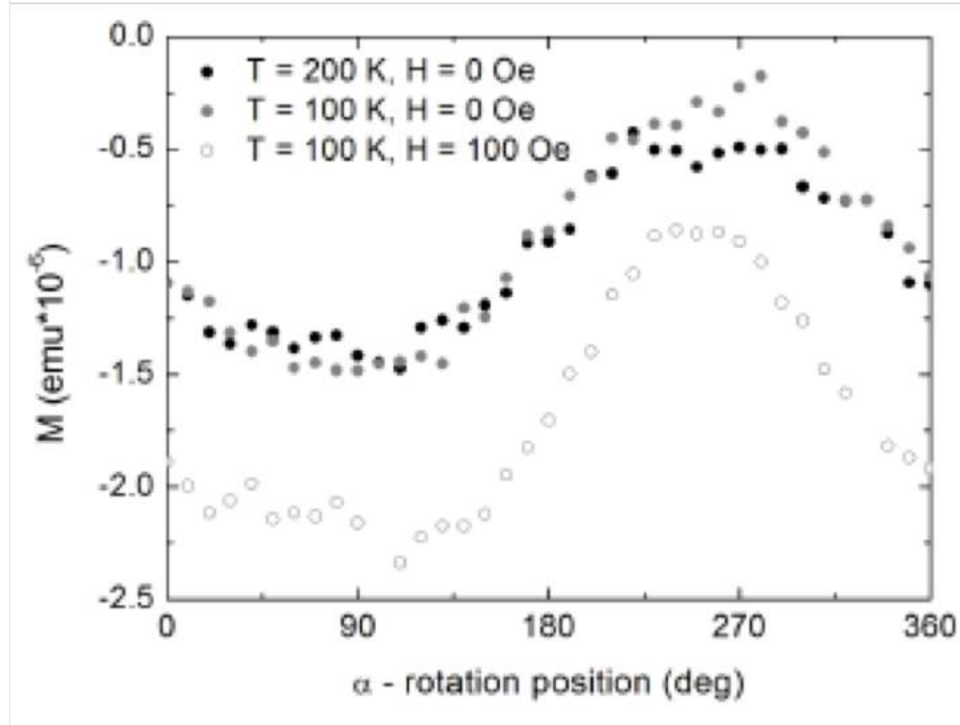


T (K)	a	c_0	c_{inf}
3.5	0.29047	7.2219	4.7438
4.0	0.32745	6.2401	3.918
4.5	0.29051	5.4031	3.4138
5.0	0.25752	4.7544	3.0251
5.5	0.21007	4.2307	2.7428
6.0	0.15537	3.8083	2.5375
6.5	0.094651	3.4630	2.3897
7.0	0.0705	3.1842	2.2393
7.5	0.11309	2.9616	2.0441

Generalized Debye fits (solid lines) of the Cole-Cole experimental plots for a polycrystalline sample at 0 Oe at different temperatures.

Magnetic Anisotropy: Measurement procedure



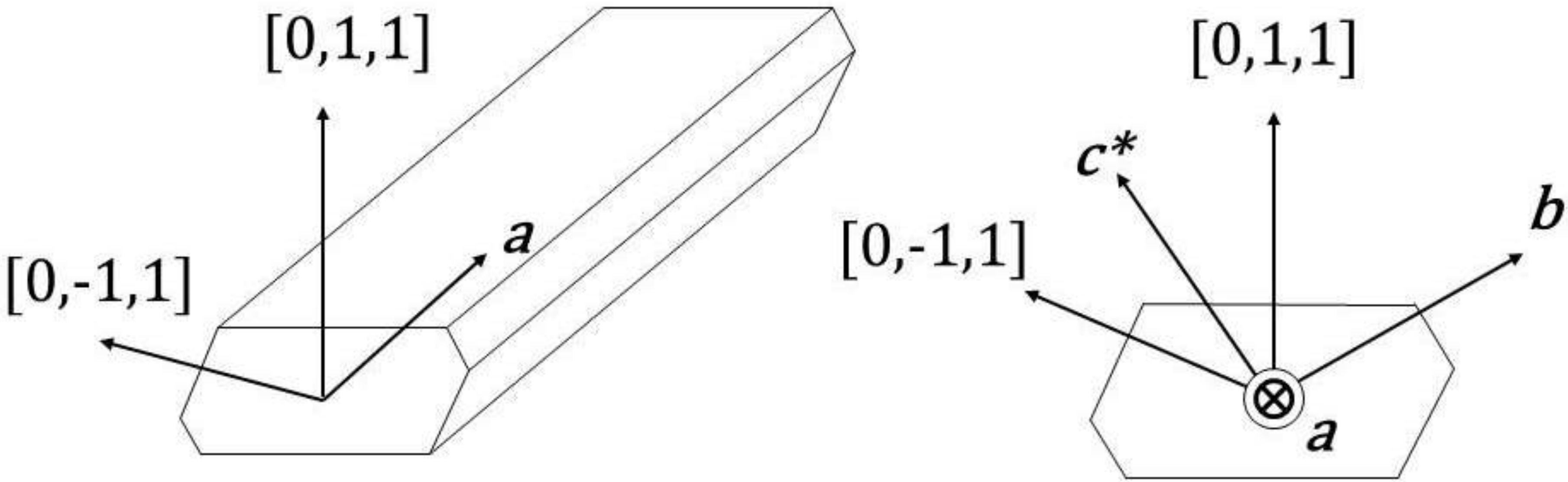


The magnetic signal from the Horizontal sample Rotator *vs* Rotation angle in chosen T & H

Horizontal Sample Rotator for MPMS

Magnetic Anisotropy: Measurement procedure

Using a Single Crystal



Perspective view (left) and side view (right) of a typical single crystal of $PPh_4[Fe(Tp)(CN)_3]\cdot H_2O$ together with selected crystallographic axes and directions.

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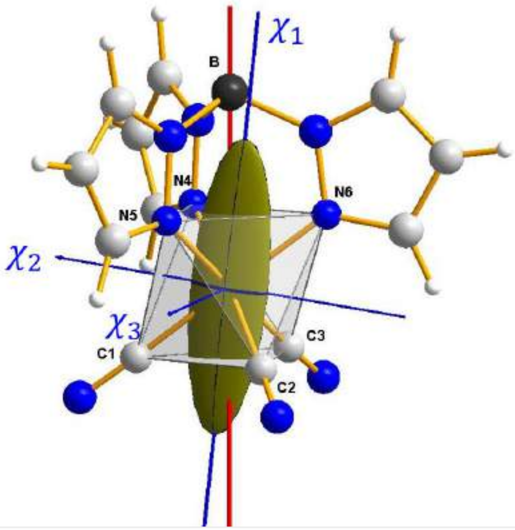
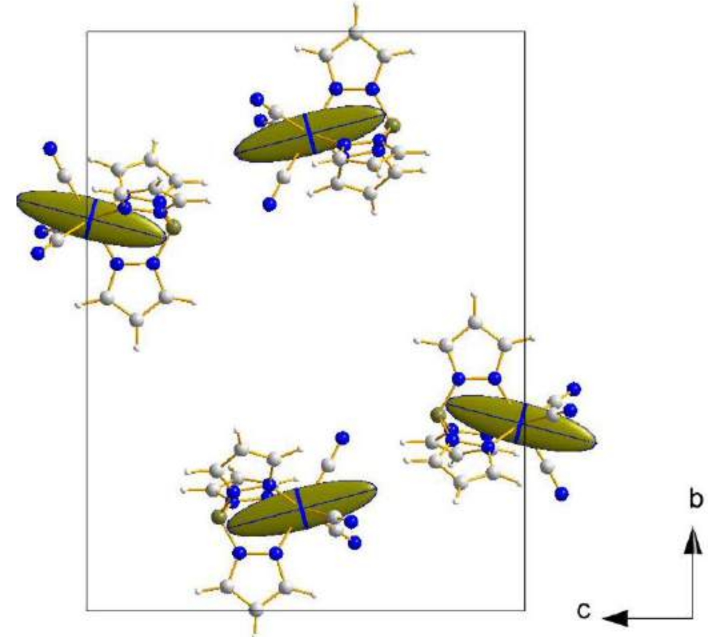
Magnetic Anisotropy: Measurement procedure

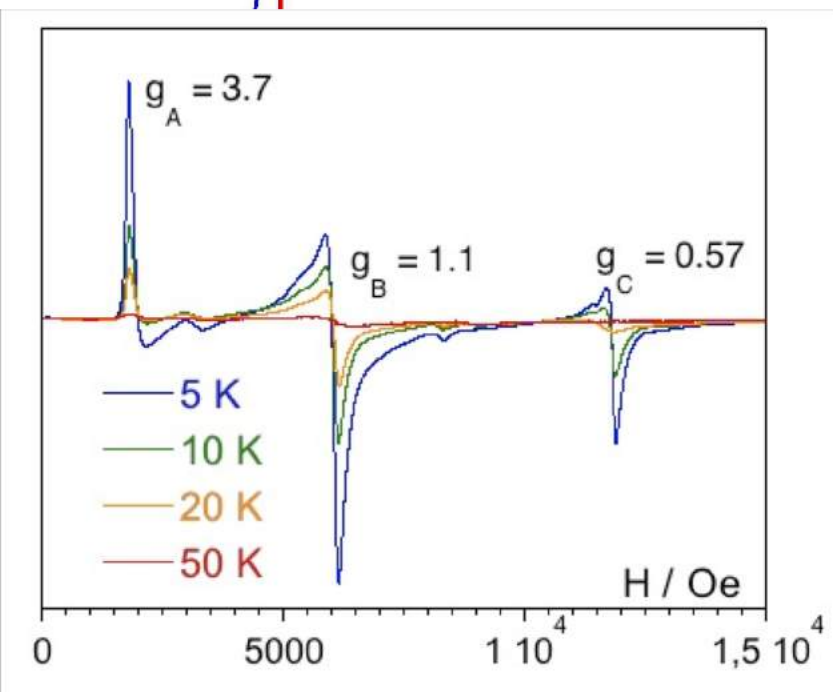
Using a Single Crystal



Fe^{3+} magnetic susceptibility ellipsoid obtained from PND within its coordination octahedron at 2 K. The local easy magnetization axis (χ_1) is nearly parallel to the χ_3 pseudo-axis (in red) of the molecule.



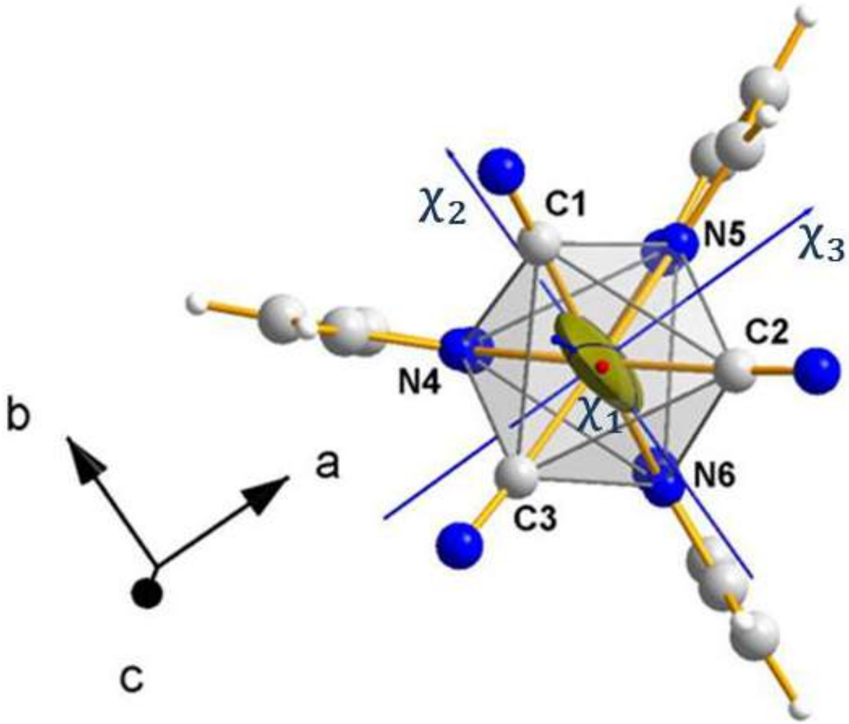
Projection of the unit cell along the a-axis and representation of the magnetic susceptibility ellipsoids determined by PND for the four molecules at 2 K.



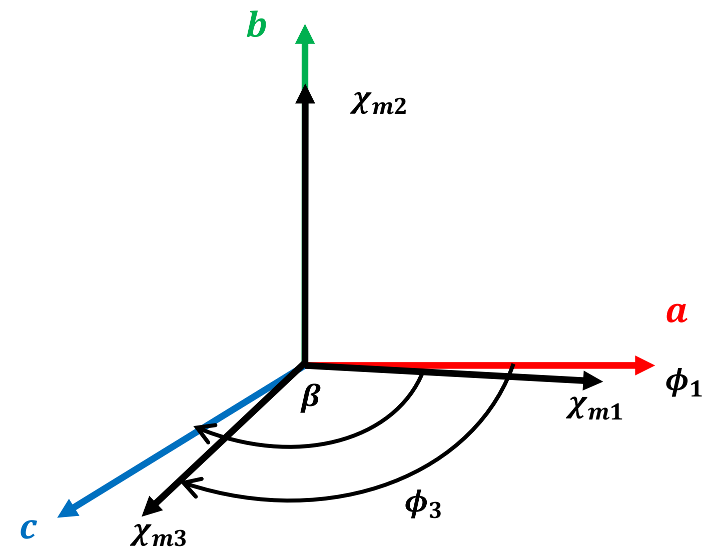
EPR spectra recorded at 9.42 GHz (X-band) on a powder sample of $PPh_4[Fe\{Tp\}(CN)_3]$ in the temperature range [5-50 K].

Magnetic Anisotropy: Measurement procedure

Using a Single Crystal



View of the magnetic ellipsoid in projection along the magnetic axis χ_1.



Magnetic axes of the crystal χ_{m1}, χ_{m2} and χ_{m3}, determined by PND at 2 K, in the monoclinic crystallographic basis set ($\beta = 100{,}34°$, $\phi_1 = 1{,}8°$ et $\phi_3 = 91{,}8°$).

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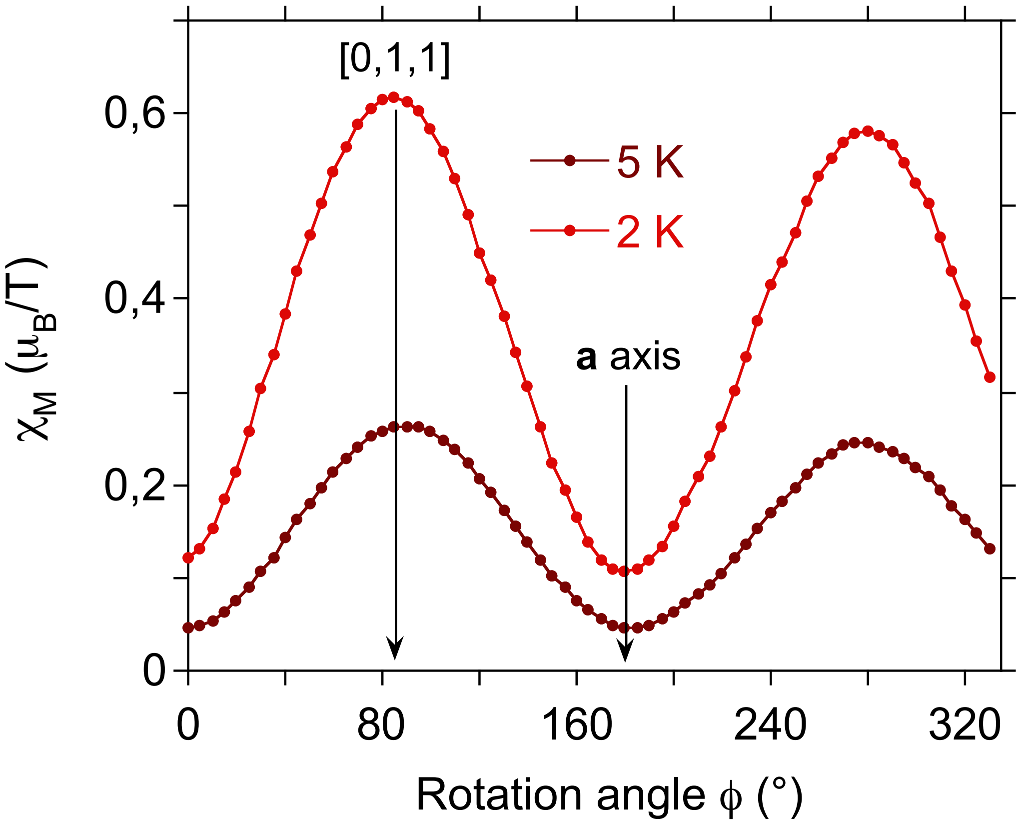
Magnetic Anisotropy: Measurement procedure

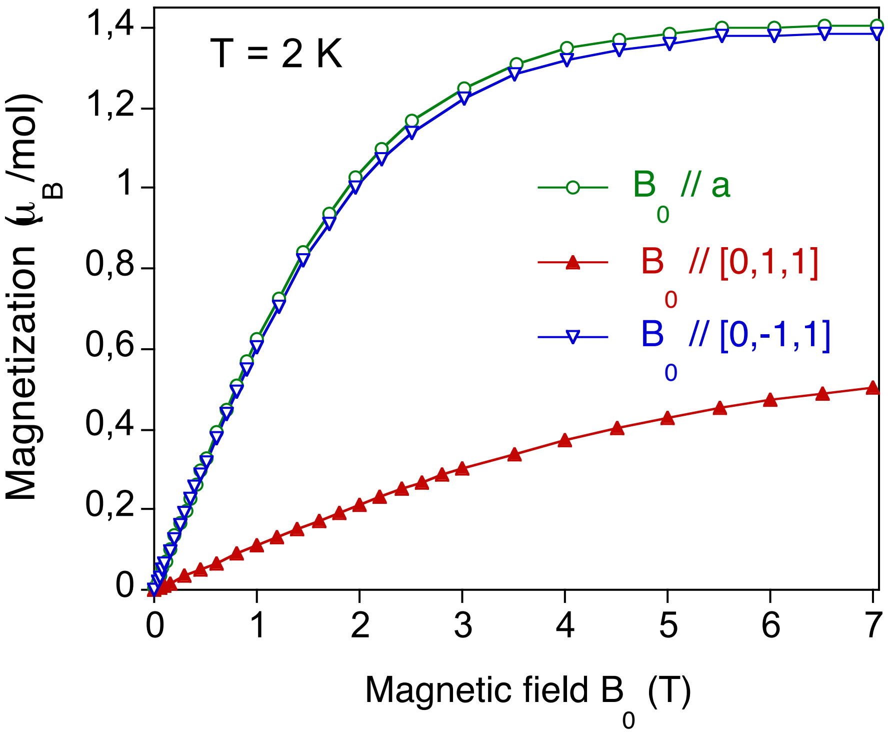
Using a Single Crystal



Magnetic susceptibility as a function of the rotation angle around an axis perpendicular to **a**-axis and [0,1,1] directions (at 2 K and 5 K, under 1 T). The $\phi = 0$ angle corresponds to an orientation where the **a**-axis is parallel to the applied magnetic field.

Magnetic Anisotropy: Measurement procedure

Using a Single Crystal



Magnetization curves at 2 K for three directions of the applied magnetic field **B**, in the range [0-7 T].

THANK YOU FOR YOUR ATTENTION

In life, nothing should be feared

everything is to be understood …

Marie Curie