Quantum Sensors for Particle Physics: the NAMASSTE R&D Project

Giuseppe Latino

(Firenze University & INFN)

(on behalf of the NAMASSTE Group)

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Overview

- **General principles of quantum sensing**
- **Quantum sensing in particle physics**
- **The NAMASSTE R&D Project**
  - **motivations**
  - **preliminary results**
- **Summary & Conclusions**

What "Quantum Sensing" Means?

"Quantum sensing" describes the use of a quantum system, quantum properties or quantum phenomena to perform a measurement of a physical quantity [1].

Quantum sensors (QSs) register a change of quantum state caused by the interaction with an external system. Then, a QS is a device whose measurement (sensing) capabilities are enabled by our ability to manipulate and/or read out its quantum states [2].

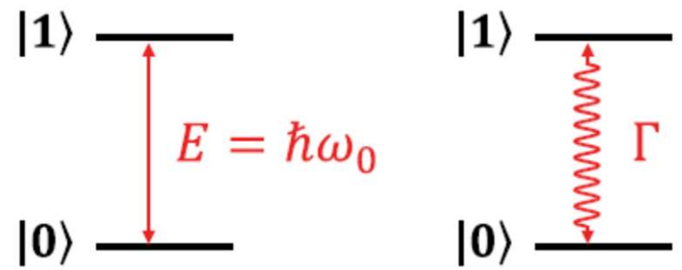


FIG. 1. Basic features of a two-state quantum system. $|0\rangle$ is the lower energy state and $|1\rangle$ is the higher energy state. Quantum sensing exploits changes in the transition frequency ω_0 or the transition rate Γ in response to an external signal V.[1]

Involved energies very low, so QS very sensitive to external perturbations:

- **Big potentialities to be exploited as precision measuring devices in specific fields of interest.**
- **<u>Why not considering them in Particle Physics?</u>**
- **Interdisciplinary (PP community, "Quantum" community, …) efforts & projects required.**
- **QS are intrinsically ideal for applications to low energy particle physics, but applications in HEP can also be pursued.**

[1] Rev. Mod. Phys. 89, 035002 (2017)
[2] arXiv:2305.11518v1 (2023)

Quantum Sensing Basic Protocol

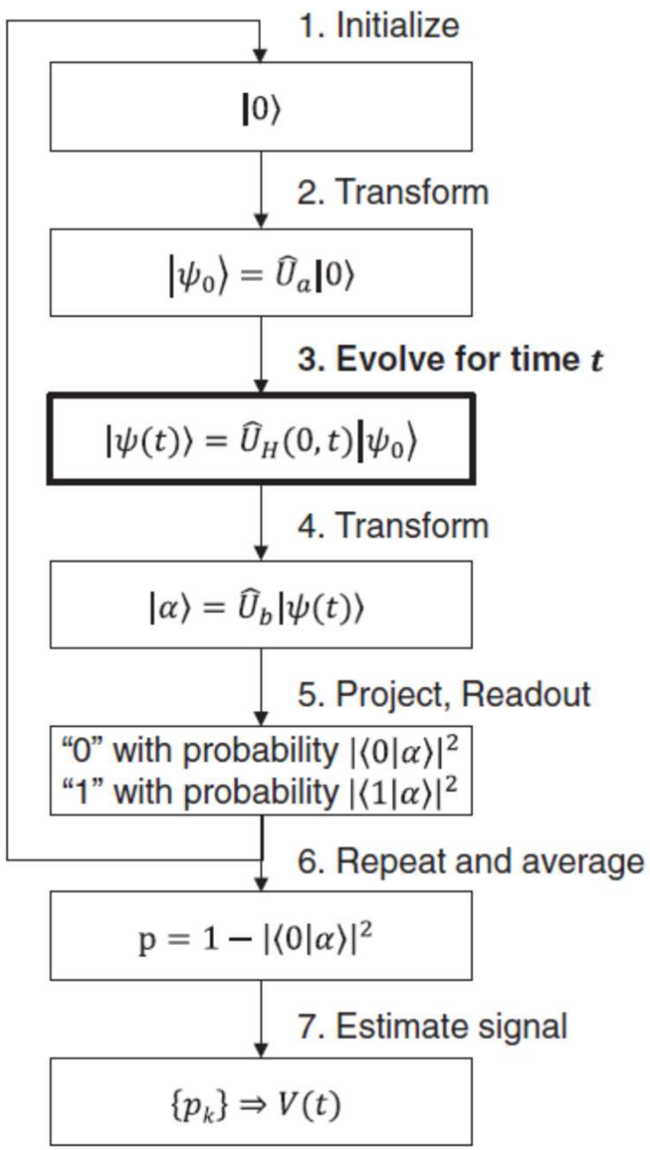


FIG. 2. Basic steps of the quantum sensing process. [1]

Quantum sensing experiments are typically performed following a basic methodology ("protocol").

In a more generic scheme the quantum sensor:

- **is initialized in a suited known state**
- **interacts with a physical quantity (signal) for some time**
- **is read out (→ evaluation of transition probability)**
- **the physical quantity is reconstructed from the readouts (signal estimation)**

The protocol can be optimized to detect <u>weak signals</u> or <u>small signal changes</u> with the highest possible sensitivity

Quantum Sensor Hamiltonian: $$\hat{H}(t) = \hat{H}_0 + \hat{H}_V(t) + \hat{H}_{\text{control}}(t)$$

"Internal" H "Signal" H "Control" H

"Control" H required to manipulate the sensor either before, during or after the sensing process.

[1] Rev. Mod. Phys. 89, 035002 (2017)

Growing Interest in Quantum Technologies @ PP Facilities

Development of quantum sensing devices for fundamental physics research represents of course one the mainstream R&D activity

CERN: Quantum Technology Initiative

https://quantum.cern/

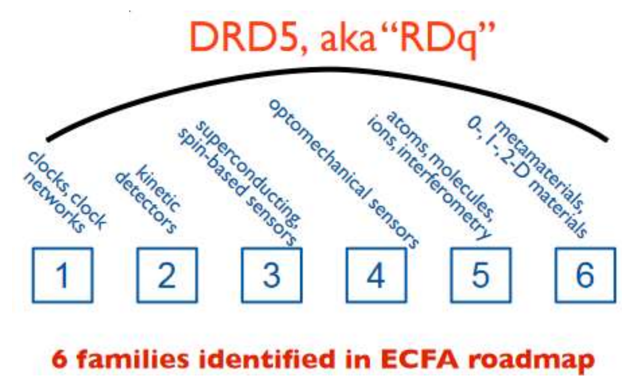
FNAL: Superconducting Quantum Materials and Systems Center

https://sqmscenter.fnal.gov/

[1] DOI: 10.17181/CERN.XDPL.W2EX

Other CERN ongoing activity: 2021 ECFA Report [1]

DRD5/RDq:
new CERN Collaboration under development to implement ECFA detector R&D roadmap for QS for PP
https://doser.web.cern.ch/



Quantum Sensors for Low Energy PP Applications

QS for low energy particle physics: the energy scale being probed is related to the one of the energy levels of the sensor itself (single interaction, typically at $\leq$ eV scale).

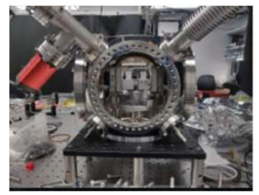
Physics Goals

- Search for NP/BSM (ex. α_{em} variations)
- Axions, ALP's, DM & non-DM UL-particle searches
- ν physics (masses)
- Tests of QM (ex. wavefunction collapse, decoherence)
- EDM searches, tests of fundamental symmetries

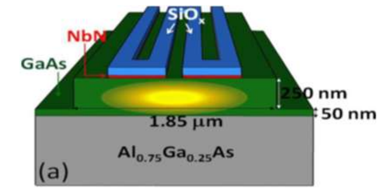
[1] DOI: 10.17181/CERN.XDPL.W2EX

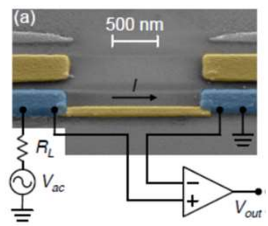
Quantum Technologies

(as identified in ECFA roadmap [1])



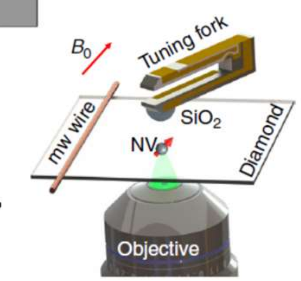
Clocks and clocks networks

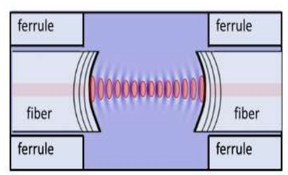




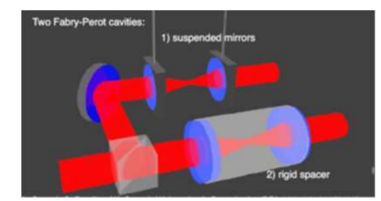
Kinetics detectors

Superconducting (TES, SNSPD, …) and spin-based (NV-diamonds, SMMs, ….) devices

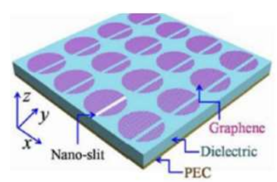




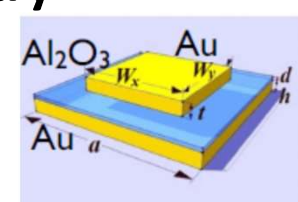
Optomechanical sensors



Atoms, molecules, ions, interferometry



Metamaterials, 0/1/2-D materials



An Example: Expected Improvements in DM Search

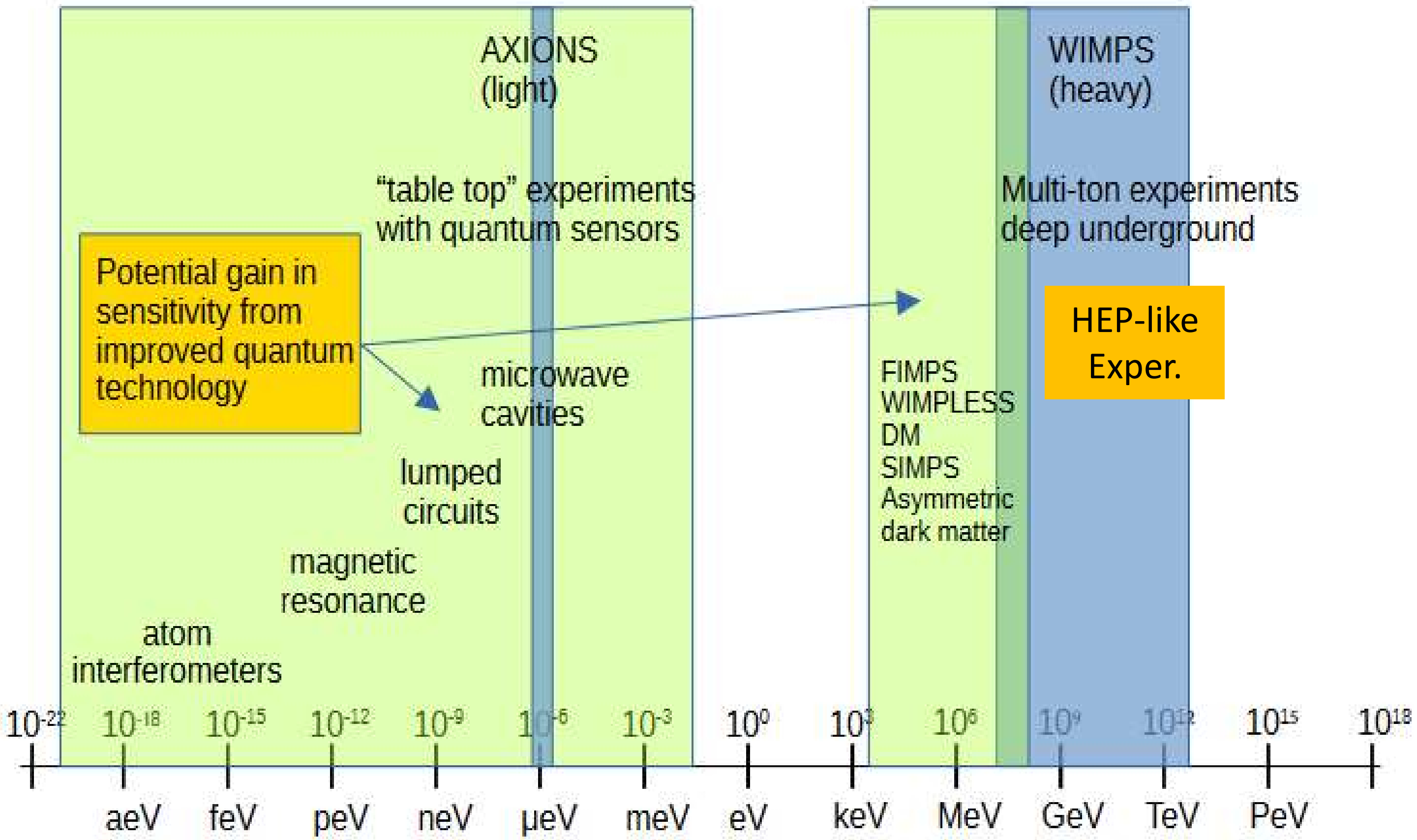
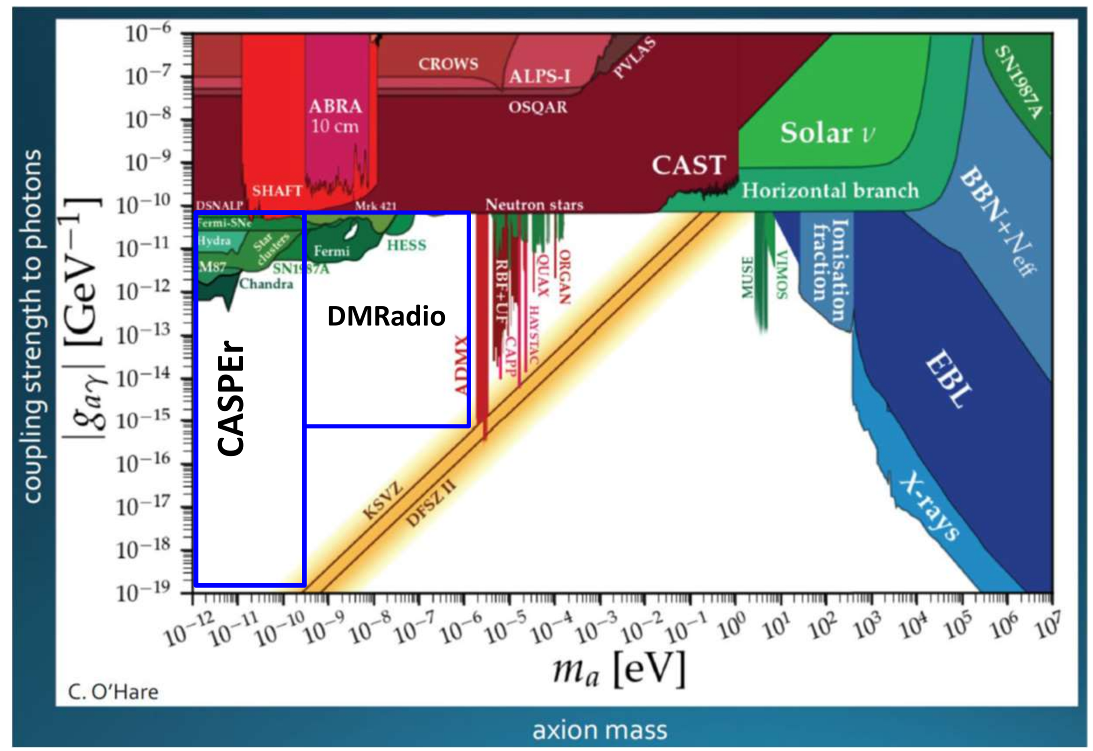


Figure 5.2: Axion mass range accessible via novel advanced quantum sensing techniques compared to current experiments. [1] **(Blue bands**: range of traditional experiments).

[1] DOI: 10.17181/CERN.XDPL.W2EX (ECFA Report)

Several proposals and development of experiments already on the table:

- **CASPEr**
- **DMRadio-50L/m^3**
- **QUAX**
- **..........**



Quantum Sensors for High Energy PP Applications

QS for high energy particle physics: quantum systems form part of a larger system, in which their specific properties enhance existing methods or enable novel types of detectors optimized for high energy particle physics (multiple interaction, typically at > KeV scale).

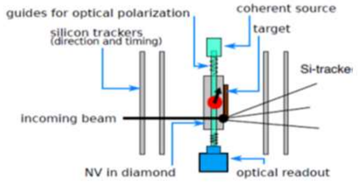
Not yet developed concepts (still speculative)

Typical Requests for Improvements in:

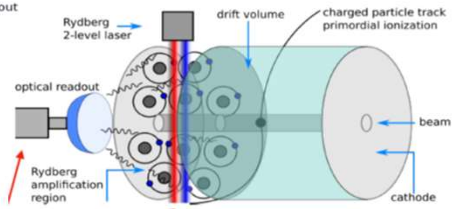
- **tracking (hit positions, material budget)**
- **timing (TOF for PID)**
- **calorimetry (shower shape, timing, granularity)**
- **novel observables (helicity/polarization)**

Applications from Quantum Technologies (as proposed in ECFA roadmap [1])

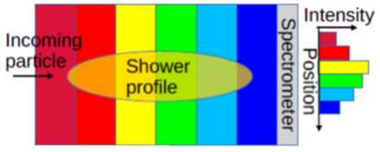
Spin-based sensors
Helicity detectors

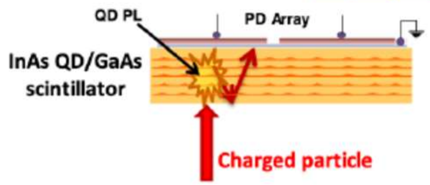


Atoms, molecules, ions
Rydberg atom TPC's



Metamaterials, 0/1/2-D materials
Ultra-fast scintillators based on perovskytes
Active scintillators (QCL, QWs, QDs)
Chromatic calorimetry (QDs)
GEMs (graphene)





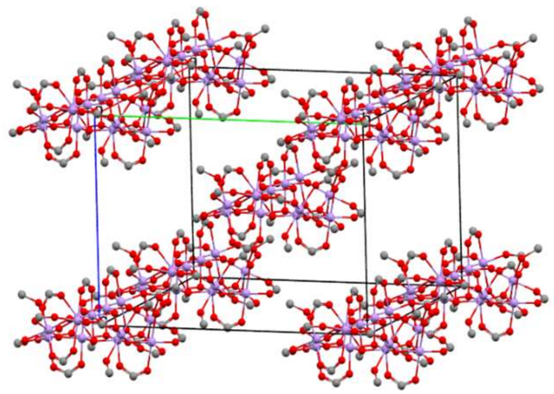
[1] DOI: 10.17181/CERN.XDPL.W2EX

Single Molecule Magnets (SMMs)

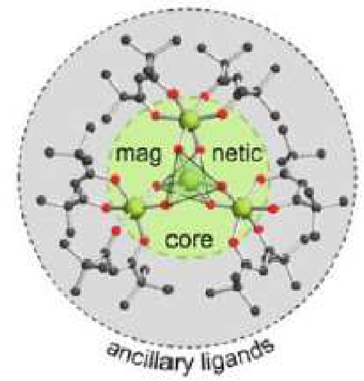
SMMs are crystalline materials characterized by [1]:

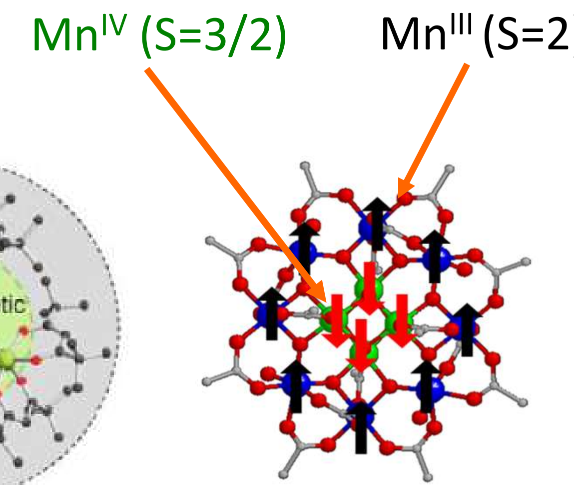
1. Regular crystalline structure, made by identical molecules with a magnetic core of a finite number (n≥1) of paramagnetic centers, with strong intramolecular exchange interactions.
2. Molecules shielded by organic ligands → weak intermolecular interactions.

→
- **Magnetically isolated molecules**
- **High spin S value**
- **Strong uniaxial anisotropy → magnetic bistability at low T**
- **Quantum tunnelling of magnetization**



Mn_{12} crystal

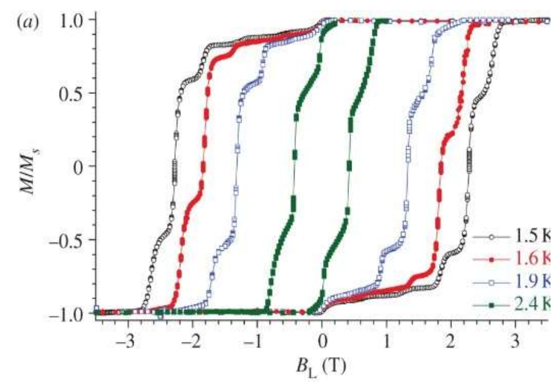


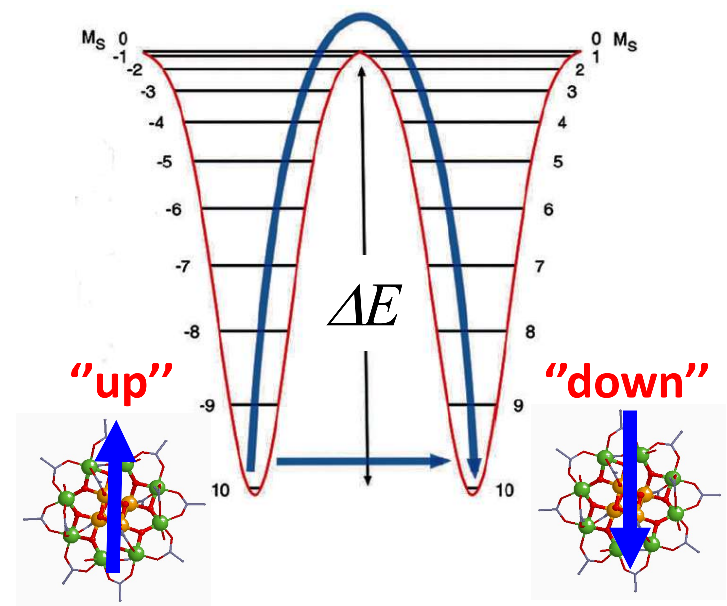


Mn_{12} core

"Reference" (the most studied) SMM, Mn_{12}:

S_{tot}= 10; $\Delta E \approx 65$ K; $\tau = \tau_0 \exp(\Delta E/k_B T)$, $\tau_0 \approx 10^{-7}$s



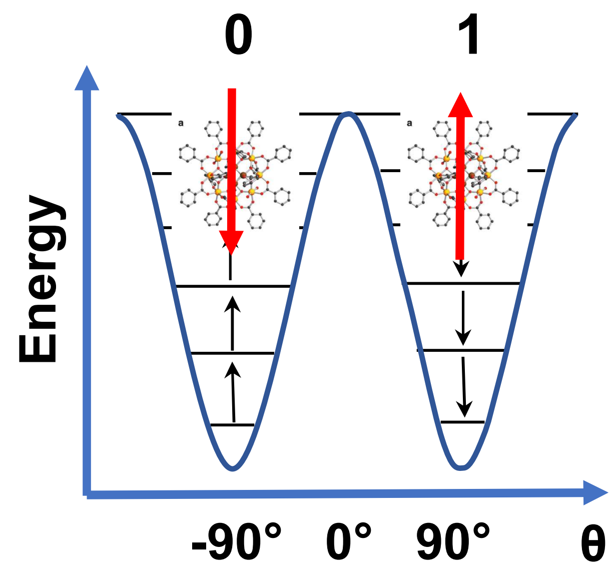


Relatively new materials with interesting potential applications …..

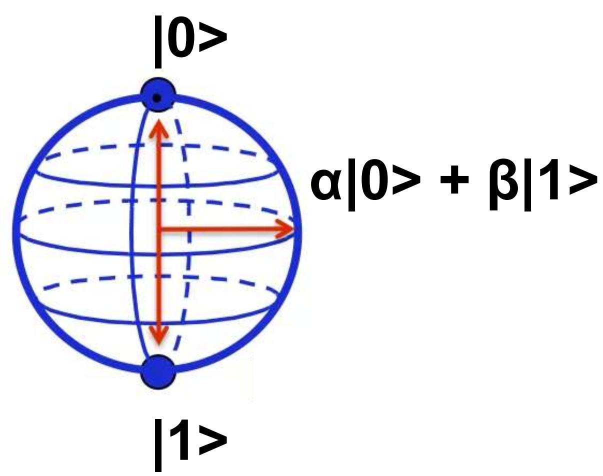
[1] Gatteschi, Sessoli, *Angew. Chem. Int. Ed.* 42 (2003)

Potential Applications of SMMs

High-density memory storage



Quantum computing [1]

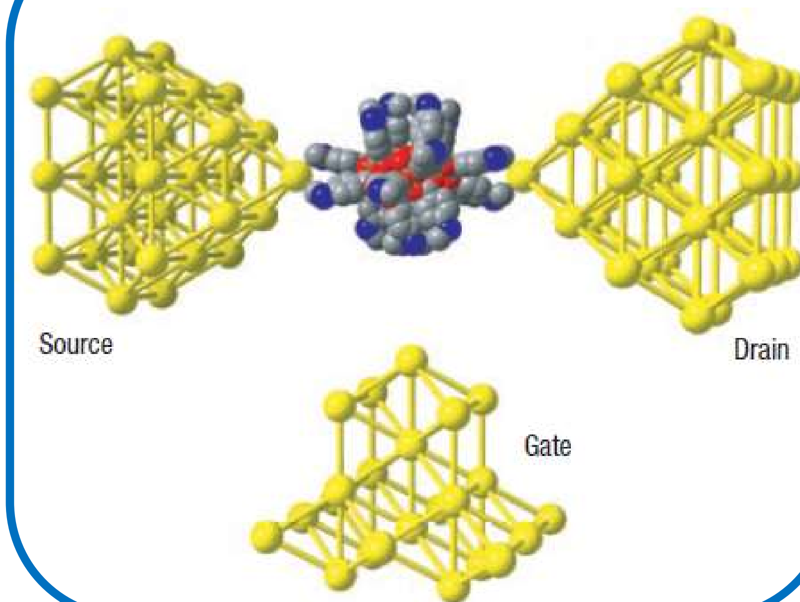


Qubit

[1] Leunberger *et al.* *Nature* **410**, 789-793 (2001)

Molecular spintronics

Molecular spin-transistor [2]



[2] Bogani *et al.* *Nat. Mater.* **7**, 179-186 (2008)

New potential application

Quantum sensors for particle detection

The INFN R&D NAMASSTE Project

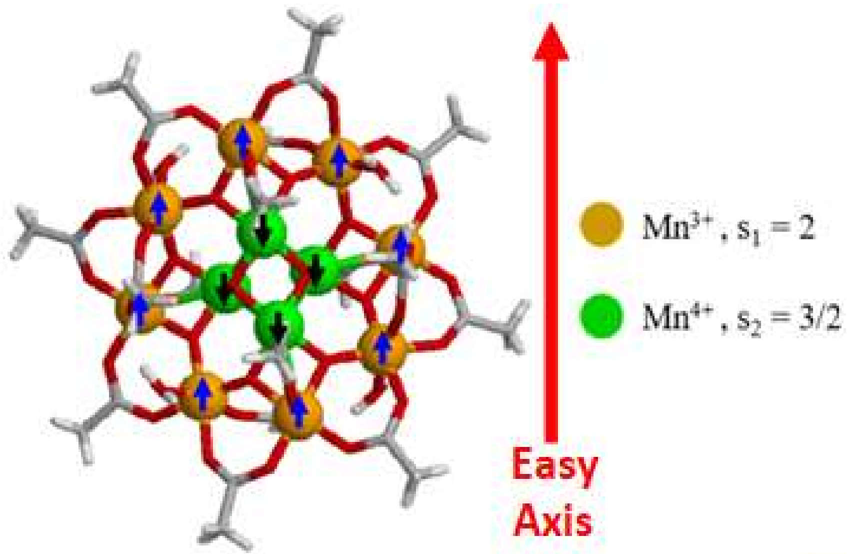
NAMASSTE: NanoMagnets for quantum Sensing and Data Storage

The project (financed by INFN, GrV) aims to design, synthesize, and characterize new molecular nanomagnets for two different applications:

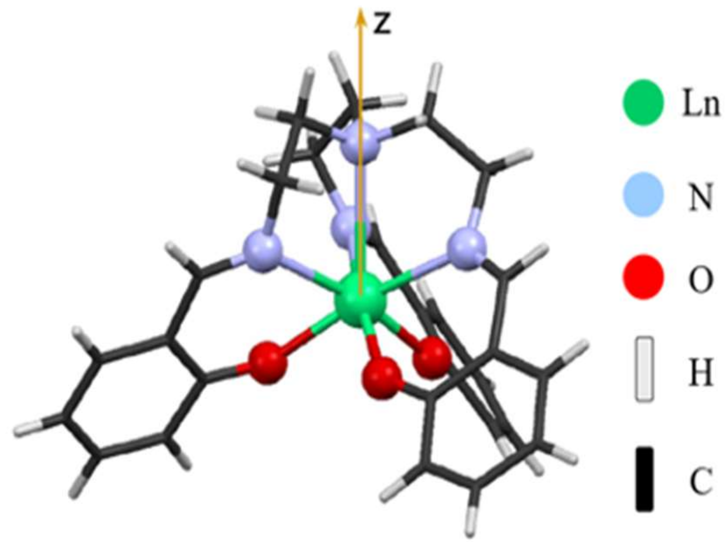
- **single molecule magnets (SMMs)**, for **high-sensitivity** sensors, potentially suited for revealing dark matter (energy sensitivity down to ~ 10^{-3} eV): hidden photon [1], …..;
- **single ion magnets (SIM)**, for **high-density** memory storage systems.

Focus of this talk

Novel combination of experimental techniques (in synergy with theoretical investigation) to achieve these goals: **Magnetometry (SQUID), NMR, EPR, μ-SR**.



Mn_{12} SMM



Ln-based SIM

[1] Bunting *et al. Phys. Rev. D* **95**, 095001 (2017)

Are SMMs of Interest for Particle Physics ?

Bunting *et al., Phys. Rev. D* 95, 095001 (2017):

→ **SMMs as sensors can be competitive for the detection of Dark Photons at low masses**

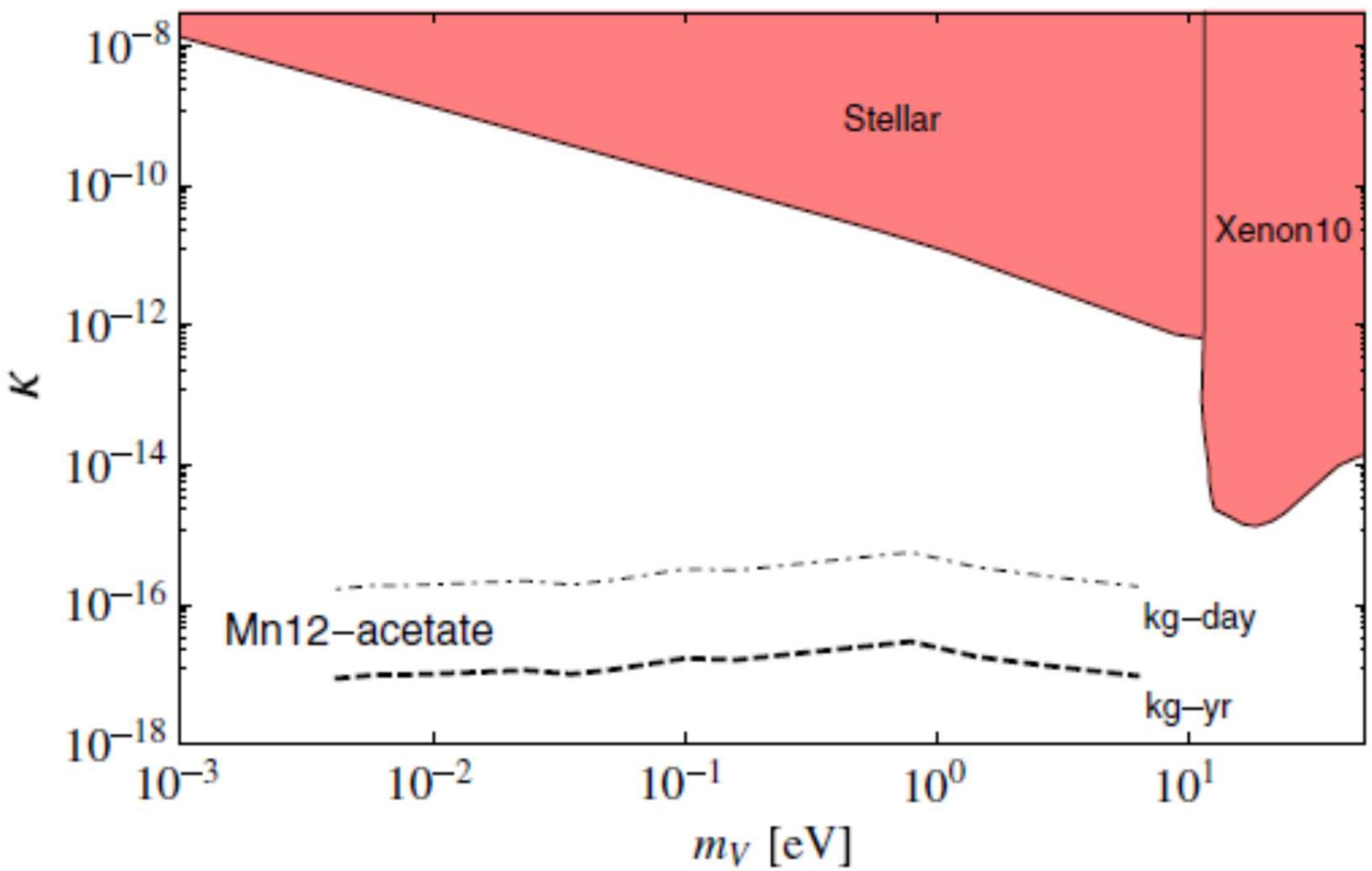


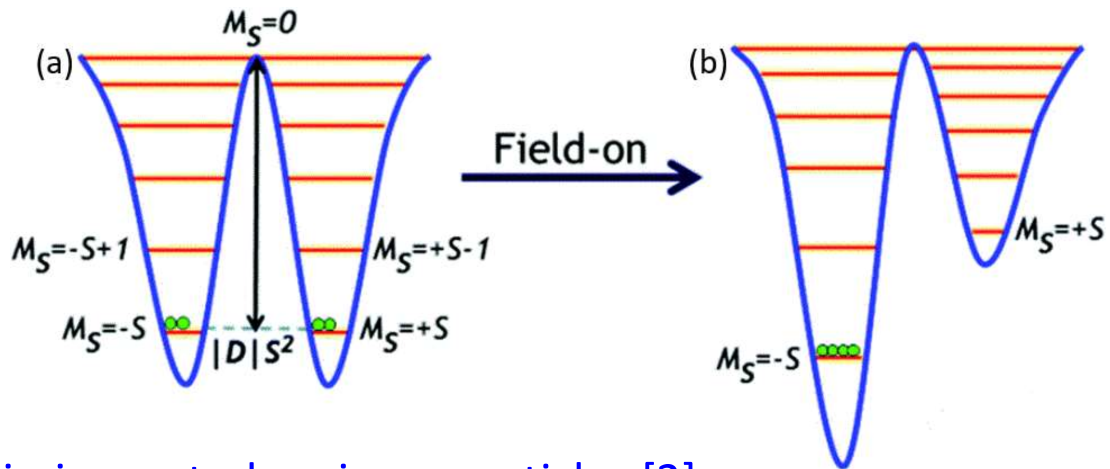
FIG. 6. Estimated sensitivity to absorption of dark vector DM in Mn_{12}-acetate, assuming an aggressive sensitivity of 1 event/kg year (dashed), and a sensitivity of 1 event/kg day (dot-dashed). The absorption data from Refs. [62,65] (described in the appendix) has been smoothed, an interpolation used in the region $m_V \sim 0.2$–0.5 eV, for which no data was available, and we use the approximation $\kappa \simeq \kappa_{\text{eff}}$ (see text).

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}^2 - \frac{1}{4}V_{\mu\nu}^2 - \frac{\kappa}{2}F_{\mu\nu}V^{\mu\nu} + \frac{m_V^2}{2}V_\mu V^\mu + eJ_{\text{em}}^\mu A_\mu$$

But the potential for other applications in PP has yet to be fully investigated ….

SMMs as Sensors

The current detection approach [1] is based on the idea that an impinging particle may induce a "***magnetic avalanche***" in SMM crystals immersed in a magnetic field. This effect is triggered by the release of the Zeeman energy stored in the metastable states of the SMM in presence of an external magnetic field.



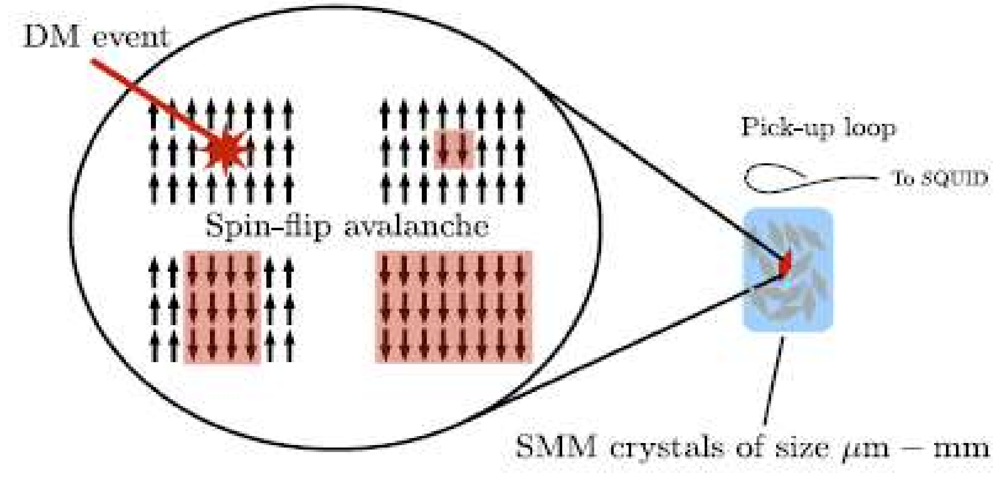
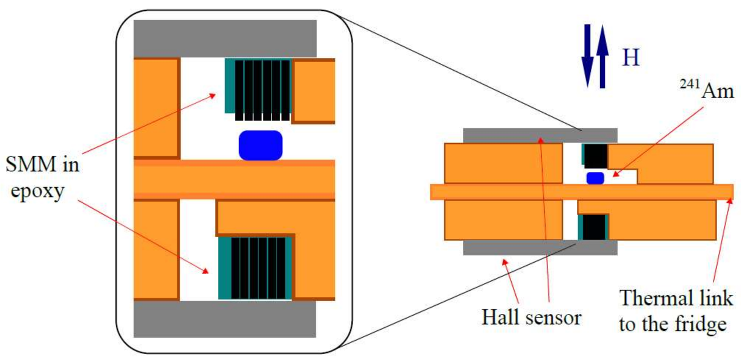
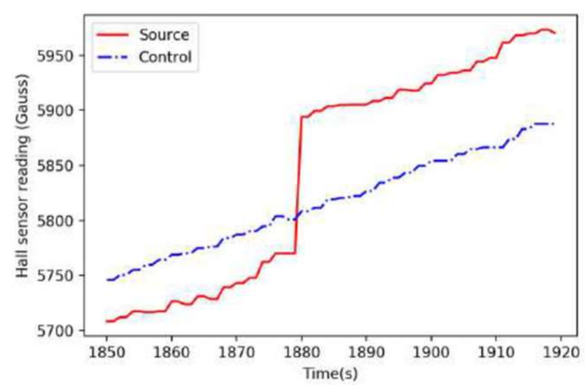


FIG. 1. DM detector concept based on magnetic deflagration in molecular nanomagnet crystals. A DM event that deposits energy in the form of heat ignites a spin-flip avalanche in the crystal which is detected by the change in magnetic flux through a pick-up loop.

[1] Bunting *et al. Phys. Rev. D* **95**, 095001 (2017)

Preliminary study using α particles [2]:
induced avalanches → <u>first evidence of Mn12 as a sensor</u>





[2] Chen *et al.* arXiv:2002.09409v2

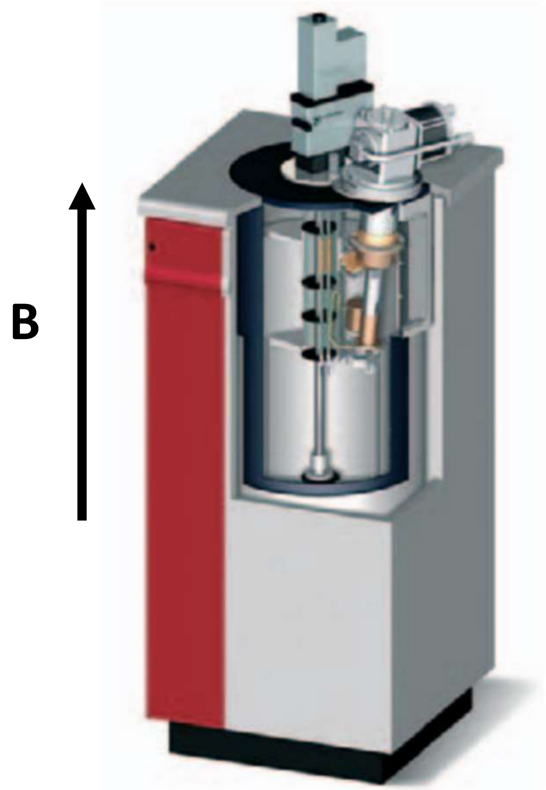
AIM OF THE NAMASSTE PROJECT:

- reproduce results with α, trying to optimize the conditions for magnetic avalanches (very promising effect for potential up-scaling in sensing volume ….);
- possibly extend to β and γ;
- investigate SMMs as sensors with other experimental techniques (EPR, NMR) characterized by an enhanced sensitivity

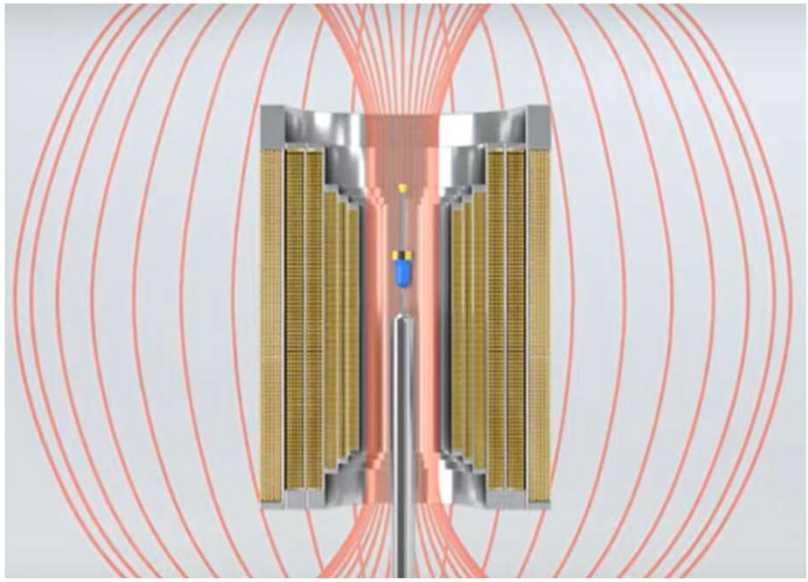
NAMASSTE: Ongoing Studies Related to Sensing

In NAMASSTE different techniques are used to study Mn_{12} in presence of **low activity** radiation sources

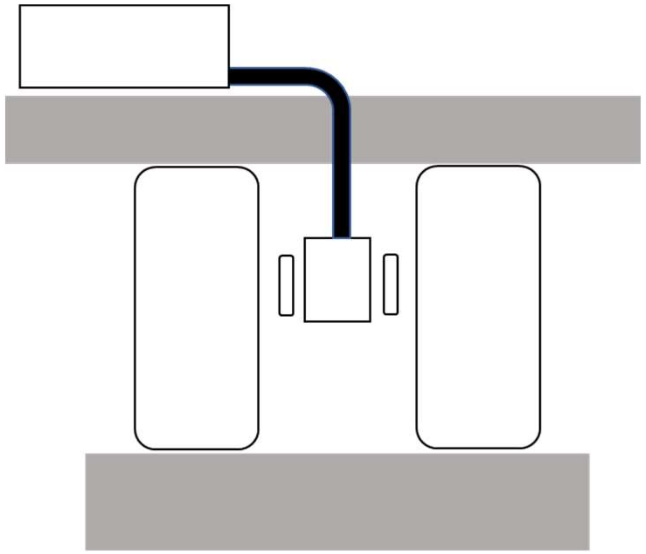
SQUID magnetometer



Nuclear Magnetic Resonance (NMR)



X-band Electron Paramagnetic Resonance (EPR)



But Mn_{12} has S = 10
→ no intrinsic EPR signal ….

Based on the measurement of the variation of the magnetization over the **entire volume** of the sensor: similar approach to the one reported in literature.

Local probe techniques: these approaches (based on the study of relaxation times) are expected to be **more sensitive** than the ones based on magnetometry.

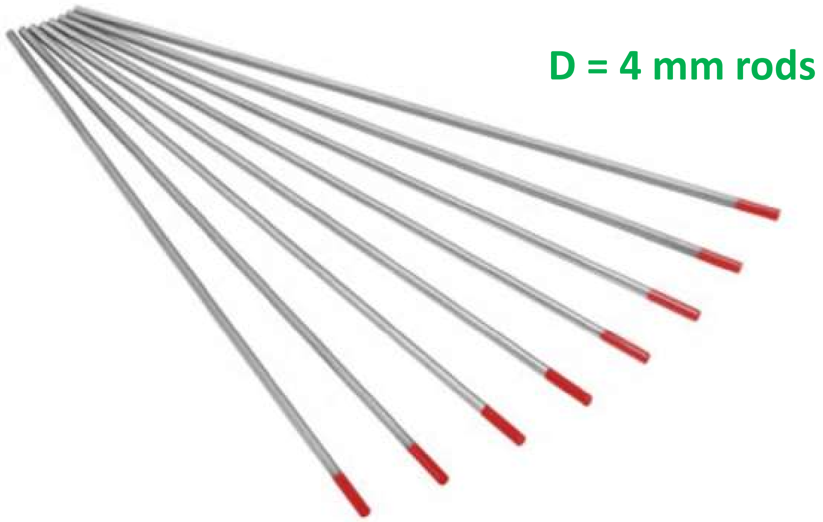
Radiation Sources

Requirements: very low activity α sources to be adapted to the small dimensions of the involved instruments

Made from electrodes used for special welding (tungsten with **2% Th)**, by precision machined cut to fit specific technical needs of the devices.

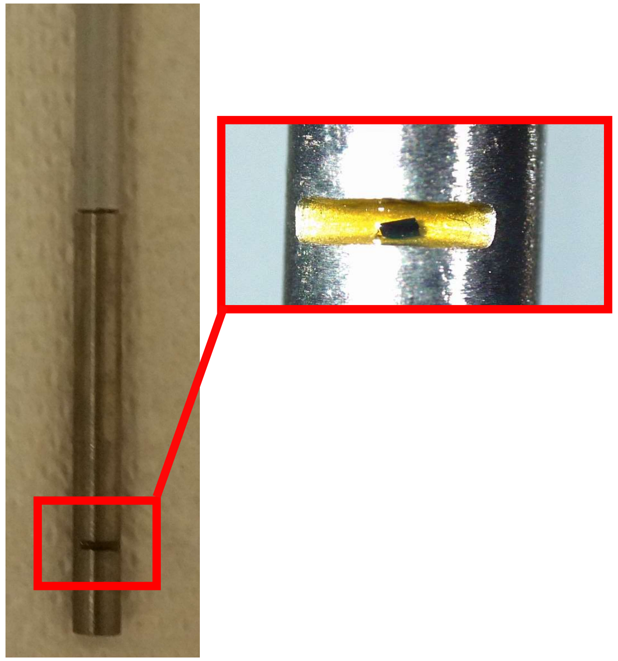
Measured surface activity:

- α (from prim./sec. decays) ~ 0.2 α /(mm^2 min)
- β (from sec. decays) ~ 20 times α activity
- γ (from sec. decays) ~ 600 times α activity



Availability of similar non-radioactive electrodes (pure W), to be used for "reference" measurements without particle radiation in the same experimental configuration.

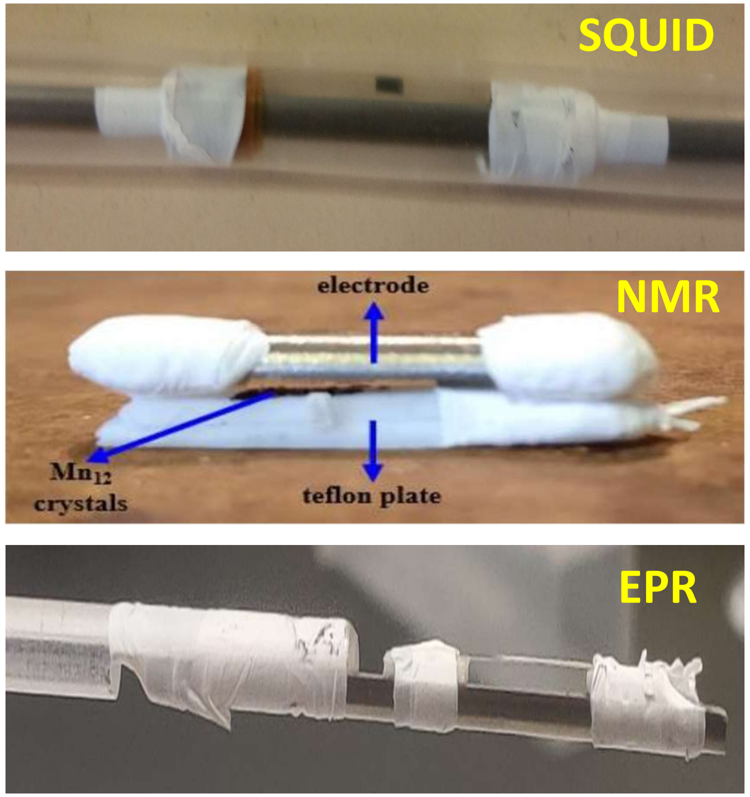
EPR-I: cylindrical geometry with small transversal cut



First approach, but:

- EPR signal very sensitive to position in cavity
- ~ 35 times reduction in EPR signal intensity w.r.t. using standard crystal sample holder

SQUID, NMR, EPR-II: semi-cylindrical geometry



- Good signals w.r.t. standard crystal sample holders
- Only ~ 5 times reduction in EPR signal intensity

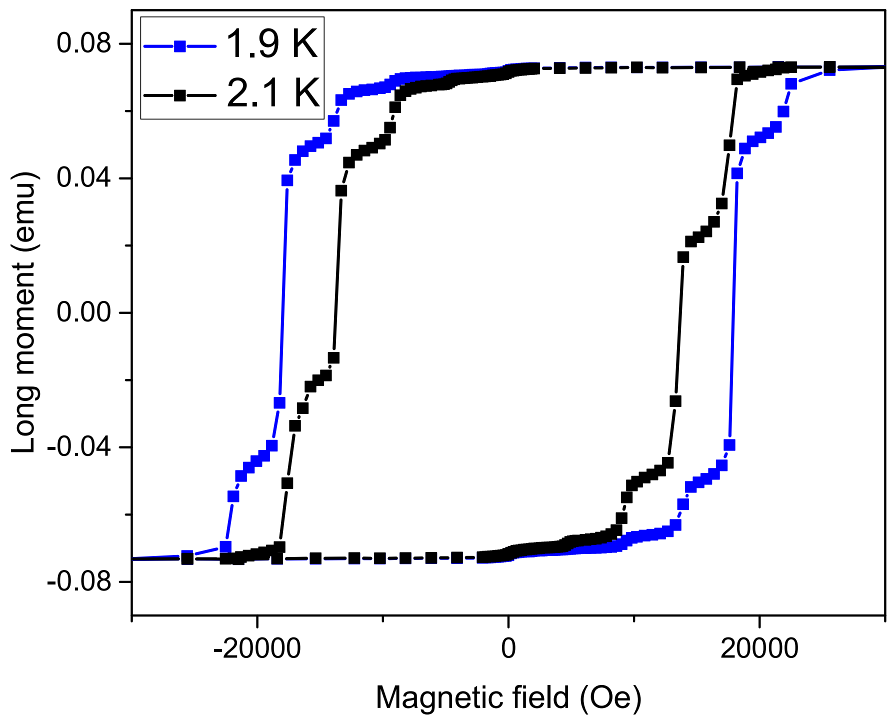
SQUID Magnetometry Studies on Mn12

Performed @ Florence Unit

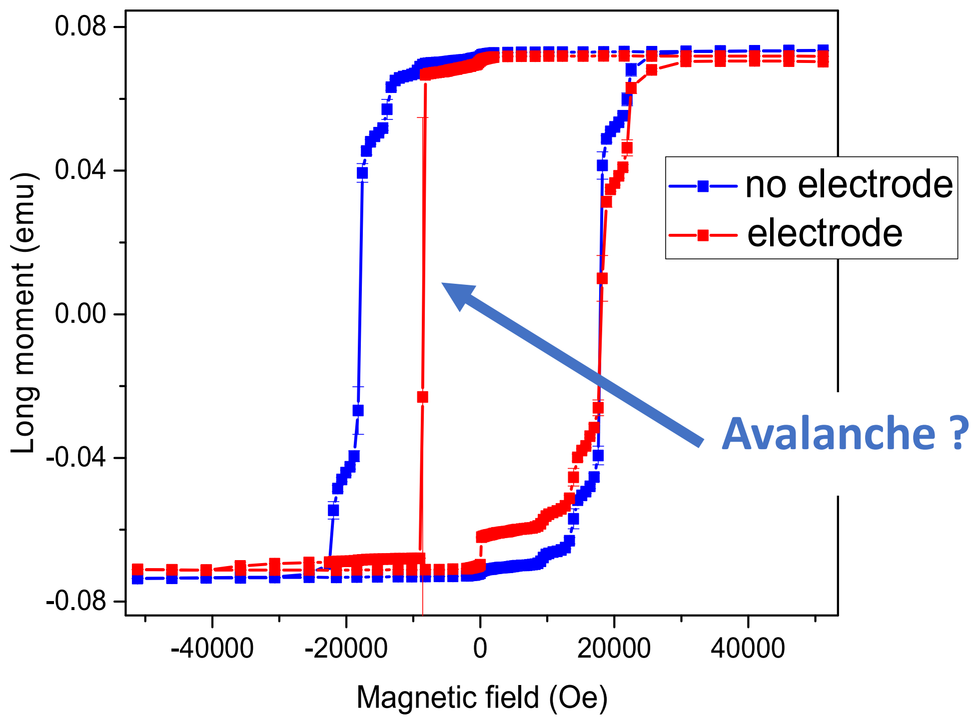
Goal: reproduce the results reported in literature and identify the optimal setup conditions to obtain them

Crystals of Mn12 with the easy axis // to the external magnetic field

Hysteresis without α source

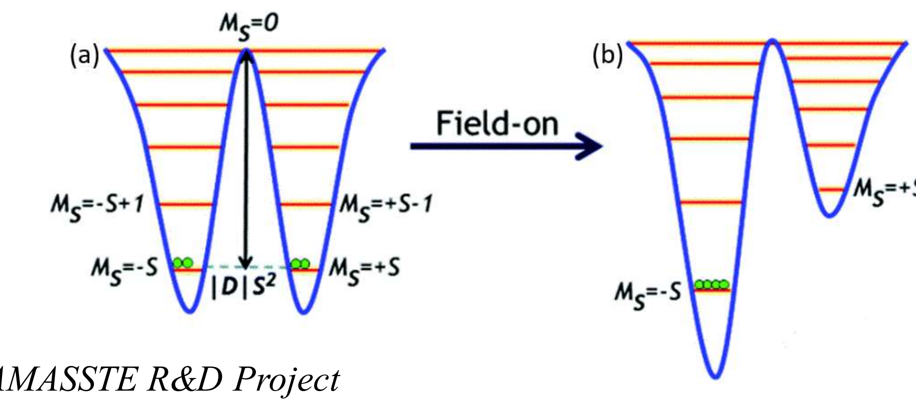


Hysteresis with α source



- **As expected, the hysteresis loops show 'jumps' at suitable B values due to quantum tunnelling effects.**
- **Abrupt reversal of magnetization, compatible with an 'avalanche' effect, observed only in one case.**

Need to carry out further studies.



NMR Studies on Mn12

Performed @ Pavia Unit

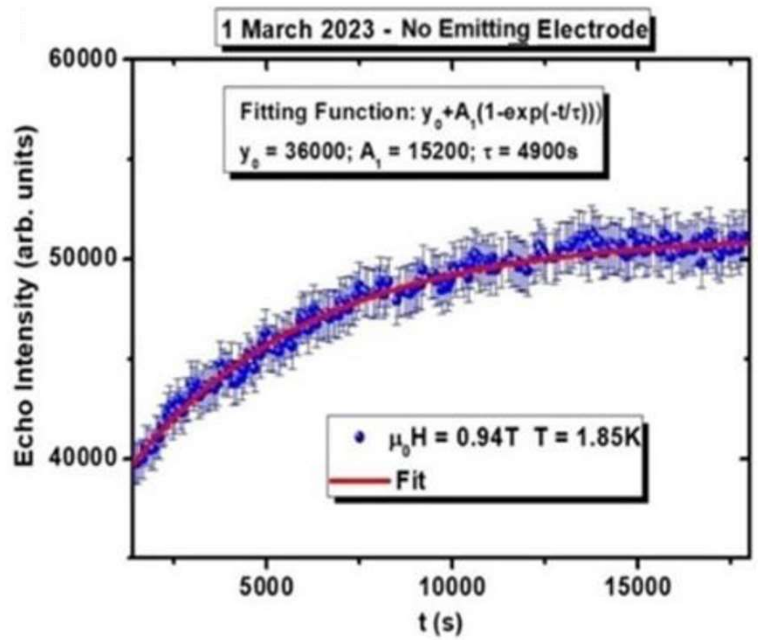
Goal: use NMR-based techniques to study relaxation times of Mn12 crystals with/without irradiation.

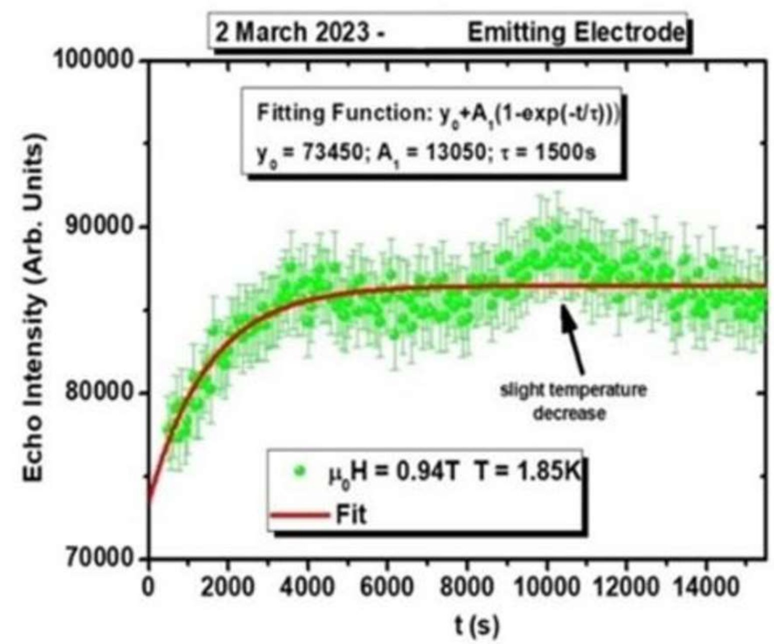
Adopted technique [1]:

- acquisition of the echo signal intensity height (related to the magnetization of the crystal) as a function of time;
- measurement of the relaxation time τ of the magnetization from the related fit.

Chosen protocol:

- Mn12 crystal cooled down to 1.85 K at B = 0 T.
- Then put at fixed B = 0.94 T (3^{rd} jump).
- Start the measurements.





Noticeable reduction in relaxation time of magnetization τ in presence of particle radiation

Run	No Emitting Electrode τ (s)	Alpha Emitting Electrode τ (s)
September 2022	10400	3500
March 2023	4900	1500

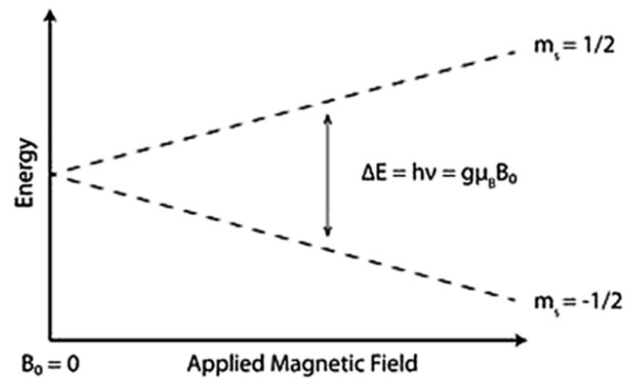
[1] Jang *et al.*, PRL 84 2977 (2000)

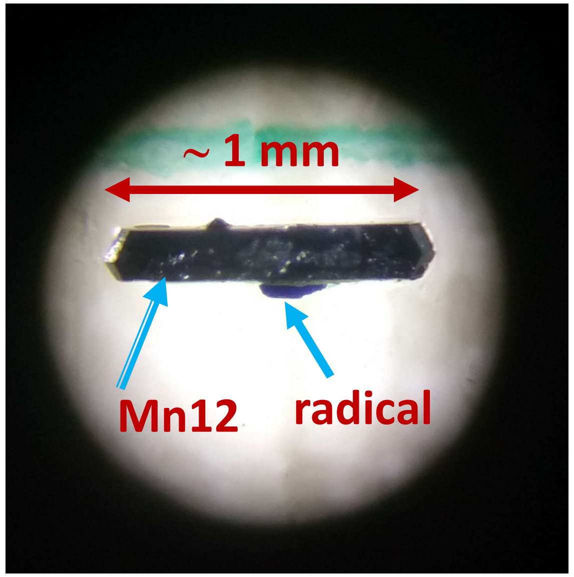
EPR Studies on Mn12

Performed @ Firenze Unit

Goal: use EPR-based techniques to study behaviour of Mn12 crystals with/without irradiation.

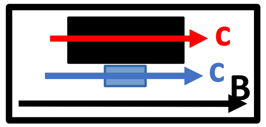
EPR: absorption spectroscopy technique used to study chemical species with <u>unpaired electrons</u>; the details of EPR spectra depend on the electron interaction with the nearby environment.





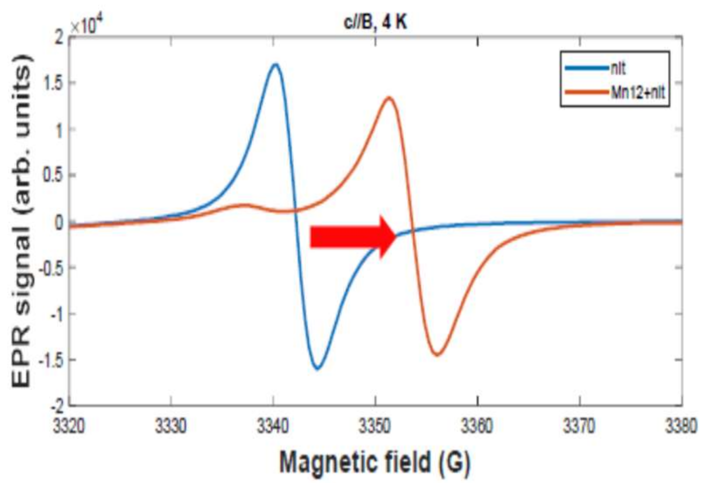
Adopted technique [1]:

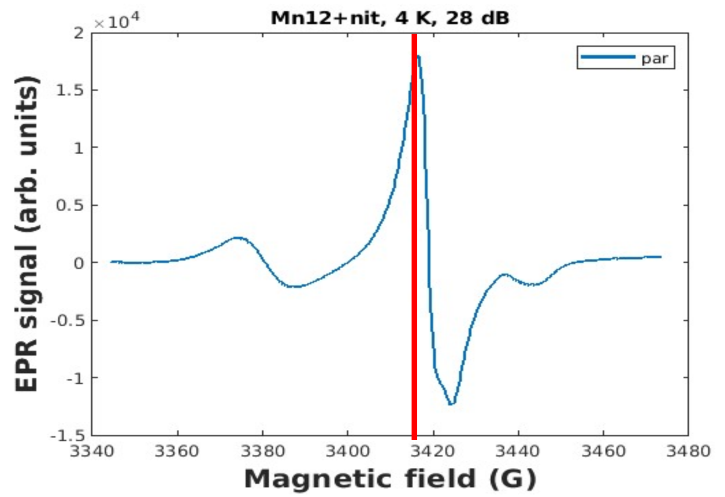
- **Mn12 does not show an intrinsic EPR signal at the frequencies of the available device (X band).**
- **Then couple the Mn12 crystal to a radical crystal (specifically: NitPBAh, an organic radical), so to have an EPR signal sensitive to variations in Mn12 magnetization.**



Chosen protocol (device driven):

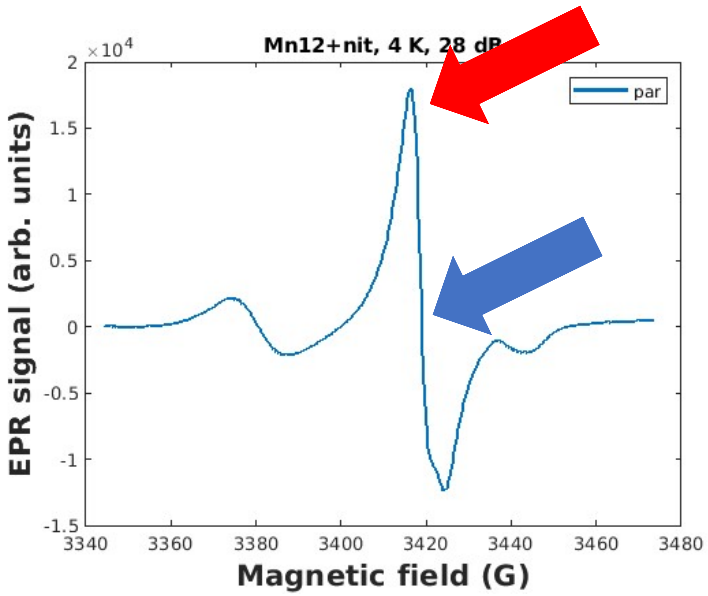
- **Mn12+radical crystals cooled down to 3.9 K at B = 0 T.**
- **Then put B (// c-axis) around working value ~ 3400 G.**
- **After proper tuning, get EPR signal (derivative of absorption spectrum) with measurements on short timescales (~ 1 ms) at a <u>fixed</u> B value.**
- **Make stability studies.**



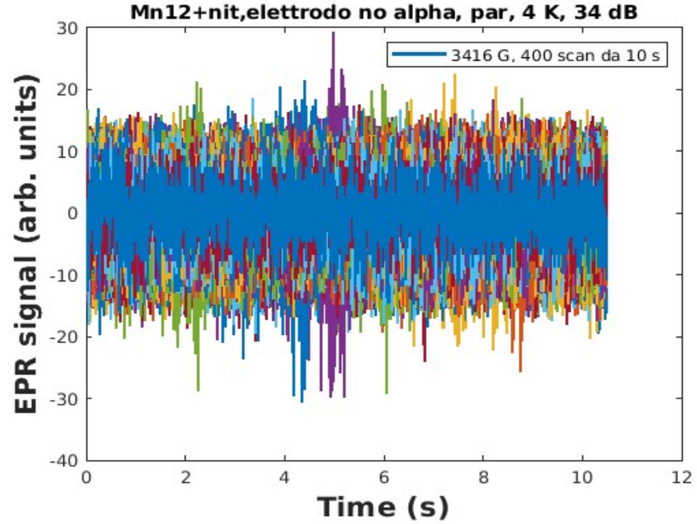


[1] Rakvin *et al.*, Jour. of Mag. Res., 165 (2003) 260-264

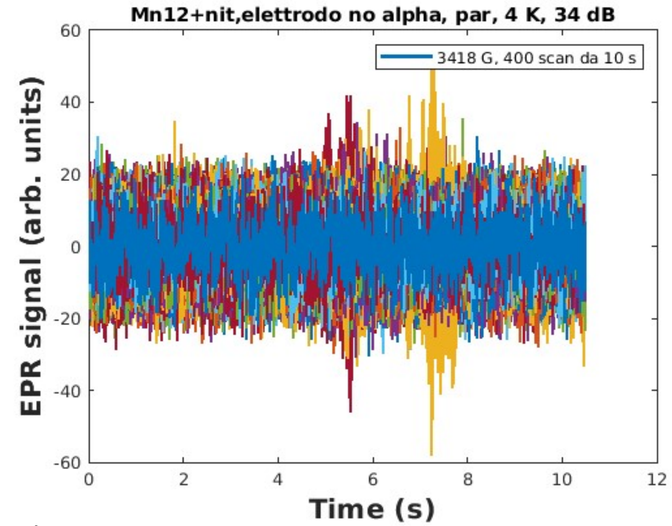
Mn12+Radical: EPR Studies without Particle Radiation



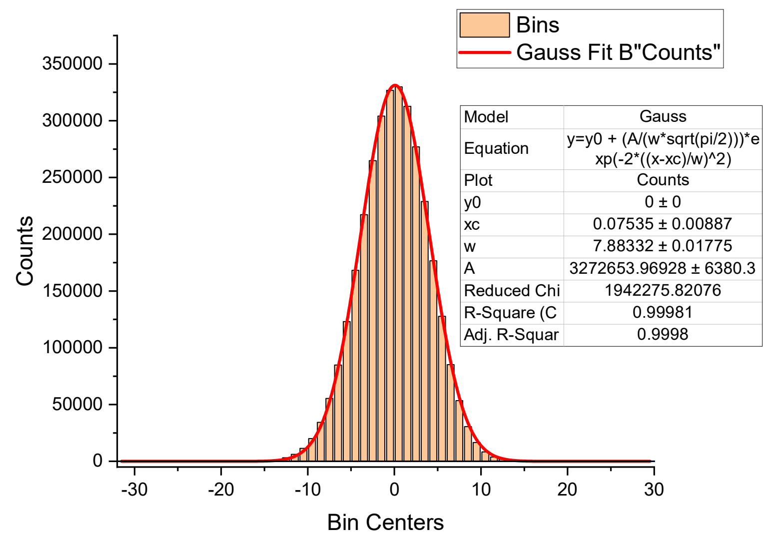
MAX

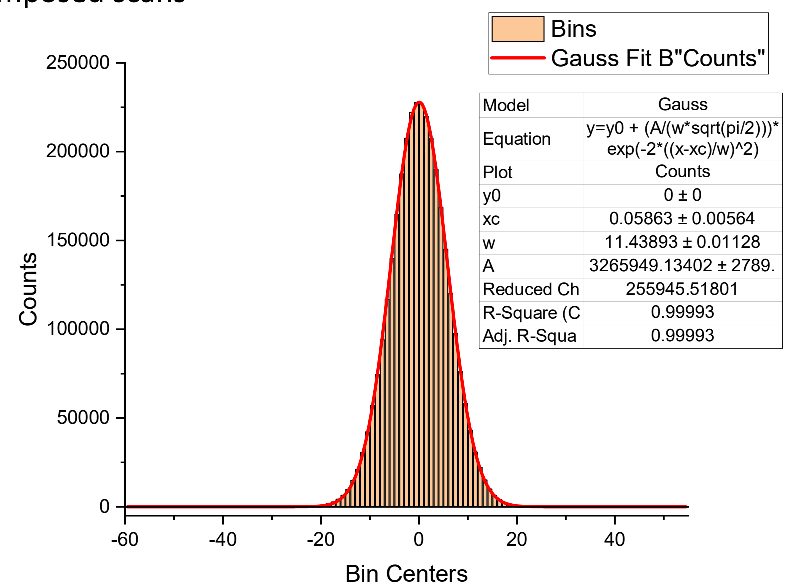


ZERO



400 superimposed scans

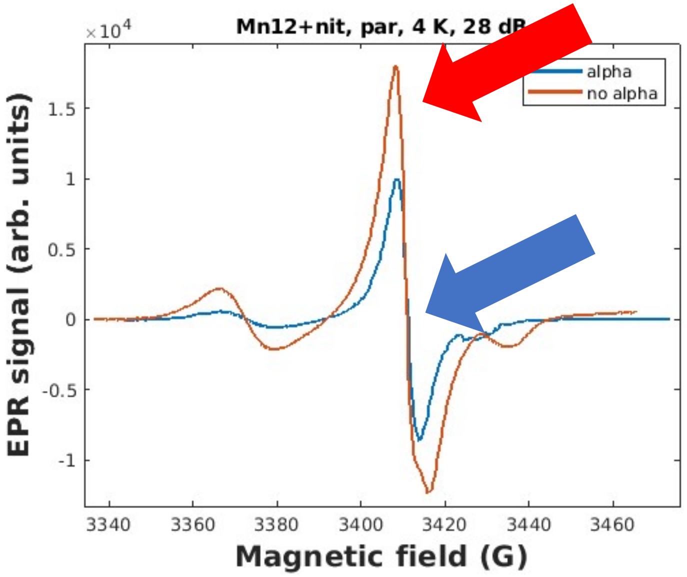




- System at T = 3.9 K, with c//B
- EPR at fixed B fields as a function of time (400 scans with sweep time = 10 s and 8192 points/scan)
- Analysis algorithm to select candidate events (values greater than 5σ w.r.t. noise fluctuations)

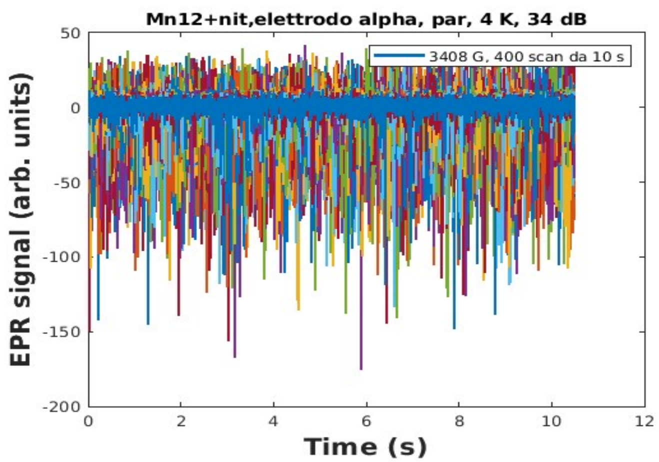
Very symmetric (Gaussian) distributions

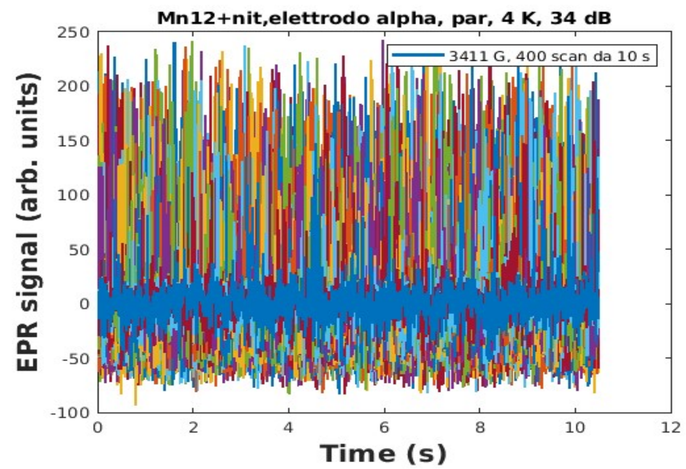
Mn12+Radical: EPR Studies with Particle Radiation



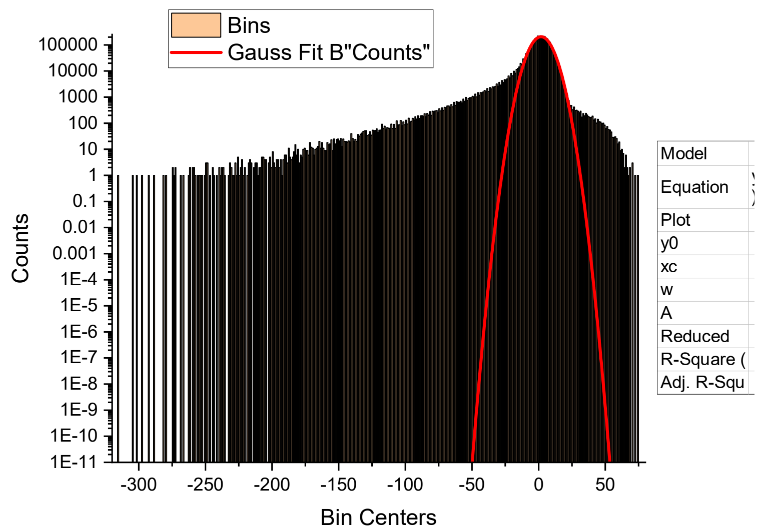
MAX

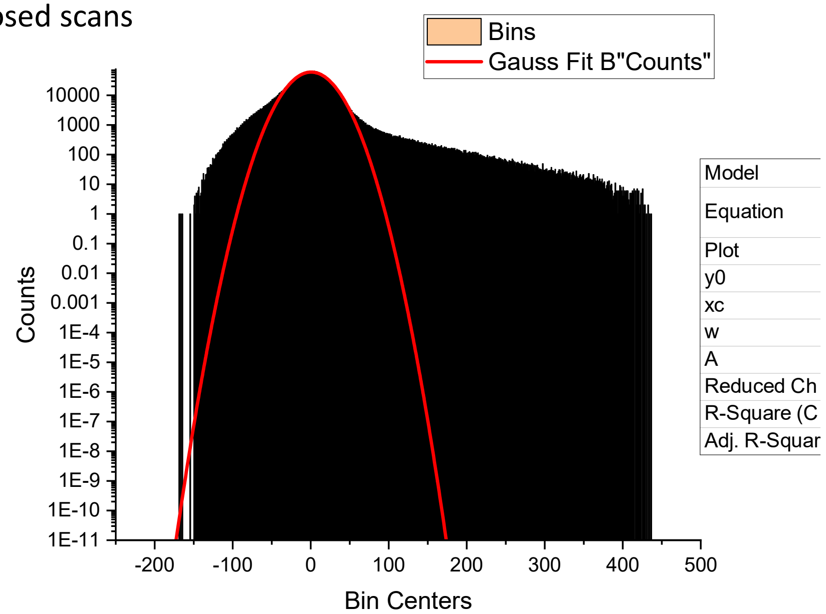
ZERO





400 superimposed scans

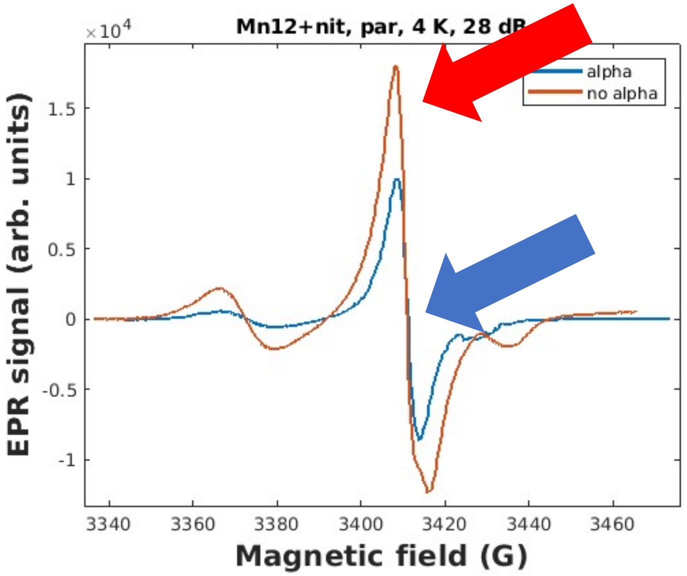




- System at T = 3.9 K, with c//B
- EPR at fixed B fields as a function of time (400 scans with sweep time = 10 s and 8192 points/scan)
- Analysis algorithm to select candidate events (values greater than 5σ w.r.t. noise fluctuations)

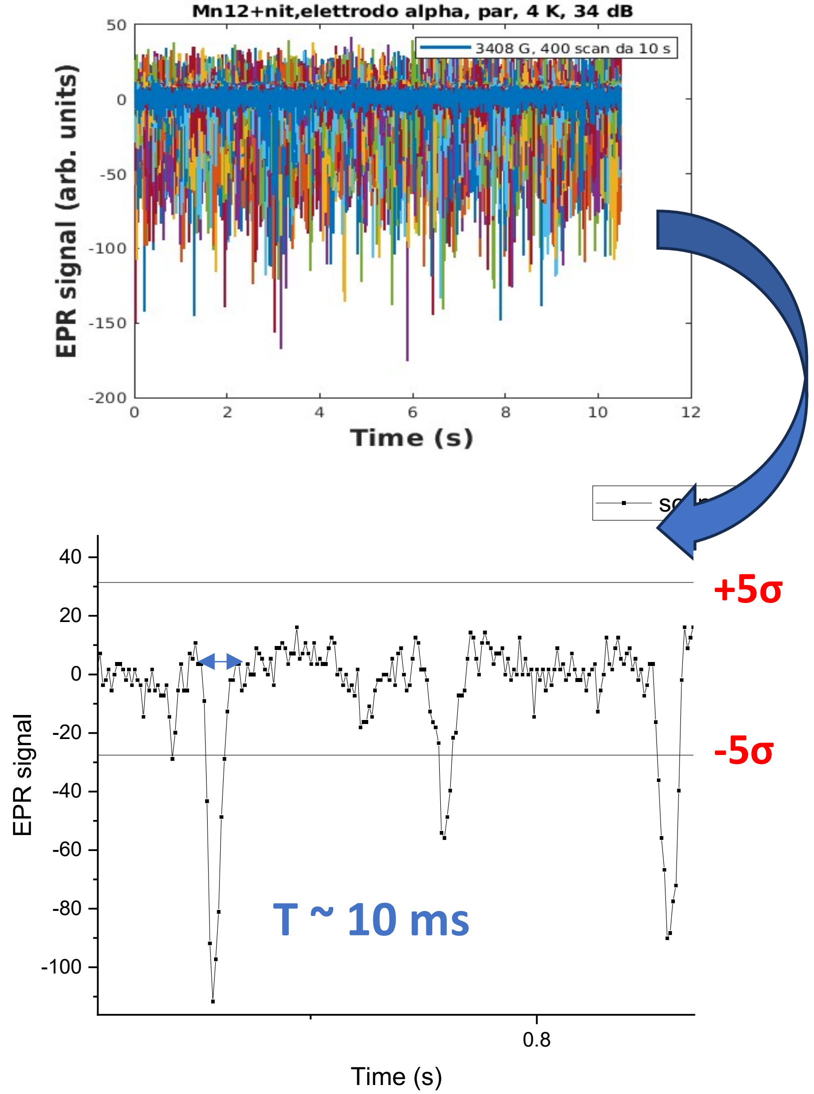
Distributions are no more symmetric: impact of particle radiation ?

Mn12+Radical: EPR Studies with Particle Radiation

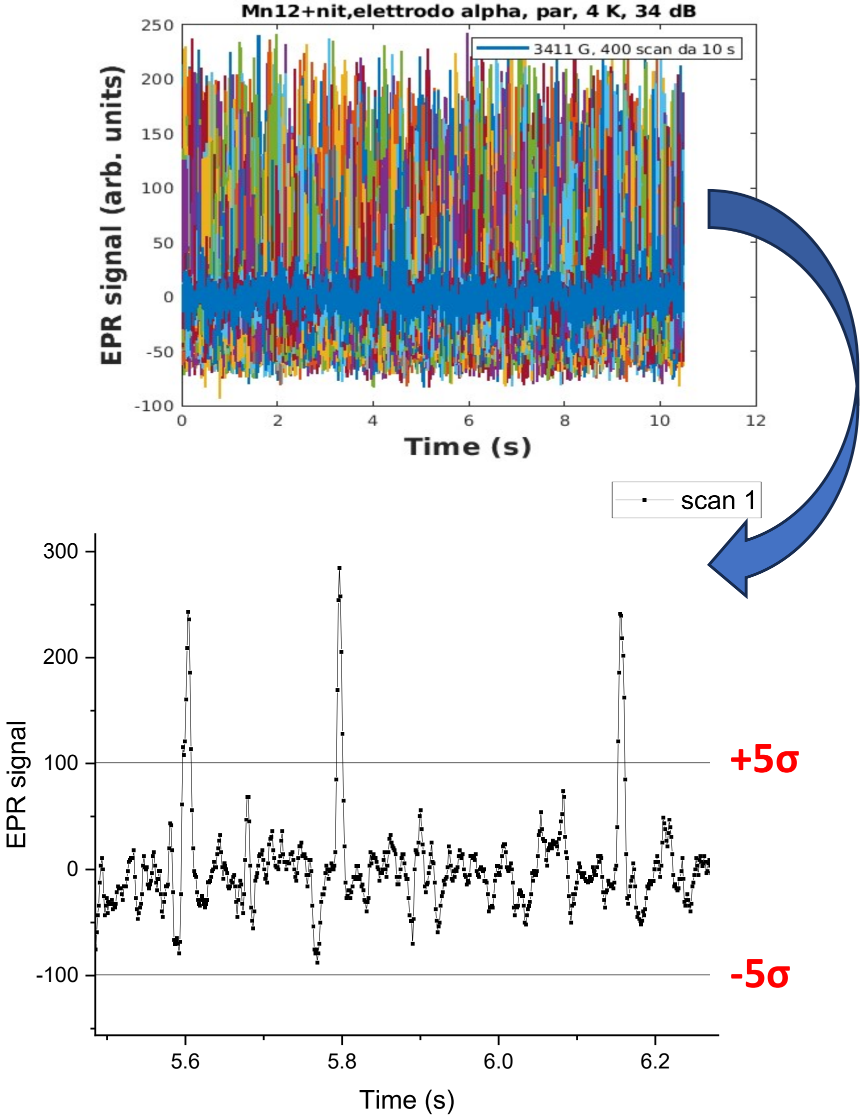


- System at T = 3.9 K, with c//B
- EPR at fixed B fields as a function of time (400 scans with sweep time = 10 s and 8192 points/scan)
- Analysis algorithm to select candidate events (values greater than 5σ w.r.t. noise fluctuations)

MAX



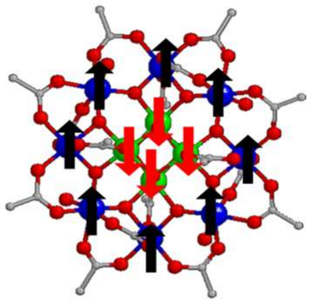
ZERO



When studying single scans we see what look clear signals .....

Summary & Conclusions

- In the search for New Physics M. Proust can be of inspiration for us .....
  "The real voyage of discovery consists not in seeking new landscapes, but in having new eyes." (M. Proust, 'In Search of Lost Time' - Vol. 5).
- The efforts for the development of Quantum Sensing in Particle Physics go in this direction.
- The aim of the NAMASSTE R&D project is to investigate the possibility to use SMMs as quantum sensors.
- The well-known SMM Mn12 is studied under the effect of low activity sources.
- SQUID magnetometry studies do not show systematic effects so far.
- NMR-based studies show a clear reduction in relaxation time of the magnetization.
- EPR-based measurements show clear temporary ($\sim$ 10 ms) changes in the absorption spectrum.
- Further measurements and checks are required to consolidate the results and to search for improvements and/or different sensing conditions.



Mn_{12} core

Conclusions (II): Pros & Cons of QS in Particle Physics

Pros: exploiting the extremely high sensitivity of quantum systems to develop new detection techniques with frontier performance ....

Cons: particle physicists are typically not used to deal directly with intrinsic quantum systems and methodologies, while on the other side physicists experts in quantum technologies and methods are not used to deal with particle physics .....

$\rightarrow$ **A change in paradigm is needed:**

- get more involved in new research fields:

  PP experts should be motivated by potential new very high performance detection technologies

  QT experts should be motivated by additional potential application of QS

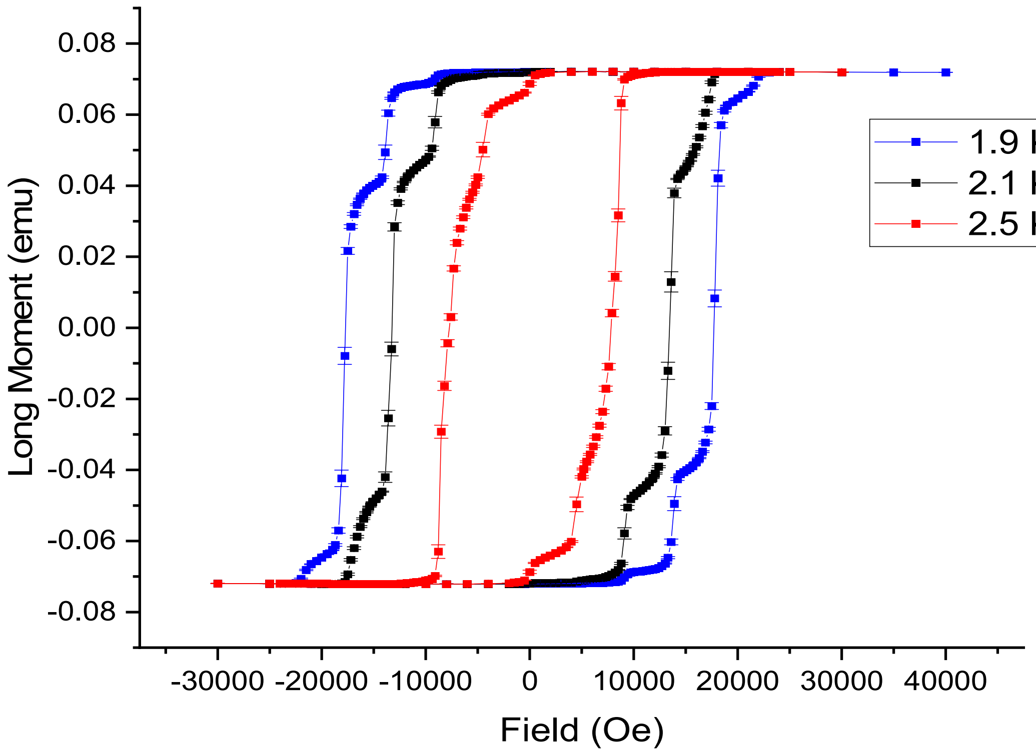
- development of interdisciplinary efforts & projects

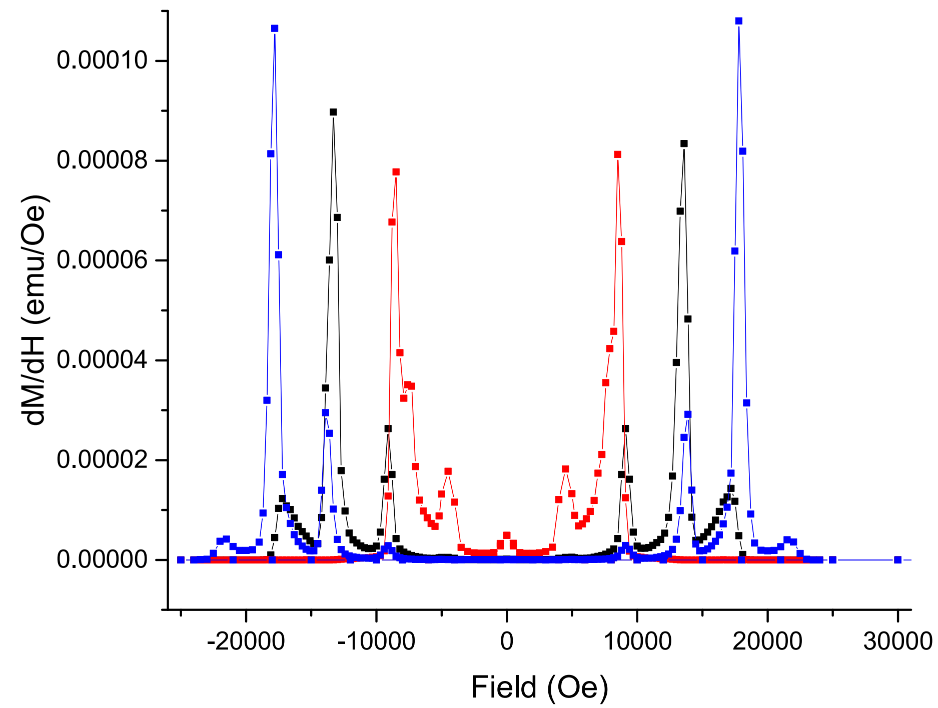
- PP funding Agencies are indeed starting to be more and more interested in that ....

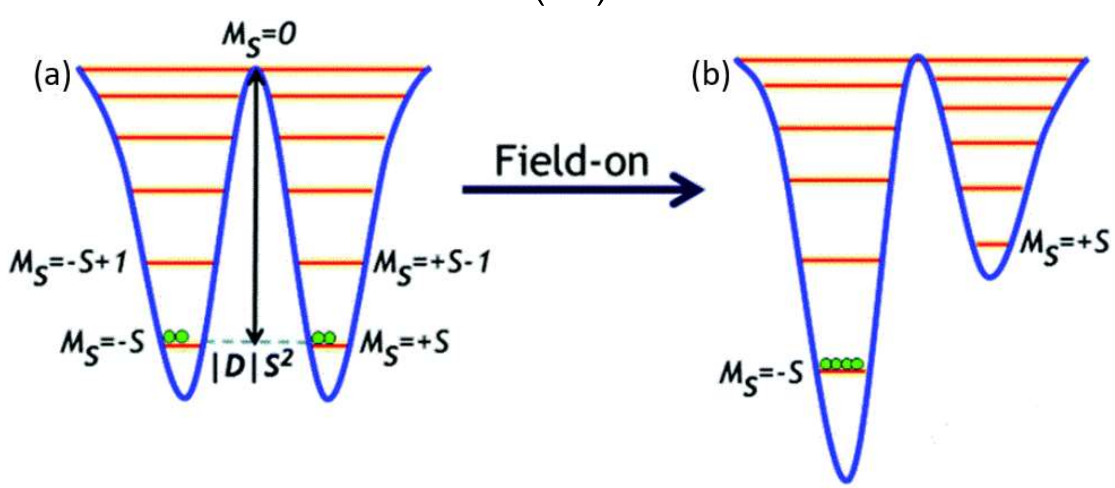
Backup Slides

Macroscopic Quantum Effects in Hysteresis Loops

Hysteresis loops on Mn12 (no α) at various T







1° jump = 0 Oe
2° jump = 5000 Oe
3° jump = 9100 Oe
4° jump = 13900 Oe
5° jump = 17800 Oe
6° jump = 21500 Oe

SQUID Magnetometry Studies on Mn12 (II)

Round - II of SQUID measurements: preliminary studies of relaxation times for the magnetization M

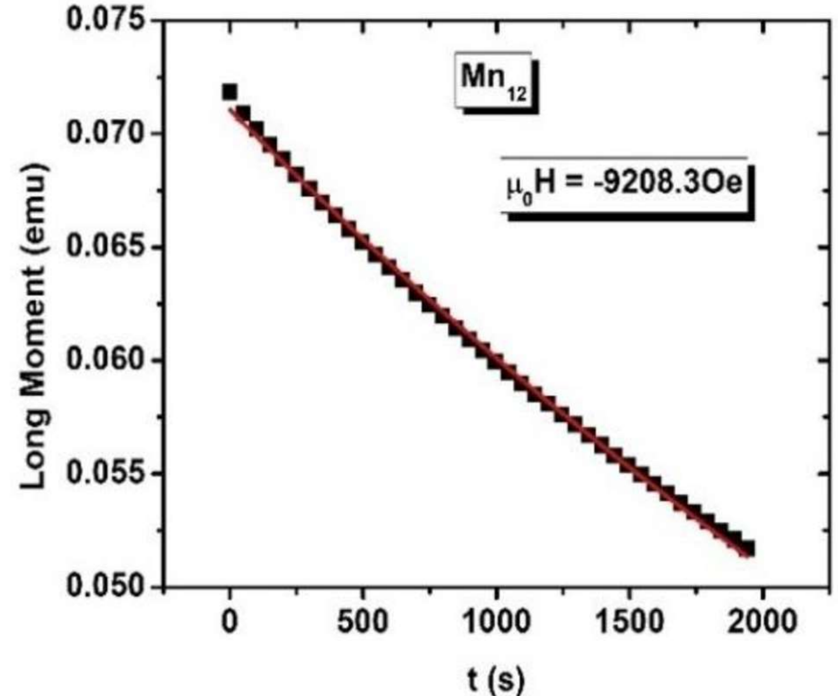
Study of relaxation times at B values around the 3rd "jump" at B ~ -9100 Oe

(T = 1.9 K; before each measurement B is set at 3T, then inverted).

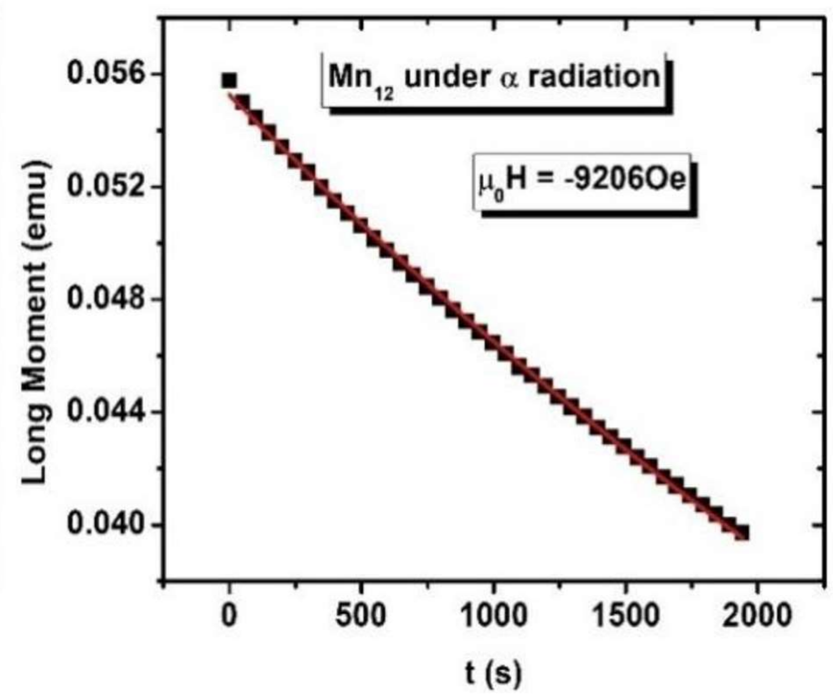
Fit of M vrs t according to:

$$M(t) = M(0)e^{-\frac{t}{\tau}}$$

Mn12 on standard sample holder



Mn2 on emitting electrode



Field (Oe)	Mn_{12} τ(s)	α-irradiated Mn_{12} τ(s)
3	1.16×10^9	0.93×10^9
-8400	9.73×10^4	9.83×10^4
-8800	4.21×10^4	5.21×10^4
-9200	5.97×10^3	5.80×10^3
-9600	2.87×10^4	2.12×10^4
-10000	7.06×10^4	5.31×10^4

- No substantial differences observed, as instead found in preliminary NMR measurements (see next slide).
- No abrupt changes of M observed under α radiation. as reported in literature (but around 2nd jump) [1].

Need to carry out further studies.

[1] Chen *et al.* arXiv:2002.09409v2

Simulation of Radiation-SMM Interaction

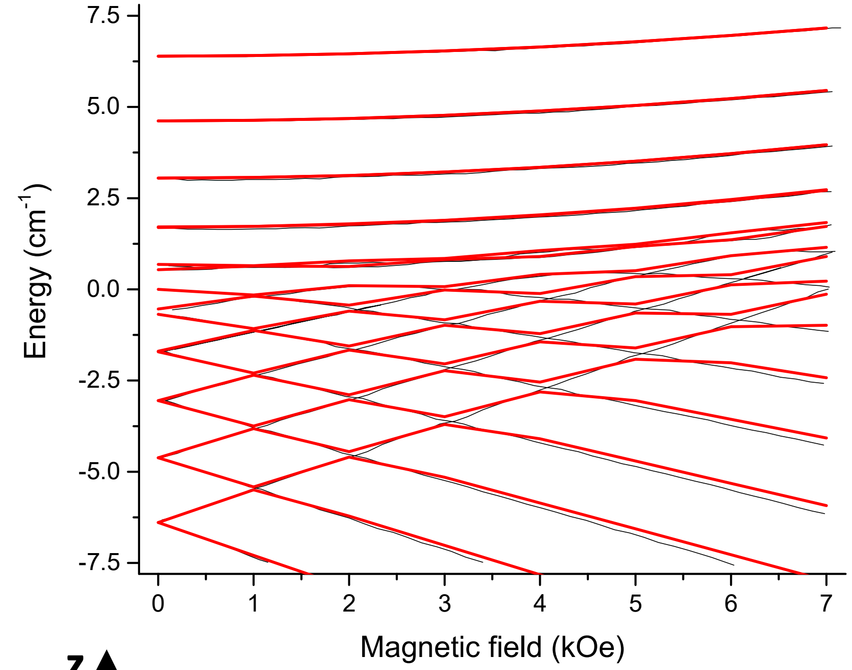
Goal: implement a model for simulating the behavior of SMM under the influence of a specific radiation; of importance for potential future applications, currently absent in the literature.

Development of Fortran program to calculate the energy levels of a classic Hamiltonian which describes the Mn12 SMM in a static magnetic field B.

$$H = H_0 + H_1 \,, \quad \text{with:}$$

“Control” H

$$H_0 = D\left[S_z^2 - \frac{S(S+1)}{3}\right] + g\mu_B \vec{B}\cdot\vec{S} \quad \text{and} \quad H_1 = E(S_x^2 - S_y^2)$$



The program has been tested by comparing its results with those reported in the literature for the same set of parameters as a function of *D*, *E* and *B*

Development in progress: preliminary approach in the simulation of the Mn12-charged particle interaction in terms of magnetic field induced by α or β particle on Mn12 molecule;
→ introduction of a perturbative term in H (time-dependent) related the passage of the particle.