# MAGNET2024

## BOOK OF ABSTRACTS

VIII Italian Conference of Magnetism

7-9 February 2024

Sala Napoleonica dell'Accademia di Brera

Milano - Italy

Istituto Lombardo
Accademia di Scienze e Lettere

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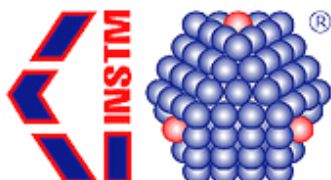delle Ricerche

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- Massimo Solzi (Università di Parma)

- Lorenzo Sorace (Università di Firenze)

- Paola Tiberto (INRiM)

- Gaspare Varvaro (ISM-CNR)

# CONFERENCE PROGRAM
# 7-9 FEBRUARY 2024
# PALAZZO DI BRERA
# MILANO

## Wednesday, February 7th

| | |
|---|---|
| 09:00 | Registration |
| 09:30 | Opening address |

### Keynote Lecture 1 (Chair: Paola Tiberto)

| | |
|---|---|
| 09:45 | **Pasquina Marzola**, Università di Verona<br>*Theranostic Applications of Magnetic Nanoparticles: Where Do We Stand?* |

### Oral Session 1 – Magnetism in Medicine and Biology (Chair: Lucia Del Bianco)

| | |
|---|---|
| 10:15 | **Gabriele Barrera**, INRIM (Torino)<br>*Factors Affecting Magnetic Particle Imaging: Frequency-Sustained Hysteresys and Dipole-Dipole Interactions* |
| 10:30 | **Daniele Marra**, Università di Napoli Federico II<br>*Magnetophoretic Biosensors Based on Core-Satellite Magnetic Particles for Rapid Monitoring of the Mycotoxin Deoxynivalenol (DON)* |
| 10:45 | **Milad Takhsha**, IMEM-CNR (Parma)<br>*Magnetic Shape-Memory Heuslers Turn to Bio* |
| 11:00 | **Luca Pellegrino**, SPIN-CNR (Genova)<br>*A Hybrid Superconductor/Nanomechanical Magnetic Field Detector for Biomagnetism* |
| 11:15 | Coffee Break |

### Oral Session 2 – Nanomagnetism, Nanoparticles and Nanostructures (Chair: Claudio Sangregorio)

| | |
|---|---|
| 11:45 | **Miran Baričić**, ITODYS-CNRS (Paris), Università degli Studi Roma Tre<br>*CoO Nanoaggregates Polyol Synthesis: Tuning Néel Temperature and Clearing the Magnetic Properties from Ambiguities* |
| 12:00 | **Alessio Gabbani**, Università di Firenze, ICCOM-CNR (Firenze)<br>*Magnetoplasmonics beyond Metals: Ultrahigh Sensing Performance in Transparent Conductive Oxide Nanocrystals* |
| 12:15 | **Beatrice Muzzi**, ICCOM-CNR (Firenze), Università di Firenze<br>*Exchange Bias in Metal-Doped Single-phase Ferrites Induced by Defect Engineering of Core@Shell Nanoparticles* |
| 12:30 | Lunch |

# Wednesday, February 7th

**Keynote Lecture 2 (Chair: César De Julián Fernández)**

14:00 | **Nicolò Maccaferri**, Umeå University
*Magnetoplasmonics in Confined Geometries: Current Challenges and Future Opportunities*

**Oral Session 3 – Spintronics
(Chair: Riccardo Bertacco)**

14:30 | **Alberto Brambilla**, Politecnico di Milano
*Hybrid Spinterfaces for Organic Antiferromagnetic Spintronics*

14:45 | **Michaela Kuepferling**, INRIM (Torino)
*Influence of the Spin Hall Angle on the Power Consumption of a SMR Field Sensor*

15:00 | **Roberto Mantovan**, IMM-CNR (Agrate Brianza)
*Spin-Charge conversion in Large-Area Topological Insulators Grown by Metal-Organic Chemical Vapour Deposition*

15:15 | **Vito Puliafito**, Politecnico di Bari
*Oscillator Ising Machines Simulated for Large Max-Cut Problems*

15:30 | Poster Session 1 + Coffee Break

**Oral Session 4 – Molecular Magnetism
(Chair: Ferdinando Borsa)**

16:45 | **Claudio Bonizzoni**, Università di Modena e Reggio Emilia, NANO-CNR (Modena)
*Quantum Sensing of Magnetic Fields with Molecular Spins*

17:00 | **Simone Chicco**, Università di Parma, INSTM (Parma)
*Proof-of-Concept Quantum Simulator Based on Molecular Spin Qudits*

17:15 | **Niccolò Giaconi**, Università di Firenze, INSTM (Firenze)
*Nanostructuring and Spin Selective Electron Transport Properties of Enantiopure Helicenes Monolayer*

17:30 | **Giulia Serrano**, Università di Firenze
*Magnetic Features of Molecules on Superconductors*

17:45 | Gruppo Infrastrutture AIMagn

18:30 | Closing

# Thursday, February 8th

**Plenary Lecture 1 (Chair: Franca Albertini)**

9:00 **Oliver Gutfleisch**, Technische Universität Darmstadt
*The Role of Magnetic Materials in the Energy Transition*

**Oral Session 5 – Thin Films and Magnonics
(Chair: Giovanni Ausanio)**

9:45 **Ilaria Bergenti**, ISMN-CNR (Bologna)
*Tuning the Blocking Temperature of CoO Antiferromagnetic Films with Organic Molecules*

10:00 **Maria Cocconcelli**, Politecnico di Milano
*Biasing Magnonic Devices via Integrated Micro-magnets*

10:15 **Alberto Ghirri**, NANO-CNR (Modena)
*Ultrastrong Magnon-Phonon Coupling in Planar Superconductor-Ferrimagnet Structures*

10:30 **Gianluca Gubbiotti**, IOM-CNR (Perugia)
*Observation of Spin-Wave Moirè Edge and Cavity Modes in Twisted Magnetic Lattices*

10:45 **Federico Motti**, ETH Zürich and Paul Scherrer Institute, Villigen
*Effect of Periodicity on the Magnetic Anisotropy in Spinel Oxide Superlattices*

11:00 Coffee Break

**Keynote Lecture 3 (Chair: Lorenzo Sorace)**

11:30 **Elena Garlatti**, Università di Parma, INSTM & INFN (Parma)
*Molecular Nanomagnets: A Promising Tool for Quantum Information Processing*

**Keynote Lecture 4 (Chair: Lorenzo Sorace)**

14:00 **Luis E. Hueso**, CIC nanoGUNE BRTA (San Sebastian), IKERBASQUE (Bilbao)
*Spin-Orbit Coupling: From Logic Devices to Twisted Layers*

12:30 Lunch

# Thursday, February 8th

**Plenary Lecture 2 (Chair: Gaspare Varvaro)**

14:15 | **Denis Makarov**, Helmoltz-Zentrum Dresden-Rossendorf
*Curvilinear and 3D Magnetism: Current Research and Technology Perspectives*

**Oral Session 6 – Sustainable Magnets, Applications and Superconductivity (Chairs: Attilio Rigamonti and Samuele Sanna)**

15:00 | **Matteo Casadei**, Università di Bologna, IMEM-CNR (Parma)
*Toward Gap Magnets: Ge, Re and Cr Doping in the $Fe_5SiB_2$ Compound*

15:15 | **Sara Laureti**, ISM-CNR, nM[2]-Lab (Roma)
*Interface Control of Co/Ni Synthetic Antiferromagnets Heterostructures on Polymer Tapes: Towards Sustainable Spintronics*

15:30 | **Nicola Pellizzi**, Politecnico di Milano
*Direct Laser Patterning of $Ni_2MnGa$ Films for Magnetocaloric Applications*

15.45 | Poster Session 2 + Coffee Break

17:00 | Assemblea AIMagn

18:30 | Closing

20:15 | Social Dinner
Ristorante "El Brellin", Vicolo dei Lavandai, Alzaia Naviglio Grande, 14 (Milano)
The location is a 6 minutes walk from Porta Genova station of M2 subway (green line)

# Friday, February 9th

### Plenary Lecture 3 (Chair: Roberta Sessoli)

9:00 | **Silvia Picozzi**, SPIN-CNR (Chieti)
*Multiferroicity and Magnetoelectricity in the Flatland*

### Keynote Lecture 5 (Chair: Roberta Sessoli)

9:45 | **Luigi Paolasini**, ESRF (Grenoble)
*Magnetic Diffraction by Polarized X-Rays*

### Oral Session 7 – Fundamental Magnetism and Theoretical Models (Chair: Carlo Gatti)

10:15 | **Alessandro De Vita**, IOM-CNR, Università di Milano, Fritz Habel Institute
*Relevance of Thermal Fluctuations in Fe(100)-p(1x1)O in Optically-Induced Ultrafast Demagnetization*

10:30 | **Samuele Sanna**, Università di Bologna
*Entangled Spin-Orbital Jahn-Teller Bipolaron in the Electron-Doped $Ba_2Na_{1-x}Ca_xOsO_6$ Dirac-Motton Insulator*

10:45 | **Jakob Baumsteiger**, University of Vienna, Università di Bologna
*Exploring Noncollinear Magnetic Energy Landscapes with Bayesian Optimization*

11:00 | **Alessandro Chiesa**, Università di Parma
*Chirality-Induced Spin Selectivity in Electron Donor-Acceptor Molecules: A Resource for Quantum Technologies*

11:15 | Coffee Break

### Oral Session 8 – Magnetic Materials and their Applications (Chair: Davide Peddis)

11:45 | **Pierfrancesco Maltoni**, Uppsala University
*From Ferrite Nanostructures to Sintered Dense Permanent Magnets*

12:00 | **Federico Maspero**, Politecnico di Milano
*Optimization and Patterning of Sm-Co Thick Films for the Integration in MEMS Devices*

12:15 | **Federico Spizzo**, Università di Ferrara and INFN Ferrara
*Functionalization of Spider Silk Threads with Magnetorestrictive FeCo Coating*

12:30 | Prizes

13:00 | Closing Remarks

# PLENARY LECTURES

## SPEAKERS

- Oliver Gutfleisch
- Denis Makarov
- Silvia Picozzi

## CHAIRS

- Franca Albertini
- Gaspare Varvaro
- Roberta Sessoli

# The role of magnetic materials in the energy transition

## Oliver Gutfleisch

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Magnets are key enablers for the green energy transition. High performance hard and soft magnets are crucial components of energy-related technologies, such as direct drive wind turbines and e-mobility. They are also important in robotics and automatization, sensors, actuators, and information technology. The magnetocaloric effect (MCE) is the key for new and disruptive solid state-based refrigeration. The rare earth elements (REEs), an important class of the critical raw materials (CRMs), are essential constituents of the highest performing magnets and are highlighted in the raw and advanced materials flow essential for (EU) Industrial Ecosystems and a net zero emission scenario.

Important questions arise around the different mitigation scenarios addressing the criticality of REEs; they are classified as strategic elements and there are many bottlenecks along the supply and value chain. Supply deficits will endanger the development of technologies which abate the climate change and will also impact on other strategic sectors. This supply chain has to be secure, affordable and sustainable and in order to achieve this, we need the diversification of primary CRMs, material science and process solutions for new efficient alloy and microstructure design, substitutional materials and effective short and long loop recycling routes.

## References

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# Curvilinear and 3D Magnetism: Current Research and Technology Perspectives

**Denys Makarov**

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Extending 2D structures into 3D space has become a general trend in multiple disciplines, including electronics, photonics, plasmonics, superconductivity and magnetism [1,2]. This approach provides means to modify conventional or to launch novel functionalities by tailoring curvature and 3D shape of magnetic thin films and nanowires [2,3]. In this talk, we will address fundamentals of curvature-induced effects in magnetism and review the envisioned application scenarios. In particular, we will demonstrate that curvature allows tailoring fundamental anisotropic and chiral magnetic interactions [4] and enables fundamentally new non-local chiral symmetry breaking effect [5,6]. Application potential of geometrically curved magnetic architectures is currently being explored as mechanically reshapeable magnetic field sensors for automotive applications, memory, spin-wave filters, high-speed racetrack memory devices, magnetic soft robotics [7] as well as on-skin interactive electronics relying on thin films [8,9,10] as well as printed magnetic composites [11,12] with appealing self-healing performance [13].

**References**
[1] P. Gentile et al., *Nature Electronics (Review)* **5** (2022), 551.
[2] D. Makarov et al., *Advanced Materials (Review)* **34** (2022), 2101758
[3] D. Makarov et al., Curvilinear micromagnetism: from fundamentals to applications (Springer, Zurich, 2022).
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[12] E. S. Oliveros Mata et al., *Adv. Mater. Technol.* **7** (2022), 2200227
[13] R. Xu et al., *Nature Communications* **13** (2022), 6587

# Multiferroicity and Magnetoelectricity in the Flatland

**Silvia Picozzi**

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Multiferroicity and magnetoelectricity (i.e. the coexistence and coupling between long-range magnetic and electric dipolar order) constitute two related landmark phenomena in quantum physics, where profound fundamental aspects (i.e. microscopic interactions between charge and spin degrees of freedom) are intimately related to technological milestones (multifunctional devices tuned by electric/magnetic fields). In this context, the reduction of dimensionality from 3D to 2D has been boosted by the recent discoveries of multiferroicity in $NiI_2$ layers [1], obtained via a joint theory-experiments approach down to the single-layer limit. I will show several examples of first-principles modelling for multiferroic and magnetoelectric 2D-materials, including vanadium dihalide-monolayers (featuring 120-degree frustrated magnetic structures, which develop on the underlying triangular lattice and induce ferroelectric polarization) and domain walls in $CrI_3$ layers (where ferroelectric polarization can be induced in both Néel- and Bloch-types), highlighting the potentiality of cross-coupling phenomena in van der Waals materials.

**References**

[1]  Song Q., Occhialini C.A., Ergecen E., Ilyas B., Amoroso D., Barone P., Kapeghian J., Watanabe K., Taniguchi T., Botana A., Picozzi S., Gedik N., Comin R., *Evidence for a single-layer van der Waals multiferroic*, Nature **602** (2022), 601.

# KEYNOTE LECTURES

## SPEAKERS

- Pasquina Marzola
- Nicolò Maccaferri
- Elena Garlatti
- Luis E. Hueso
- Luigi Paolasini

## CHAIRS

- Paola Tiberto
- César De Julián Fernández
- Lorenzo Sorace
- Roberta Sessoli

# Theranostic applications of magnetic nanoparticles: where do we stand

**Pasquina Marzola[1]**

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Magnetic nanoparticles are composed of magnetic materials such as iron oxide, often coated with biocompatible agents. These nanoparticles can be composed of various magnetic materials, such as iron, nickel, cobalt, or alloys of these elements. Due to their nanometric dimensions, magnetic nanoparticles can exhibit behaviors and properties that are unique compared to their larger-sized counterparts. Magnetic nanoparticles are widely used in various fields, including medical applications, electronics, information storage, magnetic separation, magnetic therapy, and other sectors of scientific and technological research. This contribution will be focused in the field of medicine, where they are used in both diagnosis and therapy.

Starting from the mid-1990s, several iron-oxide Magnetic Nanoparticles (NPs) were developed as MRI contrast agents. Though an unfavorable cost/benefit ratio has led to their withdrawal from the market as simple diagnostic agents, innovative applications have recently prompted a renewal of interest in these NPs.

Nowadays, magnetic NPs are regarded as valuable diagnostic and therapeutic tools. In the field of cell therapies, for example, they allow labeling and in vivo tracking of cells, as for example stem cells (1) or exosomes (2), transplanted in living organisms. In the field of cancer immunotherapy, they allow noninvasive monitoring of immune response in tumor tissue and at the same time, they can alter macrophage polarization, so producing a therapeutic effect. In addition, they can be agents for magnetic fluid hyperthermia (3,4). Magnetic NPs are applied also as drug delivery systems, since they are deliverable to the target tissue by using magnetic gradient actuation forces. Studies have also demonstrated an increased sensitivity to radiotherapy of tumor cells targeted with magnetic nanoparticles. Moreover, magnetic nanoparticles are detectable in an innovative tomographic diagnostic imaging modality, namely Magnetic Particle Imaging (MPI) and are therefore multimodal contrast agents for MRI and MPI.

In this contribution, taking a cue from the research performed in our laboratory, I will present current preclinical/clinical applications of magnetic NPs, as well as emerging trends, in the study and application of these materials.

**References**
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# Magnetoplasmonics in confined geometries: current challenges and future opportunities

**Nicolò Maccaferri**

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Plasmonics represents a unique approach to confine and enhance electromagnetic radiation well below the diffraction limit, bringing a huge potential for novel applications, for instance in optoelectronics, sensing, photocatalysis and information storage and processing[1]. To achieve novel functionalities, the combination of plasmonic properties with other material functions has become increasingly attractive. In this Keynote Talk, I will give an overview on the current state of the art, challenges, and future opportunities within the field of magnetoplasmonics in confined geometries, an emerging area aiming to merge magnetism and plasmonics to either control localized plasmons, confined electromagnetic-induced collective electronic excitations, using magnetic properties, or vice versa[2]. I will begin by highlighting the cornerstones of the history and principles of this research field, by focusing on the use of localized surface plasmons to enhance magneto-optical effects in metallic systems, in the framework of active flat-optics metamaterials for light polarization control as well as for biochemical sensing. I will then try to provide a roadmap of its future development by showcasing raising research directions in hybrid magnetoplasmonic systems to overcome radiation losses and novel materials for magnetoplasmonics, such as transparent conductive oxides and hyperbolic metamaterials[3,4]. Finally, I will provide an overview of recent developments in plasmon-driven magnetization dynamics, nanoscale opto-magnetism and acousto-magnetoplasmonics. I will conclude by showcasing new possible directions to achieve a full control of magneto-optical effects and their enhancement by using nanoscale materials, as well as drive magnetic phenomena with plasmons at the atomic and sub-fs scales.
 (grant n. 964363 'ProID').

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## Acknowledgements

# Molecular Nanomagnets: a promising tool for quantum information processing

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The potential to solve problems with large impact on science, society and economy makes the realization of quantum computers one of the hottest topics in current research. Molecular nanomagnets (MNMs) offer a promising route towards a scalable quantum computer [1]. Being controllable quantum objects, they have in fact attracted a considerable attention as molecular qubits, thanks to their highly engineerable spin Hamiltonians and long coherence times. In addition, the feature that makes them potentially disruptive for quantum technologies is that they naturally provide a multi-level energy spectrum, which can be exploited to encode qudits and thus increase the power of quantum logic applications. In particular, MNMs can be exploited to define qubits with embedded QEC in single molecules [2], thus circumventing the large overhead in the number of physical units required by standard QEC codes.

I will review some recent works on molecular qudits/qubits. I will discuss some recent results on the study of the main sources of decoherence in MNMs, focusing on interactions with phonons [3]. In particular, experimental investigations of phonons in MNMs has been undertaken only very recently and I will show that a powerful technique for these investigation is Inelastic X-ray Scattering (see Fig.1) [3]. We have also demonstrated that elementary operations of quantum algorithms can be efficiently implemented on the nuclear spin qudit of MNMs, by coherently manipulating the nuclear spin states by resonant radio-frequency pulses [4]. I will show that with an ensemble of molecular qudits and a radiofrequency broadband spectrometer we have realized the first working proof-of-concept quantum simulator [5].
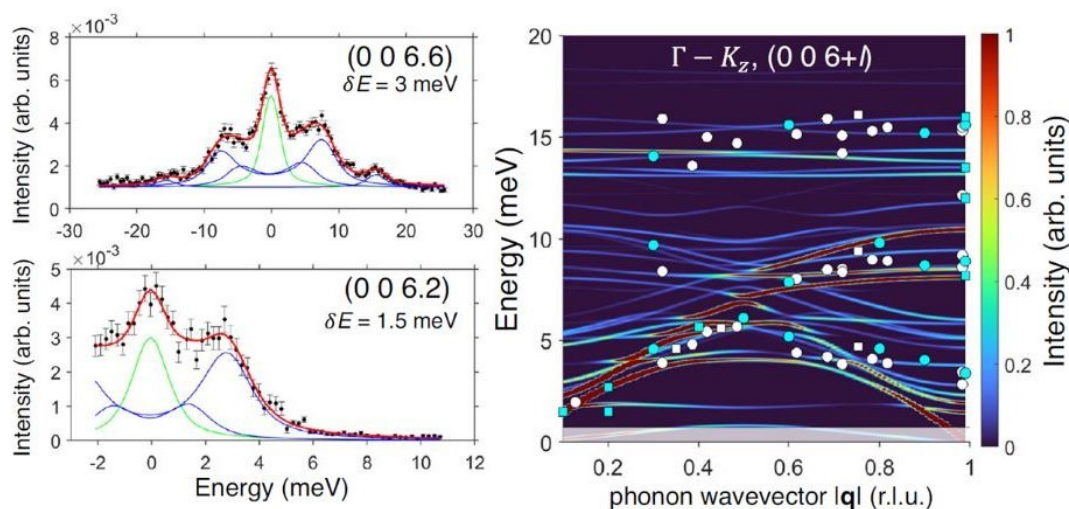


**Fig. 1** Inelastic X-ray scattering data from ID28@ESRF on the molecular qubit [VO(TPP)]. Adapted with permission from Ref.[3], under a Creative Commons Attribution 4.0 International License.

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# Spin-orbit coupling: from logic devices to twisted layers

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Spin-orbit coupling is a key ingredient in current and emerging spintronic technologies, from spin-orbit torque memories to the recent MESO proposal by Intel, which aims to integrate logic and memory in spin-based circuits.

In this talk, I will present two examples of the role of spin-orbit coupling and spin-to-charge conversion in devices, ranging from applied technology to basic science.

In the first part of the talk, I will present the status of the experimental realization of the MESO proposal, focusing particularly on the readout of the spin memory state [1-4].

In the second part of the talk, I will show how twisted, low symmetry, graphene/chalcogenide structures display a complex spin texture and charge-to-spin conversion effects that could allow us to move beyond devices with standard metallic layers [5-14].

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# Magnetic Diffraction by Polarized X-Rays

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Neutron and X-ray magnetic scattering are the unique methods to extract complementary information of the ordered magnetic structures and their relations with the crystal symmetries at the atomic level.

X-ray magnetic scattering takes advantage of the characteristic properties of hard X-ray beams at third generation synchrotron radiation facilities: tunable photon energy, controllable polarisation and polarisation analysis, excellent stability and emittance.

The relevant scattering methods can be summarized in the following:

In Non-Resonant X-ray Magnetic Scattering regime (NRXMS) the incident photon energy is tuned far from the absorption edges. The magnetic scattering amplitudes are directly related to the spin and orbital magnetic momentum and have a peculiar X-rays polarisation dependence which can be exploited to determine the magnetic structure of materials into the ordered states [1].

Resonant Elastic X-ray Scattering (REXS) is a method which uses the photon beam as a quantum probe to investigate structural, magnetic and electronic long range ordering in solids. The tensorial character of atomic scattering amplitudes can break the conventional extinction rules for forbidden Bragg reflections related to the glide planes and/or screw axis symmetries. As a result, from the analysis of the resonant reflections by polarised X-rays tuned across an absorption edge, we obtain information about the anisotropic part of the electronic and magnetic density of states, projected on the resonant atom, and to their structural order.

A quantitative measurement of the anisotropies in spin and orbital degrees of freedom of electrons in solids is provided by the atomic and crystal multipoles, that, due to their tensorial character and peculiar coupling with the x-ray polarisation, can be directly measured and disentangled by an appropriate choice of the experimental setup (azimuthal and polarisation dependence of incoming and scattered X-rays) [2].

The aim of this lecture is to give a brief historical description of the development of theoretical concepts and experimental work in the last two decades of the twentieth century and the first decade of the twenty-first century. The basic theoretical formulae are provided with the main information about their origin and a necessary link to the original literature in order to analyze the scattering cross sections in more depth.

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# ORAL SESSION 1
# MAGNETISM IN MEDICINE AND BIOLOGY

**CHAIR**

• Lucia Del Bianco

**SPEAKERS**

• Gabriele Barrera
• Daniele Marra
• Milad Takhsha
• Luca Pellegrino

# Factors affecting Magnetic Particle Imaging: Frequency-sustained Hysteresis and Dipole-dipole Interactions

**Gabriele Barrera[1], Paolo Allia[1], Paola Tiberto[1]**

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Magnetic particle imaging (MPI) is a radiation-free, non-invasive tomographic technique with highly promising applications in diagnostic imaging [1]. MPI is based on detecting the third harmonic of the $M(t)$ waveform resulting from magnetic tracers (i.e. magnetic nanoparticles) accumulated in a target tissue and submitted to a radiofrequency field.

In this work, we thoroughly investigate by a suitable magnetic model [2] how the presence of frequency-sustained hysteresis and dipole-dipole interaction among magnetic nanoparticles affect the MPI technique.

The model solution provides the overall magnetization of an assembly of nanoparticles with random anisotropy easy axes as a function of both intrinsic (i.e. size, magnetization saturation and effective anisotropy values of the MNPs, etc.) and extrinsic (amplitude and frequency of the magnetic field, temperature, degree of magnetic interaction, etc.) parameters.

The proposed magnetic model is used to describe the frequency-sustained hysteresis which appears even in nanoparticles that are superparamagnetic in quasi-static conditions. Neglecting these hysteretic properties of magnetic tracers for MPI can lead to inadequate modelling of their magnetic response and, therefore, an incorrect evaluation of the real and imaginary component of the third harmonic of magnetization ($M_3$). In particular, the frequency-sustained hysteresis affect the so-called System Function (SF), Fig. 1a, which is the core of the MPI image reconstruction.

It is shown that the SF critically depends on the actual magnetic behavior of tracers at the driving-field frequency, pointing out the importance of carefully characterizing the magnetic nanoparticles at the operating frequency in order to guarantee the optimal efficiency of a MPI setup.

Specific examples of MPI image reconstruction with both monodisperse (Fig. 1b) and polydisperse nanoparticles demonstrate that disregarding frequency-supported hysteresis has detrimental consequences on quantitative MPI. In addition, the role played in MPI image reconstruction by magnetic dipolar interaction, no longer negligible when nanoparticles accumulate in a small volume of the tissue, is also discussed [3,4].
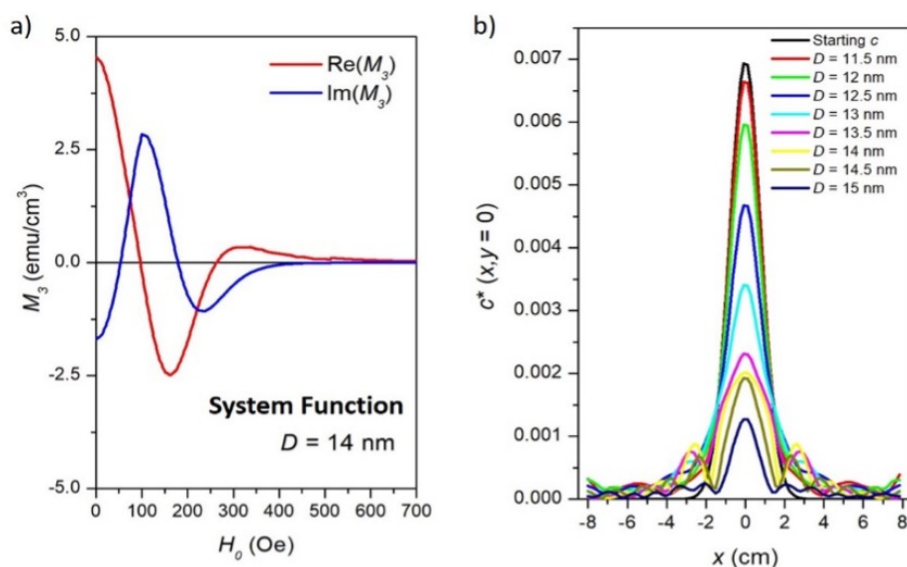


**Fig. 1** a) Real and imaginary parts of the third harmonic of the cyclic magnetization (M3) as functions of the bias field H0 (i.e. system function) for nanoparticles (D = 14 nm) at H = 100 Oe and f = 25 kHz; b) profile of starting and MPI-reconstructed nanoparticle distributions along the x axis, for different diameters of nanoparticles with frequency-sustained hysteresis.

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# Magnetophoretic Biosensor Based on Core-Satellite Magnetic Particles for Rapid Monitoring of the Mycotoxin Deoxynivalenol (DON)

**Daniele Marra[1], Nikola Sakač[2], Bojan Šarkanj[3], Maria De Luca[1], Bartolomeo Della Ventura[1], Raffaele Velotta[1] and Vincenzo Iannotti[1,4]**

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Deoxynivalenol (DON) is a toxic secondary metabolite produced by Fusarium fungi, contaminating crops worldwide and posing significant concerns for human and animal health, as well as the food economy [1]. DON adversely effects animal immune systems, alters cell morphology and function, and induce cytotoxicity and metabolic changes through oxidative stress [2]. The complete degradation of DON from grains remains a challenge, necessitating comprehensive food safety monitoring. Traditional DON monitoring techniques, such as ELISA. are expensive, time-consuming, and require specialized personnel.

Our approach involves the use of core-satellite magnetic particles coated with gold nanoparticles (CSMPs), enhancing their biocompatibility and suitability for anchoring antibodies against DON [3]. We leverage magnetophoresis. a technique where magnetic particles move in a magnetic field gradient [4].

Magnetophoresis is widely used in various research areas to separate and isolation biological materials from complex mixtures, including proteins, cells, and biomolecules. We aim to exploit specific aggregate formation in the presence of varying analyte concentrations, which act as linkers. Increased aggregate formation leads to faster separation in the solution, resulting in a rapid increase in % transmittance over time.
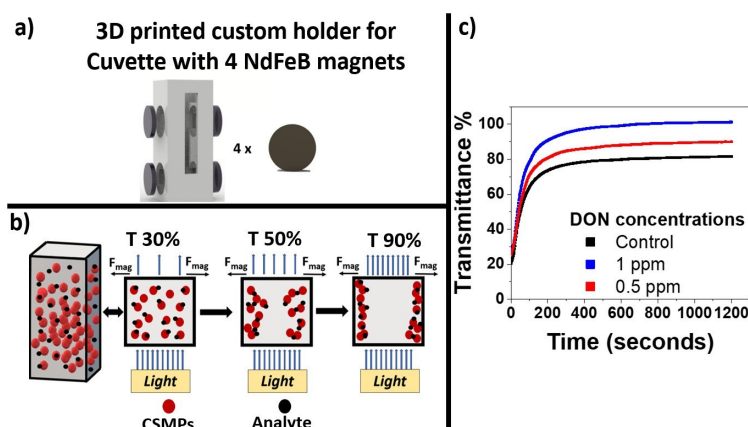


**Fig. 1** Operating principle of the sensor: (a) The cuvette is placed inside a spectrophotometer in a 3D printed holder containing 4 NdFeB magnets. (b) The functionalized nanoparticles in solution bind the analyte and utilize it to form aggregates, which will migrate toward the magnets, causing an increase in the solution's transmittance % over time. (c) Transmittance kinetic curves obtained by measuring different analyte concentrations.

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# Magnetic Shape-Memory Heuslers Turn to Bio

**Milad Takhsha[1], Franco Furlani[2], Silvia Panseri[2], Francesca Casoli[1], Vojtěch Uhlíř[3,4], Franca Albertini[1]**

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Magnetic-shape-memory Heusler (MSM) compounds are among the most important classes of materials for multiple-stimuli actuation and multicaloric applications, showing in addition promising multifunctional properties for energy harvesting, and spintronics. This multifunctionality stems from a reversible martensitic phase transformation. These materials have been considered in many studies for technological applications but have been rarely investigated for medical purposes, albeit – at least in theory – they could have promising applications in medical fields similar to the conventional shape-memory alloys [1] (*e.g.* Nitinol).

Thin films, coating layers and micro/nanostructures open up a perspective towards new-concept applications, taking also the advantage of microstructure tunability and possibility of integration into microsystems. Over the past years, we have comprehensively investigated the structure, microstructure, magnetic properties, down-scaling processes and the effects of different external stimuli on the martensitic transformation of Ni-Mn-Ga epitaxial thin films [2,3 and references therein].

In this study, we have taken the advantage of our strong background in the topic of "MSM Heuslers" and reported the biomedical perspective for these types of materials highlighting the most interesting functionalities of MSM Heuslers, which can be exploited towards the potential biomedical devices or therapies. Among the critical steps towards the realization of medical applications for MSM Heuslers is the evaluation of cytotoxicity. We report the cytocompatibility and cell morphology analysis of human fibroblast cells cultivated on Ni-Mn-Ga epitaxial thin films by *in vitro* biological tests. The samples have been also characterized looking at the morphology, microstructure, and magnetic properties by microscopic analysis, thermomagnetic and magnetization curves upon applying external magnetic fields. Our qualitative and quantitative biological characterizations reveal that Ni-Mn-Ga films are able to promote the adhesion and proliferation of human fibroblasts without eliciting any cytotoxic effect. Additionally, our findings have shown that the morphology, composition, microstructure, phase transformation and magnetic characteristics of the films are well preserved after the biological treatments (Fig.1).
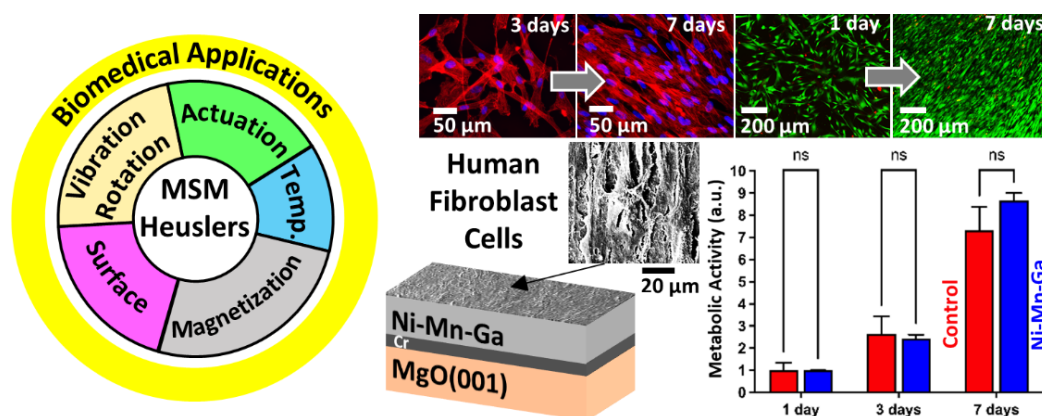


**Fig. 1** Biomedical perspective for MSM Heuslers, cytocompatibility and cell morphology analysis of human fibroblast cells cultivated on Ni-Mn-Ga epitaxial thin films.

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# A Hybrid Superconductor/Nanomechanical Magnetic Field Detector for Biomagnetism

**Luca Pellegrino[1,*], Nicola Manca[1], Alejandro Plaza[1], Leonélio Cichetto[1], Daniele Marré[2,1], Federico Maspero[3,4], Simone Cuccurullo[4], Riccardo Bertacco[3,4], Eric Wahlberg[5], Alexei Kalaboukhov[5], Floriana Lombardi[5], Torben Hänke[6], Dhavalkumar Mungpara[6], Alexander Schwarz[6], Ingo Hilschenz[7], Enrico Ragucci[7], Sara Spadone[7], Warner Venstra[8], Stefania Della Penna[7]**

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Current commercial setups for magnetoencephalography (MEG) use helmets comprising low Tc SQUIDs. SQUID sensors are barely robust to static and pulsed magnetic fields, such as the ones used in Ultra-Low Field Magnetic Resonance Imaging (MRI) and especially Transcranial Magnetic Stimulation (TMS). For this reason, integration of MEG with these techniques in a unique system at present has not yet been achieved. Our purpose is to develop a magnetic field sensor with sensitivity of the order of 10fT/sqrt(Hz) to measure the magnetic field of the human brain and at the same time quickly recovering in a strong applied field (» 1 T). This sensor would be suitable for an on-scalp MEG system integrated with multiple imaging modalities to image brain activity and connectivity with high spatial and temporal resolution. We are developing a hybrid device by coupling a high-Q MEMS/NEMS resonator having a magnetic element to a high-Tc superconducting magnetic field focuser in series to a pick-up loop that collects the external magnetic field. The biomagnetic field induces a supercurrent in the loop, which has a geometry designed to generate a strong non-uniform magnetic field in the proximity of the magnetic element of the NEMS resonator (fig.1) [1]. The resonance frequency of the resonator is modified by this magnetic coupling and detected by a fiber-optic interferometer. Optomechanical detection of biomagnetic fields has the advantage of reducing the crosstalk between the channels with respect to electrical detection. This feature requires the development of a cheap, robust and scalable optomechanical platform for a future NEMS-based helmet. We discuss the basic working principle of this hybrid sensor and the advancements made so far for the realization and characterization of the first device prototypes as well for the realization of the optomechanical platform that will host the first magnetometer to be characterized in operative environment.

$$\frac{\Delta f}{f} \propto \left( M_x \frac{\partial^2 H_x}{\partial z^2} + M_y \frac{\partial^2 H_y}{\partial z^2} + M_z \frac{\partial^2 H_z}{\partial z^2} \right)$$
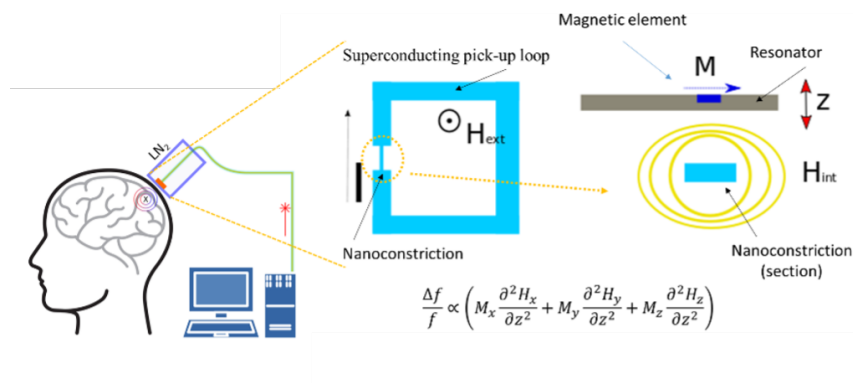
**Fig. 1** The principle of the OXiNEMS hybrid magnetometer.

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# ORAL SESSION 2
# NANOMAGNETISM, NANOPARTICLES AND NANOSTRUCTURES

**CHAIR**

- Claudio Sangregorio

**SPEAKERS**

- Miran Baričić
- Alessio Gabbani
- Beatrice Muzzi

# CoO nanoaggregates polyol synthesis: tuning Néel Temperature and clearing the magnetic properties from ambiguities.

**Miran Baričić**[1,5], **David Hrabovsky**[2], **Jorge Martin Nuñez**[3,4], **Miriam Aguirre**[4], **Souad Ammar-Merah**[1], **Carlo Meneghini**[5], **Davide Peddis**[6,7]

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Transition metal oxides (TMO) form an important class of functional materials. In the form of nanoparticles (NPs), their size distribution and aggregation state exert an strong influence on their magnetic properties [1] and, consequently, their potential applications. Although various common synthesis methods exist, colloidal chemistry routes are the most appropriate when for having control on the NPs morphology, due to the possibility to strictly control their nucleation and growth, occasionally leading to interesting phenomena, such as oriented aggregation of nanocrystals to form meso-crystals [2],[3]. Modifying the synthesis to obtain different morphologies is an interesting perspective from the point of view of magnetic properties. In this context, the growth of CoO NPs in polyol was studied focusing on the polyol chain length [4] and on the effect water quantity on the morphology of the resulting NPs. This enabled the easy adjustment of NPs' aggregate size (from ~ 20 to ~ 150 nm), shape (octahedra, octahedral aggregates, and spherical/spheroidal aggregates) and crystalline size (~ 8 to ~ 26 nm).

The crystalline size of the aggregates was found to have a regular influence on CoO's Néel temperature, thus providing an easy way to regulate it over ~ 80 K (Fig. 1). Further, some samples were found to have markedly lower $T_N$ respect to what expected from their size, suggesting new degrees of freedom with which this feature can be adjusted. Finally, the formation of layered structures [5] was found to be a possible interference in the interpretation of CoO's magnetic properties, and signs of this kind of misinterpretation were found in several papers [6],[7]. Proper synthetic conditions to avoid the interference were found. SQUID DC-Magnetometry, HR-TEM, EXAFS and routinary materials characterizations were performed in our studies.
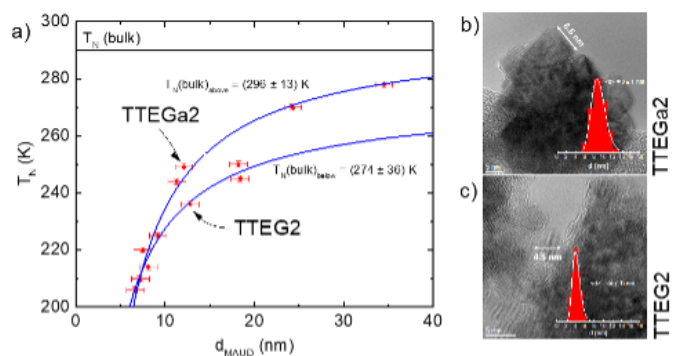


**Fig.1** a) TN vs crystallite diameter, HR-TEM pictures of b) TTEGa2 and c) TTEG2, size distribution in the inset.

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# Magnetoplasmonics beyond Metals: Ultrahigh Sensing Performance in Transparent Conductive Oxide Nanocrystals

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The excitation of free charge carriers in plasmonic nanomaterials allows the manipulation of light at the nanoscale. Tuning plasmonics with an external stimulus, i.e., active plasmonics, could provide a superior control on light-matter interaction, triggering the development of high-performance nano-optical components such as refractometric sensors or tuneable meta-lenses. To this aim the use of a magnetic field represents a promising approach, as its action on charge carriers is ultrafast and fully reversible. Nevertheless, achieving large magnetic modulation of the plasmonic resonance without broadening the optical response represents a great challenge for magnetoplasmonics, especially if the material choice is restricted to metals. In recent years, several approaches to overcome this issue are being proposed.[1]

In this talk the use of transparent conductive oxide (TCO) nanocrystals (NCs) for magnetoplasmonics will be discussed as an alternative to metal-based nanostructures. These NCs are able to support sharp plasmonic resonances in the infrared, due to the free carrier density ($10^{18}$-$10^{21}$ cm$^{-3}$) introduced through aliovalent doping.[2] Using non-magnetic plasmonic semiconductor NCs, we demonstrated experimentally an enhanced magnetoplasmonic response compared to noble metal NCs, due to the lower effective mass of charge carriers and the reduced spectral linewidth of the plasmonic resonance.[3] Furthermore, a proof-of-concept field-modulated refractometric sensing experiment revealed a superior refractive index sensitivity of our TCO NCs with respect to ferromagnetic metal-based magnetoplasmonic systems reported in the literature.

The possibility of doping plasmonic doped semiconductor NCs with magnetic cations can potentially further improve the magnetoplasmonic performance of these NCs by 2 orders of magnitudes, paving the way for their applications in real-life devices. Such perspective will be discussed, also revisiting the work on dilute magnetic semiconductors, interesting materials for spintronics,[4] where a giant magneto-optical response was demonstrated at the band gap transition.[5] The full exploitation of this effect at the plasmonic resonance would represent a game-changer in magnetoplasmonics.

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# Exchange bias in metal-doped single-phase ferrites induced by defect engineering of core@shell nanoparticles.

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The crystal site occupancy of different divalent ions and the induction of lattice defects (vacancies, dislocations, stacking faults and antiphase boundaries) represent an additional tool for modifying the intrinsic magnetic properties (e.g. high coercive field and/or exchange bias) of spinel ferrites nanoparticles.[1] An efficient strategy to introduce defects into the ferrite spinel lattice is the controlled oxidation of core@shell AFM@F(i)M $Fe_{1-x}O@Fe_3O_4$ NPs. Interestingly, with this approach also defected cobalt ferrite with very large exchange bias are obtained. However, the final NPs displayed a magnetic behaviour strongly affected by the contribution of the antiferromagnetic component, due to the formation of a large magnetic disorder spinel ferrite sub-domains.[2] A possible strategy to overcome the drawback is to add, to the defected cobalt ferrite, a second divalent cation able to restore the magnetic order while retaining the lattice defects. Here we present an investigation aimed to rationalize the effect of $Co^{(II)}$ and $Ni^{(II)}$ on the lattice defects induced in spinel ferrite NPs by solvent mediated mild oxidation of AFM@FiM precursors, and on how they affect the magnetic properties. 20 nm core@shell $Fe_{0.95}O@Fe_3O_4$, $Co_{0.3}Fe_{0.7}O@Co_{0.8}Fe_{2.2}O_4$ and $Ni_{0.17}Co_{0.21}Fe_{0.62}O@Ni_{0.4}Co_{0.3}Fe_{2.3}O_4$ NPs synthetized by thermal decomposition method,[3] were oxidized to the single-phase nanocrystals. As a result, the core@shell morphology is removed and transformed in a spinel-like nanoparticle, through a topotactic transformation. In addition, the appearance of crystal defects and antiphase boundaries improves the magnetic properties of the starting compounds and leads to the appearance of exchange bias at room temperature.

## Acknowledgments

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# ORAL SESSION 3
# SPINTRONICS

## CHAIR

- Riccardo Bertacco

## SPEAKERS

- Alberto Brambilla
- Michaela Kuepferling
- Roberto Mantovan
- Vito Puliafito

# Hybrid Spinterfaces for Organic Antiferromagnetic Spintronics

**Alberto Brambilla[1], Andrea Picone[1], Michele Capra[1], Alessio Giampietri[1], Alessandro Ferretti[1], Franco Ciccacci[1], Giovanni Vinai[2], Deepak Dagur[2], Sara Fiori[2], Federico Motti Giancarlo Panaccione[2], Marco Marino[3], Elena Molteni[3], Simona Achilli[3], Guido Fratesi[3]**

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*Spinterfaces*, i.e. interfaces between an organic semiconductor (OS) and a ferromagnetic (FM) substrate, have been raising an ever increasing interest in the last two decades, first through the realization of organic spintronics prototypical devices, then by showing new intriguing phenomena related to the formation of hybridized interface states (HIS) [1]. As a promising development of the spinterface approach within the rapidly developing fields of Antiferromagnetic (AF) Spintronics and AF Magnonics [2], we have been extending those concepts to OS/AF interfaces, with the aim of creating a novel form of transducer between electromagnetic radiation (visible and near-IR) and spin waves (SW), based on the magnetic character of the HIS at the AF spinterface. It is well-known that AF materials are particularly suited as propagating media for SW at THz frequencies, while the light-induced perturbation of the magnetic moment associated to the HIS would allow for an electrode-free excitation of the nearby AF moments, otherwise hardly accessible by external stimuli. These ideas are under development in the ongoing EU-FET project SINFONIA [3], during which we have been investigating different combinations of AF oxides, in particular $Cr_2O_3$, NiO and CoO (grown on different substrates), with suitable molecular materials. The latter include several different organic molecules, ranging from well-known ones like C60 and Pentacene, to more complex compounds, such as Metal-Tetra Phenyl Porphyrins (MTPP; e.g., CoTPP) and Metal Phthalocyanines (MPc; e.g., FePc) [4], both of which are ideal candidates for building spinterfaces, since their ion core can have its own magnetic moment, due to the presence of unpaired spins [4,5].

Here, we are going to present in details the concept of our project and a series of results related to the growth and characterization (including crystalline, morphologic, and electronic properties) of the mentioned AF oxides and of related spinterfaces, along with some intriguing results related to the magnetism at the interfaces. In particular, by X-ray Magnetic Circular Dichroism we were recently able to show the long-range ordering of molecules on specific spinterfaces. The understanding of such results is also supported by computational results based on first-principle theoretical approaches, which have been performed for selected AF spinterfaces. Finally, the expected development of the current research and its potential applications will be discussed.

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# Influence of the spin Hall angle on the power consumption of an SMR field sensor

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Spin orbit torque (SOT) sensors are considered a low power alternative to conventional spintronic sensors based on AMR, GMR or TMR. Their main advantage is the simple device structure, not requiring delicate biasing layers for linearization and domain stabilization [1].   Recently, a spin Hall magnetoresistance sensor was shown to have an excellent detectivity ($1 nT/Hz^{1/2}$) up to temperatures of 150°C [2]. The minimum power consumption of such a sensor depends on the resistivities of the materials employed and is limited by the effective spin Hall angle of the device. Through the spin Hall effect, the electrical current, used for sensing, is converted into spin current, with an efficiency that depends on the spin Hall angle, causing - in presence of a magnetic adjacent layer - a resistance change of the device, the spin Hall magnetoresistance. The resistance change sensed at a certain applied field is proportional to the square of the spin Hall angle.

In this paper we determine the spin Hall angle of Pt/FeCoB and Ta/FeCoB bilayers by performing spin Hall magnetoresistance (SMR) measurements. The bilayers with various heavy metal (HM) thicknesses (wedge $d_{HM}$=5-10nm), and a ferromagnetic (FM) layer ($Fe_{60}Co_{20}B_{20}$) thickness of 2nm were prepared at Singulus Technologies AG and patterned at AGH. The SMR was measured at INRIM following [3,4], additionally a measurement protocol for the elimination of the thermal drift and hysteresis effects was applied. The electrical conductivity and current density distribution in the multilayer system is first analysed based on a Fuchs-Sondheimer approach [5,6]. Based on our thermodynamical approach [7] the different magnetoresistance (MR) contributions are analysed and the spin Hall angle evaluated. The reproducibility of the measurement on several devices is determined and its influence on the uncertainty of the spin Hall angle. Finally, we determine the minimum power consumption for a detectable resistance change as a function of the spin Hall angle and the layer resistivities and discuss strategies to improve the performance.

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# Spin-charge conversion in large-area topological insulators grown by metal-organic chemical vapour deposition

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Topological insulators (TIs) are gaining huge attention from a technological point of view due to highly efficient spin-charge interconversion phenomena occurring at their interface with magnetic materials, which is of interest for spin-orbit torque MRAM [1] and novel processing-in-memory devices, such as the MESO proposed by Intel [2]. We developed Metal Organic Chemical Vapour Deposition (MOCVD) processes to grow epitaxial-quality $Sb_2Te_3$, $Bi_2Te_3$, and combined $Sb_2Te_3/Bi_2Te_3$ 3D-TIs on 4" Si(111) substrates [3-9]. First, their topological character has been demonstrated by combining magnetotransport and angular photoemission spectroscopy studies [6,9]. Then, we have built simple spin-charge converters by interfacing the TIs with ferromagnetic layers (FM=Fe,Co). In $Sb_2Te_3$/FM systems, we have found a large spin-charge conversion efficiency, as measured by spin pumping ferromagnetic resonance (SP-FMR), which, when interpreted as occurring through the inverse Edelstein Effect, leads to a conversion efficiency of $l_{IEE}$ ~0.3 nm [7,8]. More recently, we have developed combined $Sb_2Te_3/Bi_2Te_3$ heterostructures, where the top $Bi_2Te_3$ layer displays a remarkable shift of the Fermi level towards the Dirac point, as visualized by angular resolved photoemission spectroscopy [9], see Figure 1. This led to an almost total suppression of bulk states' contribution, resulting in the emergence of ideal topologically-protected surface states, which are successfully exploited to enhance the spin-charge conversion efficiency up to $l_{IEE}$ ~0.44 nm, see Figure 1. Our results open interesting routes toward the use of chemical methods to produce TIs over large area Si substrates, which may bring them closer to the future technology transfer of spintronic devices based on them. We acknowledge the H2020 project SKYTOP (FETPROACT-2018-01, n. 824123) and the PNRR MUR project PE0000023-NQSTI.
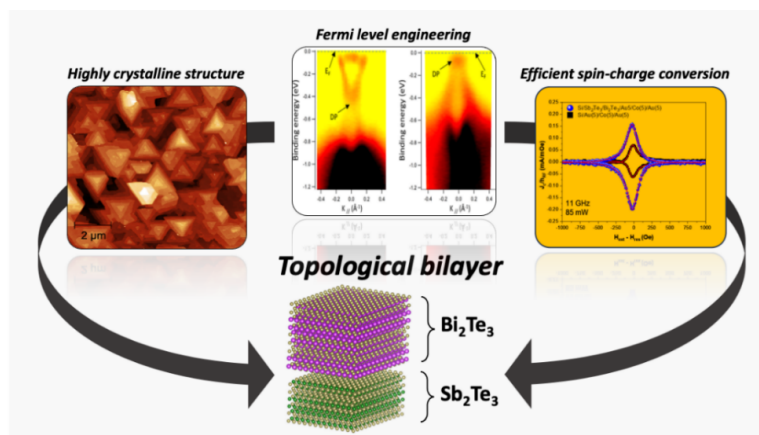


**Fig. 1** "Process-flow" for the use of the combined $Sb_2Te_3/Bi_2Te_3$ topological insulator in efficient spin-charge converter.

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# Oscillator Ising Machines simulated for large Max-Cut problems

**Vito Puliafito[1], Luciano Mazza[1], Andrea Grimaldi[2], Eleonora Raimondo[2], Pietro Tullo[1], Davi Rodrigues[1], Kerem Camsari[3], Vincenza Crupi[2], Mario Carpentieri[1], Giovanni Finocchio[2]**

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Heuristic paradigms like Ising machines are recently gaining interest in the academic and industrial world for their capability of finding good solutions for NP problems in limited times.

We simulate an Oscillator Ising machine (OIM) to find good solutions for massively large Max-Cut problems. Evaluating the Max-Cut of a undirected and weighted graph corresponds with binarize the starting network into two groups in such a way that the cut connections are maximized.

The starting graph, of which an example is shown in Fig. 1(a), is encoded into a network of oscillators that is randomly initialized and that evolves towards a local minimum. The system has been realized in such a way that the minima of the oscillator network correspond with good solutions of the former problem. In our specific case, the binarization between oscillators happens considering the in phase and out of phase ones. To ensure that these two phases are energetic minimum of the system, we add an alternated signal tuned with their second harmonic. In this way, we observe only phases of zero, π, or multiples of π, as shown in Fig. 1(b). Fig. 1(c) shows the binarization of the system.

We simulate the oscillators with Kuramoto model [1], where coupling between the oscillators represent the edges of the graph. We add a second harmonic signal to binarize the phases to multiples of π, and this will determine where to 'cut' the former graph. We simulated a system with up two million of oscillators [2][3], which is the largest Max-Cut problem ever attempted by means of our knowledge.

We did a systematic statistical analysis for the quality of the solutions obtained for problems with different size and density. We observed solutions consistently better than the deterministic solver described in [4]. Regarding solving times, a cubic problem with one thousand nodes requires ten hours to be solved with the deterministic solver and less than one second with the proposed solution.
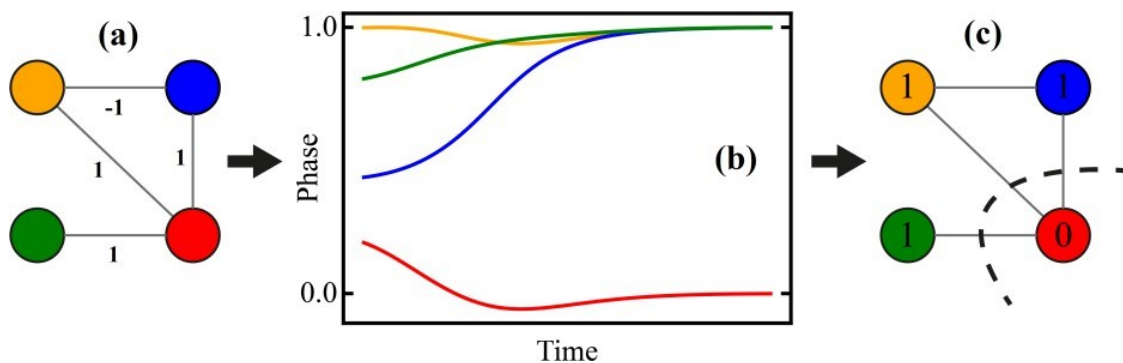


**Fig. 1** (a) Schematic illustration of a 4-nodes Max-Cut problem. (b) Plot of the phase evolution of the oscillator system represented in (a). (c) Schematic illustration of the solution of the problem, the evaluated Max-Cut is 3.

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# ORAL SESSION 4
# MOLECULAR MAGNETISM

**CHAIR**

- Ferdinando Borsa

**SPEAKERS**

- Claudio Bonizzoni
- Simone Chicco
- Niccolò Giaconi
- Giulia Serrano

# Quantum Sensing of Magnetic Fields with Molecular Spins

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Molecular spins hold potential for quantum technologies. Along this line, we have shown that it is possible to embed molecular spin ensembles into planar superconducting microwave (MW) resonators [1] and to coherently manipulate them though resonators by using suitable MW pulse sequences [2], eventually down to sub-nanoliter sample volumes [3]. Molecular spins can work also as temporary memories for information [2], in which the readout of output signal/s can be further assisted by machine learning methods to improve either amplitude or phase inference [4]. Due to their long coherence time, the relatively easy possibility of manipulation and readout and their intrinsic quantum nature and properties (such as entanglement), molecular spins have been proposed also for quantum sensing schemes [5]. However, experimental demonstrations of such sensing schemes have not been reported yet.

Here we investigate molecular spin qubits for quantum sensing of magnetic fields [6]. To this end, we first consider a diluted VO(TPP) molecular spin ensemble embedded into a planar MW superconducting resonator, as in Fig. 1.a. The sensing protocol consists in a MW pulse sequence which is used to coherently drive the spins and to obtain a Hahn's echo, while the radiofrequency (RF) signal to be detected is sent during the free spin precession time through an additional RF coil. We show that it is possible to detect changes in both echo amplitude and phase and to relate them to the presence of the RF field, as in Fig. 1.b [6].
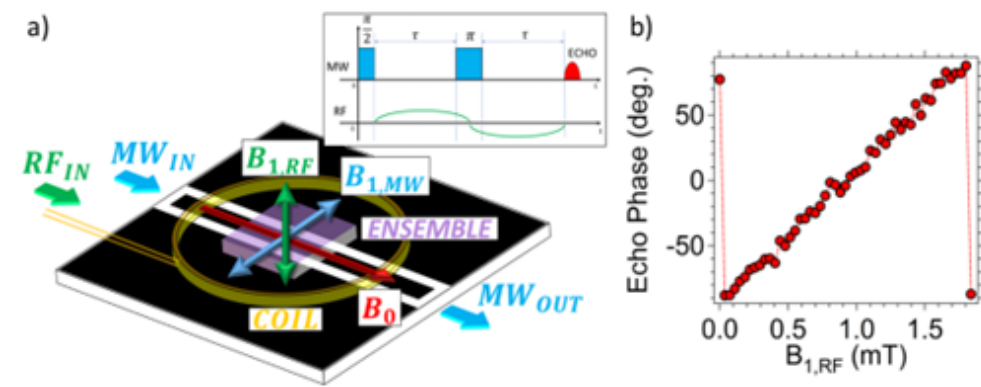


**Fig. 1** a) Sketch of the sensing experiment showing the planar microwave (MW) resonator with the radiofrequency (RF) coil and the ensemble added on it. The arrows represent the static magnetic field (red), the MW field (blue) and the RF field (green). Input and output MW/RF signals are indicated with the same colorcode. The inset shows an example of protocol used. b) Phase of the spin echo measured as a function of the applied RF magnetic field for a VO(TPP) sample.

We also extend our sensing protocol to the case of Dynamical Decoupling sequences [2], and we apply them to drive an ensemble of diluted BDPA organic radical [6,3]. The effect of the RF field on the echo is found to increase with the number of $\pi$ pulses used in the MW sequence. The resulting magnetic field sensitivity can reach values as high as $nT/(Hz)^{1/2}$ with a relatively low number (4-5) of $\pi$ pulses applied, which is comparable with the typical values reported for Nitrogen Vacancy centers magnetometry performed through Optically Detected Magnetic Resonance spectroscopy [6]. These results show, for the first time, quantum sensing protocols successfully implemented on molecular spins.

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# Proof-of-concept Quantum Simulator based on Molecular Spin Qudits

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Molecular Nanomagnets (MNMs) are spin systems that are considered promising building blocks for quantum technology devices.[1] In fact, they feature several advantages with respect to other prototypical platforms, such as long coherences and engineerable spin Hamiltonians. However, what makes MNMs potentially disruptive for quantum technologies is that they naturally provide a multi-level energy spectrum, that can be exploited to encode qudits. Using qudits as elementary computational units increase significantly the power of quantum logic for many applications, such as quantum simulation and quantum error correction.[2]

In the last decade many theoretical efforts focused on using MNMs as quantum simulators (QSs);[3] however, an experimental realization of a QS based on MNMs was still missing. In this work we successfully realized the first proof-of-concept quantum simulator based on an ensemble of 173Yb(trensal) qudits [4] and we implement the quantum simulation of models representative of two different classes of problems: an integer spin > 1/2 subject to quantum tunnelling of the magnetization (QTM) and a pair of spins 1/2 coupled by Ising interaction in presence of a transverse field (TIM). Coherent control over each energy gap of the qudit is realized with a flexible broadband NMR spectrometer equipped with a tailored multi-frequency probe.[5] Having reproduced correctly the modeled time evolution of both the physical models simulated, we proved the effectiveness of this prototypical quantum simulator, also confirming the suitability of MNMs to realize quantum technology devices.
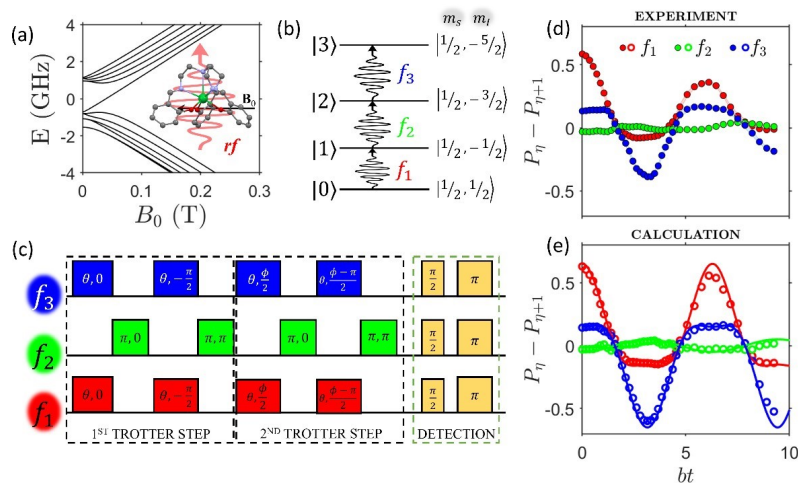
**Fig. 1** (a) $^{173}$Yb(trensal) nuclear energy levels (molecule in inset). (b) Scheme of the nuclear state subspace exploited for the quantum simulation. (c) Radiofrequency pulse sequence used for implementing the quantum simulation of the interacting (1ST Trotter) and non-interacting (2ND Trotter) transverse Ising model, under Suzuki-Trotter decomposition. (d,e) comparison between the experimental and calculated results (respectively) of the quantum simulation, in terms of populations difference between neighboring levels; in panel (e), the exact model (line) is compared with the calculated Lindblad dynamics (dots).

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# Nanostructuring and Spin Selective Electron Transport Properties of Enantiopure Helicenes Monolayer

**Niccolò Giaconi[1], Lorenzo Poggini[2], Michela Lupi[1], Matteo Briganti[1], Anil Kumar[3], Tapan K. Das[3], Andrea L. Sorrentino[1], Caterina Viglianisi[1], Stefano Menichetti[1], Ron Naaman[3], Roberta Sessoli[1], Matteo Mannini[1]**

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The initialization, control, and detection of electronic spins are necessary for spintronics to be realized. Nowadays, inorganic materials are the most used for this purpose, this view however has recently been challenged[1] after the Chiral Induced Spin Selectivity (CISS) effect discovery[2], where effective spin conversion was detected in purely chiral organic molecules. The CISS effect describes the capability of chiral molecules to act as spin filters discriminating flowing electrons according to their spin state (**Fig. 1a**). In this context, aiming to focus on the investigation of spin filtering properties of chiral molecular systems, we recently reported the deposition of an enantiopure helicene radical cations monolayer on gold via non-covalent interactions[3]. Herein, moving toward a more robust architecture, we investigated the synthesis, assembly, and spin selective conductivity properties of a novel thioacetyl derivative of thia-bridged triarylamine helicene (HelSAc) that is suited for direct chemisorption on an Au(111) surface (**Fig. 1b**). An in-depth characterization was performed to investigate the morphology (STM) and the chemical structure (XPS) after the deposition process. In addition, theoretical calculations were carried out to gain further insight into the molecular configuration at the surface level. Finally, the occurrence of the CISS effect was monitored by assembling a stacked micrometric device with a monolayer of these molecules embedded between ferromagnetic and diamagnetic electrodes and observing an asymmetric trend of the magnetoresistance, with an inversion of the signal according to the handedness of molecules (**Fig. 1c**). In addition, magnetic conductive-Atomic Force Microscopy (mc-AFM) revealed efficient electron spin filtering at room temperature, even at unusually low potentials[4] (**Fig. 1d**). Our results demonstrate that thiahelicenes represent key candidates for the development of chiral spintronics devices.
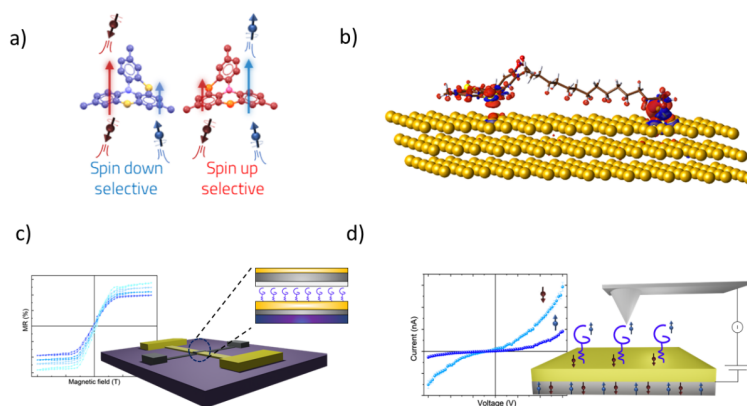


**Fig. 1** a) Schematic representation of Chirality Induced Spin Selectivity (CISS) effect on thia[4]helicene. b) DFT simulation of HelSAc anchored on an Au(111) surface. c) micrometric device embedding a molecular monolayer of HelSAc to perform magnetoresistance measurement. d) experimental setup of magnetic conductive Atomic Force Microscopy experiment used to acquire I/V curves on a molecular deposit.

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# Magnetic features of molecules on superconductors

__Giulia Serrano[1], Lorenzo Poggini[2], Andrea Luigi Sorrentino[3], Niccolò Giaconi[3], Brunetto Cortigiani[3], Philippe Sainctavit[4], Andrea Cornia[5], Matteo Mannini[3] and Roberta Sessoli[3]__

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The magnetism of molecular systems on superconductors has raised increasing interest in the last years triggered by the new phenomena occurring by coupling magnetism and superconductivity.[1],[2] Magnetic molecules consisting of organic molecules embedding transition lanthanide or transition metals present tunable magnetic features ranging from extremely long magnetization relaxation time and magnetic hysteresis in Single Molecule Magnets (SMMs)[3] to high coherence time for molecular spin qubits.[4] Depending on the molecular ligand, molecules experience a different interaction with the surface, when deposited as thin films. [5] In SMM monolayers, the magnetic hysteresis loop can be quenched by strong interactions with conducting substrates but preserved - or even boosted - by decoupling layers. Here it is shown that superconducting substrates can be used as a further tool to manipulate the magnetism and quantum features of the diverse SMMs systems.[6],[7] $Fe_4$ complexes and $TbPc_2$ SMMs are investigated on type I and type II superconductors by scanning tunnelling microscopy, photoemissions techniques and synchrotron experiments probing the magnetic peripeties of the molecular layers. The abrupt transition of type I Pb crystal to the superconducting activates the quantum tunneling regime on Fe4 SMMs compounds which locally switch from a blocked magnetization state to a resonant regime. On Pb, $TbPc_2$ films - from monolayer to thick films – sense the hysteresis loop of the underneath SC surface caused by the different topology of the magnetic flux when exits or enters the substrate. The coupling between $TbPc_2$ films and type II SC substrates is investigated by Nb and $NbSe_2$ SC crystals. Striking differences are observed in the magnetic hysteresis of the molecular single layers, whose opening is promoted by the charge density wave layered structure of $NbSe_2$.
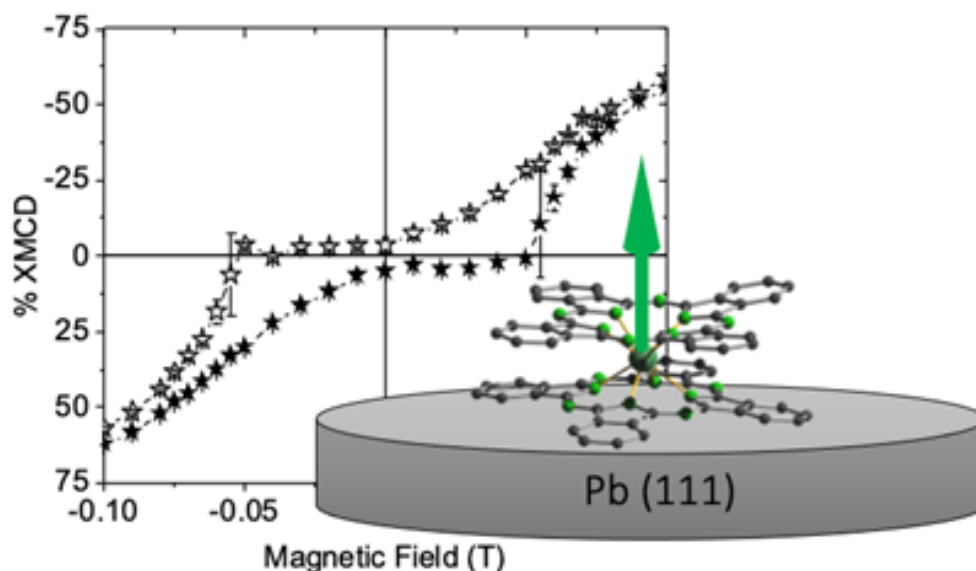


**Fig. 1** Magnetic hysteresis of a $TbPc_2$ Single molecule magnet on a Pb(111) surface.

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# ORAL SESSION 5
# THIN FILMS AND MAGNONICS

**CHAIR**

- Giovanni Ausanio

**SPEAKERS**

- Ilaria Bergenti
- Maria Cocconcelli
- Alberto Ghirri
- Gianluca Gubbiotti
- Federico Motti

# Tuning the Blocking Temperature of CoO Antiferromagnetic Films with Organic Molecules

**Luca Gnoli[1], Corrado Del Conte[2], Mattia Benini[1], Alberto Riminucci[1], Rajib K. Rakshit[1], Manju Singh[1], Samuele Sanna[2], Simona Achilli[3], Elena Molteni[3],Guido Fratesi[3], Valentin Dediu[1], Mirko Cinchetti[4], <u>Ilaria Bergenti[1]</u>**

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Molecular spintronics is an emergent field combining the flexibility of molecules with the advantages of spintronics [1]. Its main goal is the manipulation of the electron spin by a wise combination of ad-hoc molecules and magnetic substrate [2]. In this work, we adopted an innovative approach by investigating the effects of spinterface formation with antiferromagnetic (AFM) thin films. This is motivated by the recent discovery of interesting spin-orbit effects able to manipulate the magnetic moments in AFM making these materials interesting for spintronics. We investigated then the effects of two well-known molecules in molecular spintronics, Fullerene and Gallium-quinoline, when they are coupled with a prototypical AFM material, Cobalt Oxide (CoO). To detect the magnetic response of CoO, we coupled it to a ferromagnetic Cobalt layer generating exchange bias effect. The effects of the AFM-organic coupling are then detected through changes induced in the CoO-Co exchange bias coupling. With this aim, we performed both static and dynamic characterization by Magneto optical Kerr effect (MOKE). The deposition of organic molecules on the CoO layer affects the magnetic response of Cobalt, evidenced by an increase of exchange bias coupling suggesting an enhanced stability of the antiferromagnetic state. In terms of magnetization dynamics, we detected larger precession frequencies of Cobalt magnetic moments in samples coated with organic molecules.

We interpret our data considering that the hybridization with molecular layer generates an imbalance of Energy barrier for AFM reversal in CoO[3]. DFT calculations on model CoO/C60 slab support the experimental findings indicating a more stable energetic landscape for flipping AFM spins when the molecule is adsorbed on the surface

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# Biasing Magnonic Devices via Integrated Micro-magnets

**Maria Cocconcelli[1]**, Federico Maspero[1], Andrea Cattoni[1], Björn Heinz[2], Philipp Pirro[2], Raffaele Silvani[3], Marco Madami[3], Silvia Tacchi[4], Riccardo Bertacco[1]

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The development of integrated magnon technology, highly promising for high-frequency data processing [1,2], has encountered significant challenges, primarily due to the requirement of a bias magnetic field. Traditionally, generating this bias field involves bulky and power-intensive components that are challenging to incorporate into commercial devices.

To address these limitations, we are developing tunable magnonic devices where the bias field is provided by permanent micromagnets integrated on micro-actuators.

In this contribution, we offer an initial example of on-chip integration involving SmCo permanent micromagnets and magnonic conduits, developed as part of the European M&MEMS project [3]. Our devices feature two permanent SmCo micromagnets symmetrically positioned with respect to a CoFeB magnonic conduit at varying distance (d), as illustrated in Fig. 1a. To excite spin waves (SW) in the Damon-Eshbach geometry, we apply an external bias field of 60 mT, parallel to the short axis of the conduit, and a radio frequency signal to a coplanar waveguide. Micro-focused Brillouin Light Scattering (BLS) is employed to investigate the SWs within the conduit. As expected for CoFeB conduits, we observe a propagation length of a few microns.

The spatially localized bias field generated by the permanent magnets, which varies with their distance (d) as shown in Fig. 1b, induces a localized shift in the SW dispersion relation. When the field of the permanent magnets aligns with the external bias field, the low-frequency mode propagating in the CoFeB conduit exhibits a strong decrease of the decay length l (Fig. 1c) for increasing stray field strength produced by the SmCo micromagnets at small d values.

This phenomenon is attributed to the mismatch in the dispersion relation within the conduit, specifically between the region of excitation below the antenna and the propagation region situated between the magnets. As a result, over a realistic propagation distance of 12 microns, a notable rise in attenuation by 32 dB is achieved by decreasing the distance d from 8 μm to 4 μm.

These preliminary findings underscore the potential of combining permanent micro-magnets and magnonic conduits for realizing tunable RF attenuators and filters.
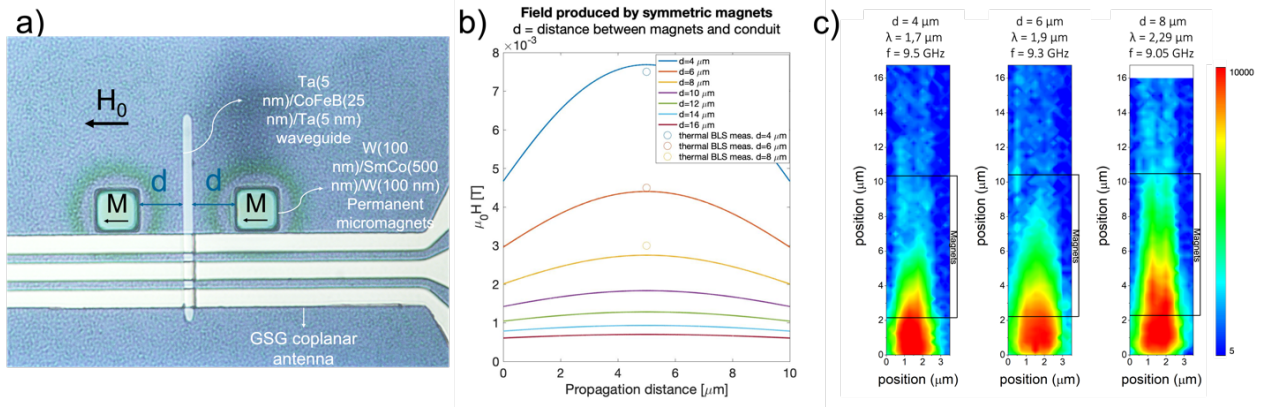


**Fig. 1** a) Device layout; b) Simulated field generated along the propagation distance by SmCo magnets at distance d from the conduit; c) BLS measurements of devices with magnets placed at varying distance d form the conduit, showing the dependency on the magnet distance of the attenuation of the intensity.

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# Ultrastrong Magnon-Photon Coupling in Planar Superconductor-Ferrimagnet Structures

**Alberto Ghirri[1], Claudio Bonizzoni[2,1], Maksut Maksutoglu[3], Alberto Mercurio[4], Omar Di Stefano[4], Salvatore Savasta[4], Marco Affronte[2,1]**

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Coherent coupling between spin-wave excitations (magnons) and microwave photons in a cavity may disclose new paths to unconventional phenomena as well as novel applications. Here, we present a systematic investigation of yttrium iron garnets (YIG) films on top of coplanar waveguide resonators made of superconducting $YBa_2Cu_3O_7$ (YBCO). We first show that spin-wave modes with frequency higher than the Kittel frequency can be excited by putting in direct contact a 5-μm-thick YIG film with the YBCO coplanar resonator (cavity frequency $\omega_c/2\pi$ = 8.65 GHz) (Fig. 1). With this configuration, we obtain very large values of the collective coupling strength $\lambda/2\pi \approx 2$ GHz and cooperativity C = 50000 [1].

Transmission spectra are analyzed through a modified Hopfield model, for which we provide an exact solution, that allows us to well reproduce spectra by introducing a limited number of free parameters. It turns out that the coupling of the dominant magnon mode with photons exceeds 0.2 times the cavity frequency, thus demonstrating the achievement of the ultrastrong-coupling regime with this architecture [1]. Our analysis also shows a vanishing contribution of the diamagnetic term, which is a peculiarity of pure spin systems.
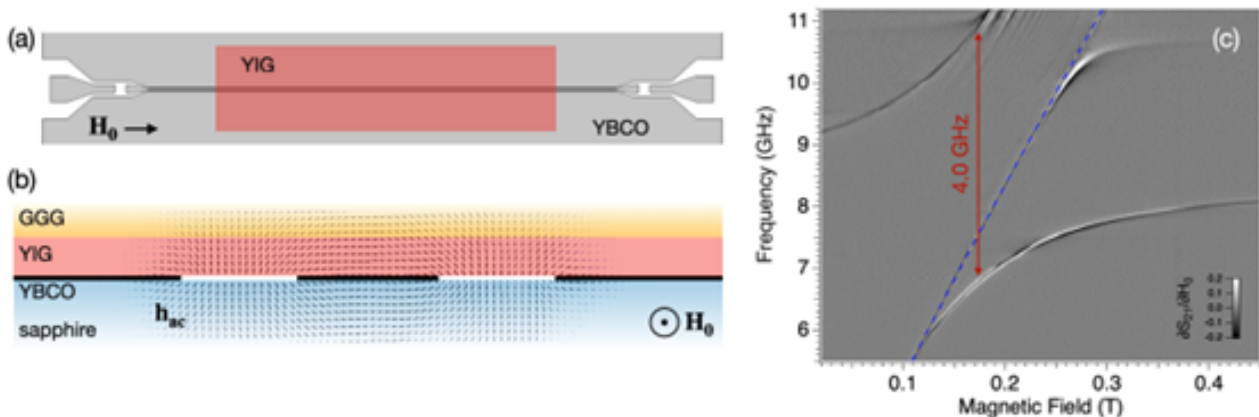
**Fig. 1** (a) Top view and (b) vertical section of the YBCO resonator with the the YIG film stacked on top. (c) Transmission spectral map measured at 30 K showing the formation of polaritonic branches with splitting $2\lambda/2\pi \approx 4$ GHz.

Further experiments carried out at varying temperatures crossing the critical temperature of the YBCO film ($T_c$= 88 K), and by means of resonators and broadband transmission lines operating at different microwave frequencies, allowed us to address the correlated effects due to the spatial distribution of the electromagnetic field and to the interplay between ferrimagnet and superconductor at the interface. In particular, we show that the splitting of the polaritonic branches and the shift of the normal modes can be successfully related to the temperature dependence of the penetration depth [2].

These results provide a deeper understanding of the fundamental phenomena in hybrid magnon-photon systems and open a path for the achievement of even larger couplings. We finally discuss the possibility to experimentally observe the superradiant phase transition as theoretically predicted in the ultrastrong coupling regime.

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# Observation of Spin-Wave Moirè Edge and Cavity Modes in Twisted Magnetic Lattices

**Gianluca Gubbiotti[1], Marco Madami[2], Hanchen Wang[3], Jilei Chen[4], and Haiming Yu[3,5]**

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Moiré superlattices have been extensively studied rerecently in both electronic and photonic systems, e.g., the superconductivity of graphene with magic angle [1] and twisted photonic double-layer crystals leading to magic-angle lasers.[2] However, moiré physics is barely studied in the field of magnonics, i.e., in using spin waves for information processing.

In this paper, we experimentally investigate the spin-wave propagation in a moirè magnonic superlattice consisting of two antidot sublattices, with a relative twist angle, merged in a single yttrium iron garnet (YIG) thin film [Fig. 1(a)]. A single antidot lattice acts as a conventional magnonic lattice with a lattice constant a= 800 nm and an antidot diameter of 260 nm. We use microfocused Brillouin light scattering (µBLS) to directly visualize two types of spin-wave modes in a moiré magnonic lattice, namely, (i) spin waves propagating along the edges of a moiré unit cell [Fig. 1(b)], which we refer to hereafter as moiré edge modes or simply edge modes, and (ii) spin waves strongly confined in the center of a moirè unit cell [Fig. 1(c)], which is referred to as moiré cavity modes or simply cavity modes in analogy with their photonic counterpart.

The dependence of the magic angle on the applied magnetic field suggests that the dipolar interaction between the twisted magnonic sublattices plays an important role in the formation of the moiré edge modes. The magnetic field, in additional to twist angle, provides an additional degree of freedom for tuning the magnonic edge mode and thus greater versatility to magnonic moiré devices. The micromagnetic simulations show that the edge mode arises at the crossing point between a moiré flatband and a propagating magnon branch near the first Brillouin zone boundary.
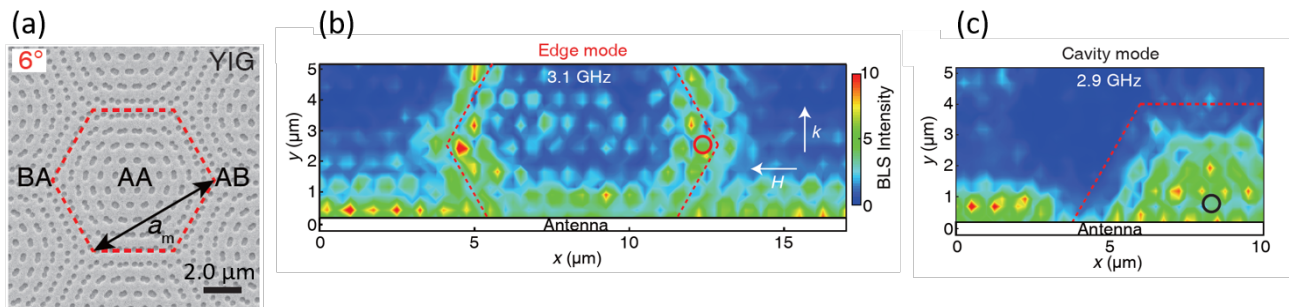


**Fig. 1** (a) SEM image of a moiré magnonic lattice based on YIG grown on a GGG substrate with a twist angle of 6°. The red dashed line indicates a moiré unit cell with commensurate AA region at its center and incommensurate AB (BA) region at its edge. Moirʹe lattice constant am is marked by the black arrow. Two-dimensional spin-wave intensity maps measured by µBLS at (b) edge mode at 3.1 GHz and (c) cavity mode at 2.9 GHz.

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# Effect of Periodicity on the Magnetic Anisotropy in Spinel Oxide Superlattices

Federico Motti[1,2*] , Lauren Riddiford[1,2], Diana Vaclavkova[2], Sourav Sahoo[1,2] , Arnold Milenko Müller[3] , Christof Vockenhuber[3] , Ali Baghi Zadeh[4] , Cinthia Piamonteze[2] , Christof Schneider[2] , Valerio Scagnoli[1,2] , Laura Heyderman[1,2]

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Metamaterials fabricated by assembling different compounds at the nanoscale can have properties not found in naturally occurring materials, and therefore offer new avenues to develop novel devices. In the realm of spintronics, the quest for such new functional materials has expanded towards magnetic oxides, where finding methods to control their magnetic anisotropy is crucial to achieve higher memory density and longer stability. In order to address this challenge, we combined two oxides with a spinel crystal structure, synthesizing $CoCr_2O_4/CoFe_2O_4$ superlattices with layers only few unit cells thick. I will show that the superlattices present a reorientation of the magnetic easy axis from in-plane to out-of-plane when warmed up, at a temperature determined by the periodicity. We can describe this with a model that includes the strain-induced anisotropy of the two materials and their different temperature dependence. This approach to create new artificial materials, involving engineering superlattices to tailor the magnetic anisotropy, can be generalized to a wide range of compounds that can be grown strained on suitable substrates.
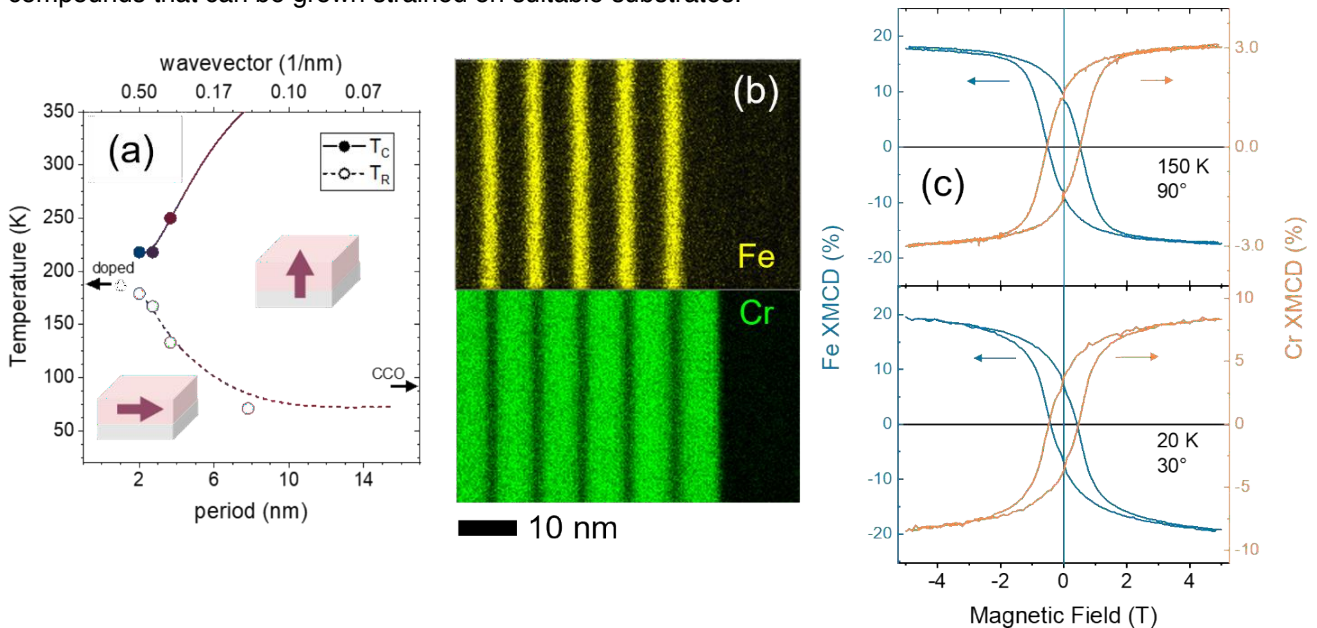
**Fig. 1** (a) Curie temperature TC and reorientation temperature TR of different superlattices characterized by different periods. The magnetic easy axis is in-plane below TR and out-of-plane above TR. (b) Transmission electron microscopy - electron energy loss images of a superlattice, showing that the ferrite and chromite layers are separated by sharp interfaces. (c) Element-specific hysteresis loops at different temperatures, obtained by x-ray magnetic circular dichroism. The identical remanence and coercive field of Fe and Cr testify the strong mangetic coupling through the interface.

## References

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# ORAL SESSION 6
# SUSTAINABLE MAGNETS, APPLICATIONS AND SUPERCONDUCTIVITY

**CHAIRS**

- Attilio Rigamonti, Samuele Sanna

**SPEAKERS**

- Matteo Casadei
- Sara Laureti
- Nicola Pellizzi

# Towards Gap Magnets: Ge, Re and Cr Doping in the $Fe_5SiB_2$ Compound

**Matteo Casadei[1,2], Mostapha Alsayed[1], Lorenzo Tincani[1], Giovanna Trevisi[2], Simone Fabbrici[2], Riccardo Cabassi[2], Giuseppe Allodi[3], César De Julián Fernández[2], Vincent Fournée[4], Samuele Sanna[1], Franca Albertini[2]**

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Rare earth (RE) magnets are of fundamental importance in the transition from fossil fuels towards renewable energy alternatives. However, in the last decade, more concerns have been risen regarding their supply risks, volatile prices and environmental impact. One possible way to reduce the demand for critical materials is to develop a new class of cheap magnets, called "gap magnets" [1]. Gap magnets should possess intermediate magnetic properties and could replace RE magnets in those applications that do not require extreme performances. Since iron is one of the most abundant elements on Earth, iron-based magnets are desirable for this new class of materials. $Fe_5SiB_2$ is a noticeable candidate due to its high saturation magnetization and Curie temperature. However, its magnetic anisotropy energy is too low for any practical applications. According to experimental and theoretical reports, the anisotropy energy can be tuned by chemical substitution of Si or Fe with other elements [2,3]. We synthesized and characterized polycrystalline samples of $Fe_5SiB_2$ with different levels of Ge, Re and Cr substitutions. Here we report and discuss on the main intrinsic magnetic properties of these compounds, such as Curie temperature, saturation magnetization and anisotropy field as measured by AC susceptometry, Vibrating Sample Magnetometry, Singular Point Detection and Nuclear Magnetic Resonance. The effect of chemical substitutions on the magnetic properties will be discussed (Fig 1a). An anomalous behavior in the SPD measurements was found (Fig 1b) that could indicate that this compound does not have an easy axis of magnetization at high temperature as commonly reported in literature [4], but rather an easy plane or easy cone configuration.
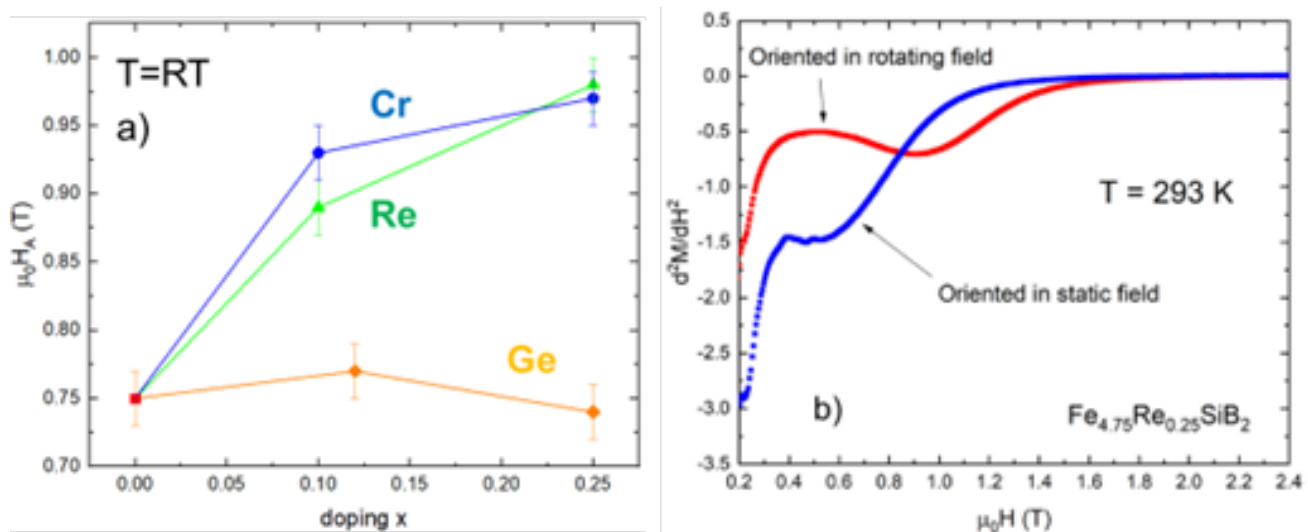


**Fig 1** a) Anisotropy field as a function of chemical doping. b) Anomalous behavior in the SPD measurements for powders oriented in different ways

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# Interface Control of Co/Ni Synthetic Antiferromagnets Heterostructures on Polymer Tapes: towards sustainable spintronics

**Sara Laureti**[1], **Mariam Hassan**[1,2], **Christian Rinaldi**[3], **Federico Fagiani**[3], **Gianni Barucca**[4], **Francesca Casoli**[5], **Alessio Mezzi**[6], **Eleonora Bolli**[6], **Saulius Kaciulis**[6], **Mario Fix**[2], **Aladin Ullrich**[2], **Manfred Albrecht**[2] and **Gaspare Varvaro**[1]

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Synthetic antiferromagnets with perpendicular magnetic anisotropy (PMA-SAFs) have caught big interests for both conventional and advanced spin-based applications. Although great progress of PMA-SAF spintronic devices on rigid substrates has been achieved, only few examples on flexible thin film heterostructures, all containing platinum group metals (PGMs), are reported in the literature [1-2]. In this regard, Co/Ni system can offer additional advantages (e.g., low damping, high spin polarization) for the development of advanced spin-based devices. Moreover, decreasing the content of critical PGM elements is responsible for relieving the demand for strategic raw materials and reduce the environmental impact of related technologies, thus contributing to the transition towards a more sustainable future [4].

In this work [5], flexible Co/Ni-based PMA-SAFs and GMR spin-valves (SVs) containing a SAF reference electrode and a Co/Ni free layer were deposited on flexible polyethylene naphthalate tapes with different combinations of buffer (BL) and capping (CL) layers (i.e., Pt, Pd and Cu/Ta). High quality SAFs with a fully compensated AF region and SVs with a sizeable GMR ratio, in line with the values reported in the literature for similar systems on rigid substrates, have been obtained in all cases. However, due to the different interdiffusion mechanisms occurring at the interface between the metallic layers, we demonstrated that while PGMs allow obtaining the best results when used as BL, Cu is the best choice as CL to optimize the properties of the stacks. The results thus indicate that complex Co/Ni-based heterostructures with reduced content of PGMs can be deposited on flexible tapes, allowing the development of novel shapeable and sustainable spintronic devices.
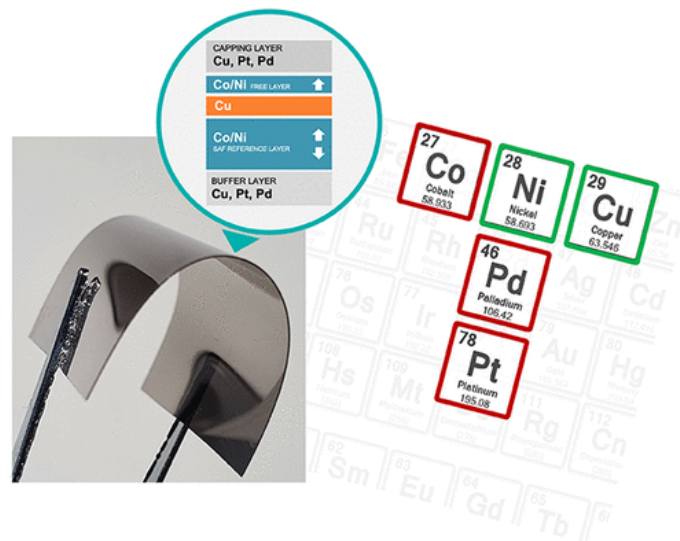


**Fig. 1** Photograph and sketch of a flexible Co/Ni-based GMR spin valve consisting of a synthetic antiferromagnet reference electrode (SAF-RL) and a free layer (FL) separated by a Cu spacer.

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# Direct Laser Patterning of Ni2MnGa films for magnetocaloric applications

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Since the recent discovery of giant magnetocaloric materials, significant efforts have been dedicated to research new materials for applications as refrigerant media in magnetic refrigeration cycles and energy harvesting. In this framework, ferromagnetic-shape-memory (FSM) Ni2MnGa Heusler alloys, due to the interplay between thermal, magnetic, and mechanical properties, are promising materials for the fabrication of magnetocaloric regenerator microdevices [1]. The advantage of such materials is that their magnetocaloric hysteresis cycle, based on the martensitic-austenitic phase transition, is close to room temperature. Furthermore, small percentage variations in stoichiometric ratios result in noticeable changes in the characteristic temperatures of phase transitions. [2]. Due to these remarkable properties, research has advanced in the quest to obtain micro and sub-micrometer structures composed of FSM materials. Significant results have been achieved in creating geometries with interesting thermomechanical properties, such as sub-micropillars, through Focused Ion Beam [3] with superelastic properties, and other micrometric arbitrary microstructures, using UV lithography [4], where the size and shape effects on thermal hysteresis have been studied, paving the way for the development of MEMS and NEMS. However so far, conventional lithographic techniques did not allow to precisely tune the phase transition hysteresis with micro- nanoscale resolution. In this work, we utilize an approach based on phase nanoengineering [5] to tune the magnetic properties and phase transition of a thin film (200nm) of Ni2MnGa at the micro- and nanoscale, as shown in the magnetic force microscope (MFM) image in Figure 1a. By using direct laser writing (DLW) with different powers, we pattern squares with different magnetic contrast, which shows also different transition temperatures. This allows a precise control of both temperature and width of the magnetocaloric hysteresis (in the order of Kelvin degrees), as illustrated in Figure 1b. Furthermore, we demonstrate submicron-level resolutions, with a minimum feature size below 500 nm, as shown in the MFM of Figure 1c, which is crucial for the development of highly integrated magnetocaloric devices. This approach could play a pioneering role in the development of magnetocaloric circuits for cooling and energy harvesting, based on a homogeneous film that can be customized for the working temperature range. In perspective, this allows to enhance the performance of magnetocaloric regenerators by increasing the temperature span and regulating the operating point.
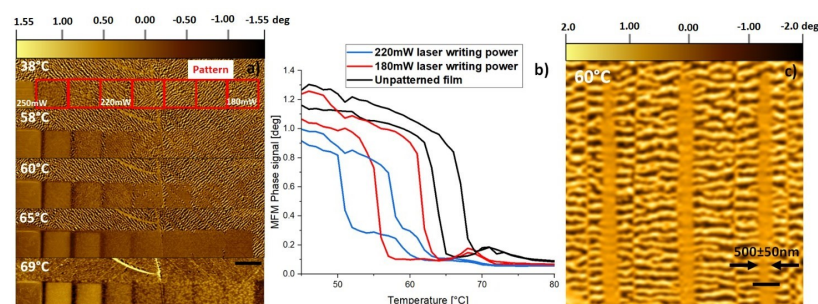


**Fig. 1** a) Magnetic Force Microscopy (MFM) image of 10x10$\mu m^2$ squares patterned in a Ni2MnGa film acquired at different temperatures. The different squares were written at varying laser power levels. Scale bar: 5 $\mu m$. b) Magnetic contrast evaluated from the MFM images in a) for two power levels, 180 and 220 mW, and for an unpatterned NiMnGa film. c) MFM image of lines presenting a minimum feature size below 500 nm. Scale bar: 1 $\mu m$.

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# ORAL SESSION 7
# FUNDAMENTAL MAGNETISM AND THEORETICAL MODELS

**CHAIR**

- Carlo Gatti

**SPEAKERS**

- Alessandro De Vita
- Samuele Sanna
- Jakob Baumsteiger
- Alessandro Chiesa

# Relevance of Thermal Fluctuations in Fe(100)-p(1x1)O in Optically-Induced Ultrafast Demagnetization

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Since the first observation of ultrafast demagnetization in a 3d ferromagnet following optical excitation [1], a variety of pump-probe techniques have addressed this challenging aspect of solid dynamics. The comparison with theoretical models has suggested that a Stoner picture cannot explain the observed dynamics [2] and that temperature-dependent spin fluctuations play an important role [3].

To confirm such scenario, we separately investigate the electronic and spin degrees of freedom in Fe(001)-p(1x1)O after pump excitation (1.55 eV energy, 50 fs duration), by means of two time-resolved (TR) photoelectron spectroscopies: angle-resolved photoemission (TR-ARPES) with 21.7 eV probe energy and spin polarization (TR-SP) of the total electron yield at threshold photon energy (4.8 eV).

In the former measurement, we identify the sudden appearance of non-thermal electrons in a specific region of the valence band, and, after few tens of fs, an increase of the electronic temperature across the whole Fermi surface. Conversely, the average magnetic moment retrieved from SP measurement quenches only after the electron gas is fully heated and the thermalization with the lattice is activated, and then recovers with a slower time constant (Figure 1).

The interpretation of experimental results with a microscopic 3-temperature model (m-3TM) [4], resulting in the fit curves in Figure 1, highlights the role of thermal disorder in the quenching of the average spin magnetic moment and indicates Elliott-Yafet type spin-flip scattering as the main mechanism, with a spin-flip probability of 0.1 and a rate of energy exchange between electrons and lattice of 2.5 K fs$^{-1}$.
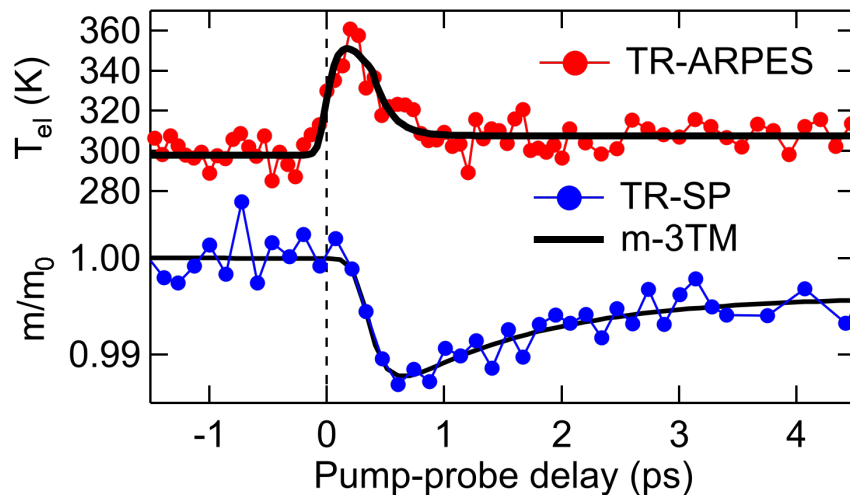


**Fig. 1** Electronic temperature (top, from the TR-ARPES experiment) and relative magnetic moment (bottom, from the TR-SP experiment). Black lines are fits based on the m-3TM model.

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# Entangled spin-orbital Jahn-Teller bipolaron
# in the electron-doped Ba2Na1−xCaxOsO6 Dirac-Mott insulator

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The Dirac-Mott insulator $5d^1$ $Ba_2NaOsO_6$ (BNOO) offers an optimal playground to study the effect of the intricate interplay between electron correlations and spin-orbit (SO) coupling when their energy scales are comparable in size. As a result, this material shows local distortions from the cubic symmetry revealing the presence of a broken local point symmetry (BLPS) phase as a precursor to a canted-antiferromagnetic state driven by a multipolar order, most likely of the antiferro-quadrupolar type [1].

Here we investigate the evolution of the magnetic and BLPS phases as a function the electron charge doping induced by the Ca/Na heterovalent substitution of $Ba_2Na_{1-x}Ca_xOsO_6$ in the whole $0<x<1$ doping range (Fig.1) by combining local experimental probes, namely nuclear magnetic resonance and muon spin spectroscopy, with density functional theory calculations (DFT). We show that injecting electrons does not leads to a metal-insulator transition (MIT), differently from the most commons 3d cases, but the Mott Gap remains open up to full doping, when all $d^1$ sites are converted in $d^2$ [2]. We show the persistence of the BLPS phase indicating that these materials preserve the multipolar character, most likely of the antiferro-quadrupolar type for $x < 1$ [3]. We show that this effect is favored by the fact that the excess electrons injected into the Mott-insulator are not uniformly distributed to form a metallic band but stay trapped in Os sites and distort the local phonon field. With a very successful combination of ab initio calculations and measurements we give evidence for the first time [4] that an essential ingredient which characterizes the physics of Dirac-Mott insulators is the formation of spin-orbital bipolarons, responsible for blocking the MIT. They are subjected to thermally activated hopping, revealed by anomalous peaks in the spin-lattice and spin-spin relaxation rates (Fig.1b), attributed to fluctuation of the electric field gradients driven by a charge-related time dependent perturbation (Fig1.c). Polaron charge trapping, favoured by the Jahn-Teller lattice activity, converts the Os $5d^1$ spin-orbital $J_{eff} = 3/2$ levels into a bipolaron $5d^2$ $J_{eff}=2$ manifold. This new polaron quasiparticle, responsible for the locking of the Mott gap in a relativistic and flexible lattice, provides a new conceptual framework to interpret the complex concerted interaction between Jahn-Teller, SO and polaron opening new research scenarios for condensed matter system with strong SO and electron-phonon interaction.
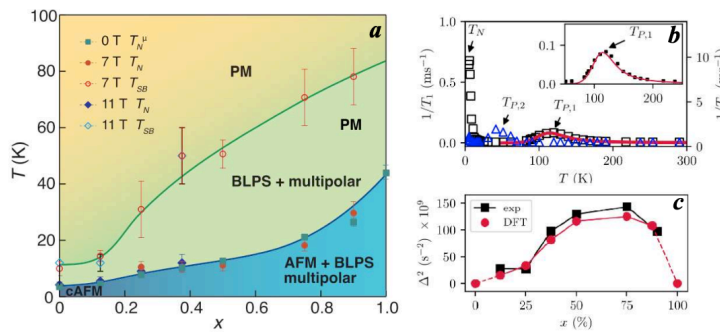


**Fig. 1:** a) Phase diagram of **$Ba_2Na_{1-x}Ca_xOsO_6$**. b) NMR spin-lattice (square) and spin-spin (triangles) relaxation rates showing anomalous peaks at $T_{P,1}$ and $T_{P,2}$ due to the polaronic dynamical process. c) Second moment $\Delta^2$ of the fluctuating field at the Na nucleus reflecting the amplitude of the localized polaron-induced-distortion from experiments (squares) and Density Functional Theory (circles).

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# Exploring Noncollinear Magnetic Energy Landscapes with Bayesian Optimization

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Canted magnetic orderings appearing in materials with strong spin-orbit coupling raised particular interest in recent years due to its intriguing underlying physics as spin-lattice coupling and multipolar interactions. Modeling these phases within density functional theory (DFT) revealed to be particularly resource demanding, leaving the investigation of large spin-configuration spaces often unfeasible. We approach this problem by using Bayesian Optimization, an active machine learning scheme that has proven to be efficient in modeling unknown functions and finding global minima [1]. We evaluate the performance of this approach by focusing on the transition metal oxides $Ba_2NaOsO_6$ [2,3], $UO_2$ [4] and $Sr_2IrO_4$ [5,6], three magnetic materials that exhibit strong spin-orbit coupling and have already been studied both experimentally and computationally. With this approach we are able to recreate previous results with significantly less computational costs by reducing the number of required DFT calculations. Furthermore, we are able to efficiently explore large configuration spaces that exceed the ones investigated previously by defining specific canting angles individually for each magnetic site. Thereby new, previously unexplored magnetic configurations can be investigated. Our results show that the combination of DFT and Bayesian Optimization is a versatile and easy-to-handle protocol to explore large magnetic configuration spaces.

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# Chirality-Induced Spin Selectivity in Electron Donor-Acceptor Molecules: a resource for quantum technologies

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Chirality-induced spin selectivity (CISS) is attracting a growing interest for its possible role in biological processes and for potential applications in spintronics and quantum technologies [1], especially if investigated at the molecular level, in electron-transfer (ET) processes. Due to CISS, electrons flowing through chiral molecules are spin polarized, even at room temperature and without any magnetic field.

Here we show that the disruptive potential of CISS in locking spin to charge can be exploited to make spin information easy to be initialized and read-out [1]. Indeed, the difficulty to access the state of molecular spins at the single-molecule level, due to their weak interaction with external fields, strongly limits their great potential for quantum information processing, e.g. thanks to their capability to encode qubits self-corrected qubits. We propose CISS in donor-chiral bridge-acceptor (D-$\chi$-A) ET as an innovative solution for this problem (see Fig. 1). In our setup, a molecular spin qubit (Q) is linked to A. Spin polarization induced by CISS can be transferred from A to Q with simple microwave pulses, even at high temperature. After a sequence of gates, the state of the qubit can be readout by a CISS-enabled spin-to-charge conversion mechanism. Indeed, charge recombination (Fig. 1b) is only allowed for a specific spin projection and hence the final (easily accessible) charge state of the donor implements qubit readout [1]. To demonstrate the feasibility of our approach, we also report [2] the first observation of CISS effect on isolated molecules in solution, not bound to any substrate. This is achieved by studying the spin dynamics of photo- excited D-$\chi$-A molecules in liquid crystals through time-resolved electron paramagnetic resonance (trEPR). We observe peculiar features in the trEPR spectrum when the chiral bridge is orthogonal to the external field, which are absent for the parallel orientation as well as in the achiral analogue (Fig. 1c). We rationalized these features by numerical simulations as a clear signature of CISS.
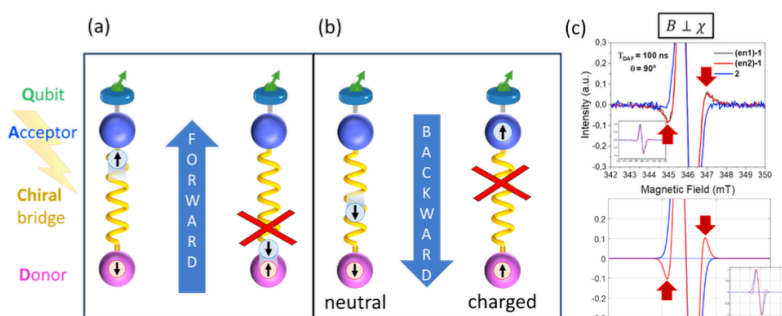


**Fig. 1** Donor-chiral bridge-acceptor-qubit (D-c-A-Q) setup, with spin-selective (a) charge separation induced by photo-excitation and (b) spin-selective recombination, where the opposite spin recombines and hence the charge state of D depends on the spin state of A. (c) Measured (top) and simulated (bottom) trEPR spectra of D$^+$-$\chi$-A$^-$ radical pairs oriented by liquid crystals with external field perpendicular to the chiral bridge, where D is peri-xanthenoxanthene, $\chi$ is a pair of naphthalene-1,8-dicar- boximides and A is naphthalene-1,8:4,5-bis(dicarboximide). 2 is the achiral analogue, while (en1)-1 and (en2)-1 are the two enantiomers. Red arrows indicate CISS features observed and simulated in the chiral molecules.

This first evidence of CISS in isolated molecules clearly points out the crucial role of the chiral bridge and sets the basis both for a deeper theoretical understanding and for their exploitation in quantum technologies [1].

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# ORAL SESSION 8

# MAGNETIC MATERIALS AND THEIR APPLICATIONS

**CHAIR**

- Davide Peddis

**SPEAKERS**

- Pierfrancesco Maltoni
- Federico Maspero
- Federico Spizzo

# From Ferrite Nanostructures to Sintered Dense Permanent Magnets

**Pierfrancesco Maltoni[1], Gianni Barucca[2], Maria Chiara Spadaro[2], Bogdan Rutkowski[3], Petra E. Jönsson[4], G. Varvaro[5], Nader Yaacoub[6], Jose´ A. De Toro[7], Roland Mathieu[1], Davide Peddis[5,8]**

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Among the relevant strategies to design Rare-Earth-free permanent magnets (PM), combining two or more prototypical magnetic phases have become a well-established route to maximize the energy product of permanent magnets at the nanoscale [1]. Within this context, achieving an optimal exchange-coupling at the interface between the phases has resulted significantly demanding: over the last years a huge number of experimental studies have been carried out, however it is still a highly debated topic [2]. The next critical step is to consolidate the nanopowders into a final dense magnet, while avoiding excessive growth of crystallites, lack of magnetic alignment and secondary impurities.

In this work, we have investigated the role of magnetic interactions in multiphase nanosystems made of $SrFe_{12}O_{19}$ and $CoFe_2O_4$ (with different weight fractions), obtained by a simple low-cost sol-gel self-combustion method [3]. The unique combination of first order reversal curves (FORCs) analysis and relaxation measurements in a reverse field could define the limits to achieve superexchange-coupling between particles with different magnetic anisotropy. The achieved local texture at the interface observed by electron microscopy was a critical parameter to obtain the uniform response and avoid further deteriorations (as shown in the figure 1). Next, a set of samples, including the individual $SrFe_{12}O_{19}$ and several composites, was selected for the subsequent compaction step to produce dense assemblies, and thus reveal their potential. During the compaction of the nanopowders, performed by spark plasma sintering (SPS) as shown by [4], the controlled thermal treatment permitted the self-alignment of the particles without the application of a magnetic field along the c-axis of the $SrFe_{12}O_{19}$, and thus the corresponding and high-density bulk magnets showed square loops with an enhancement of remanent, with corresponding higher (~45%) $(BH)_{MAX}$.
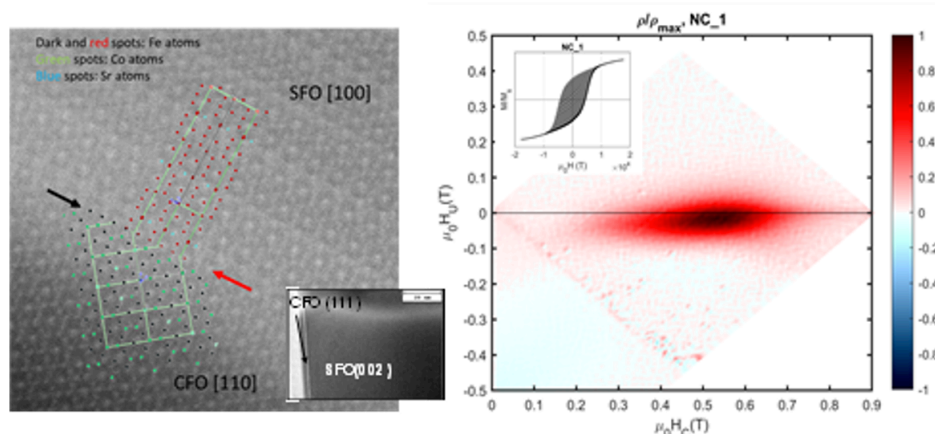


**Fig. 1** (left) STEM picture for a nanocomposite 90/10 w% (HRTEM picture in the inset); (right) FORCs heatmap.

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# Optimization and Patterning of Sm-Co Thick Films for the Integration in MEMS Devices

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Rare-earth based magnetic materials are known for their excellent properties as hard magnets both at the macro and microscale. Samarium-cobalt (SmCo) films have proven very large coercivity and high curie temperatures and are a good candidate for the integration in microdevices [1]. The magnetic properties of SmCo strongly depend on the adhesion and capping layer used during the growth and the annealing temperature of the deposited film [2]. Moreover, different groups adopted different adhesion layers and growing conditions, making the comparison of SmCo performance more challenging. For this reason, in this work, we focused on finding the optimal buffer layers for the growth of SmCo, while maintaining all other parameters untouched. The optimal buffer not only guarantees good magnetic performance, but also integrity of the film and good adhesion to support subsequent integration steps.

We tested five different adhesion layers and for each layer different annealing temperatures. In specific conditions we were able to achieve coercivity up to 3.65T with remanence in the order of 0.42T, while preserving good films morphology and adhesion on the substrate (Fig.1a).

As the goal of this research is also the integration of SmCo in microdevices [3,4], we also focused on finding new techniques for patterning relatively thick magnetic layers to form micromagnets. In this sense, we show the possibility of using inorganic masks for defining micromagnets trough a lift-off process (Fig. 1b). Such mask offers the possibility of growing films at high temperatures, usually not compatible with standard photoresist and avoiding long etching processes.

Overall, this work shows the possibility of growing and patterning very hard micromagnets with thickness in the range of 1 micron and micrometer size, enabling integration in MEMS and other devices.
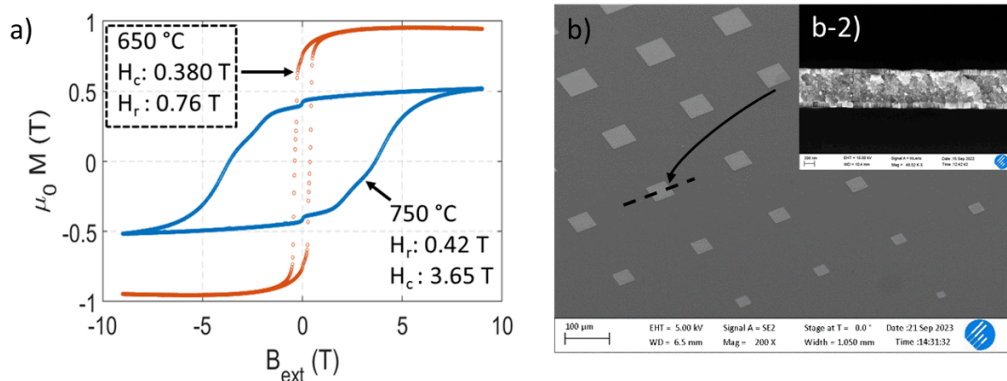


**Fig. 1** a) In-plane hysteresis curves of SmCo annealed at different temperatures; b) Pattern of micromagnets obtained by lift-off using partially inorganic resist. b-2) SEM image of a cross-section of the magnetic film.

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# Functionalization of Spider Silk Threads With Magnetostrictive FeCo Coating

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Flexible hybrid functional materials are attracting an increasing interest due to their technological potential [1]. In particular, these systems could display novel features, resulting from the combination, e.g., of electrical and magnetic properties, often found in hard metallic materials, with stretchability and deformability, typical of soft materials. Silk is a remarkable soft material as, due to its excellent mechanical properties, it can be used in composites to provide compliance, stretchability and strength.

In this contribution, an original hybrid material is presented, consisting of spider silk threads coated with a metallic and magnetostrictive FeCo alloy [2]. The 100nm-thick FeCo layer was deposited using a dc magnetron sputtering apparatus, in Ar atmosphere. The durability and the homogeneity of the obtained fibers are validated, as well as the good mechanical properties. Due to the metallic coating, hybrid threads are electrically conductive, showing a ohmic behavior; their resistance, even under strain, is of the order of ~ 10 kΩ.

The magnetic study, carried out by SQUID and MOKE magnetometry and Magnetic Force Microscopy, reveals that the magnetic behavior of the hybrid system is ruled by the silk thread–FeCo layer interaction, especially under mechanical stress. In fact, the application of a tensile strain to the thread changes the magnetic response, which therefore can be exploited to reveal the tensional state of the sample itself. In conclusion, this hybrid system represents a proof of concept demonstrating the possibility of functionalizing spider silk by imparting it electrical conductivity and stress-sensitive magnetic properties. The obtained results pave the way to foreseen applications in flexible electronics and magnetic actuation.
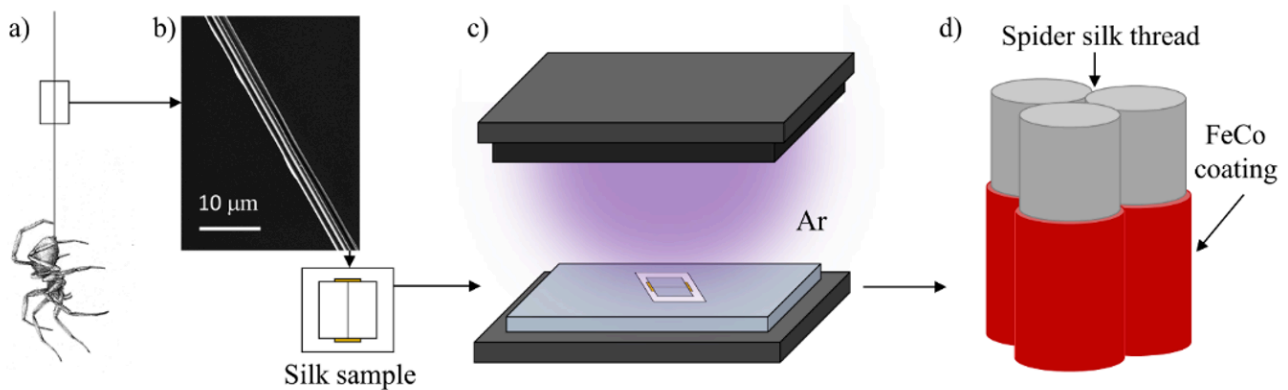


**Fig. 1** Schematic of the sample preparation. a) The silk samples were collected from dragline threads spun by the spider (Cupiennius salei). b) SEM image of the native silk thread. c) The samples, mounted on a frame, were coated homogeneously with a 100nm-thick FeCo layer, as depicted in d).

## Acknowledgements

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# POSTER SESSION 1/A

# MAGNETIC MATERIALS AND THEIR APPLICATIONS

# Preparation and Characterization of BXFO High-Entropy Oxides

**Saba Aziz[1]\*, Anna Grazia Monteduro[1], Silvia Rizzato[1], Giuseppe Maruccio[1]**

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The increasing demand for functional materials crucial for advancing new technologies has driven significant scientific and industrial research efforts in recent years. High-entropy materials, with their adjustable functional properties by tuning their chemical composition, have attracted increasing attention as primary components in high-frequency transformers, devices related to microwave technology, elements based on multiferroics, and high-density magnetic memory components [1], [2]. The initial exploration of high-entropy materials (HEMs) started with high-entropy alloys (HASs), such as CrMnFeCoNi, CuCoNiCrAlxFe and AlCoCrTiZn HEA paving the way for a multitude of HEM variations, including alloys, oxides, oxyfluorides, borides, carbides, nitrides, sulfides, and phosphides [3], [4].

In this study, we fabricated a novel high-entropy oxide (HEO) $B_{0.5}(X_5)_{0.1}FO_3$ (X=La+In+Y+Nd+Gd) (BXFO) multiferroic compound through solid state synthesis method, under strict control of precursor's stoichiometry. Preliminary RT magnetic measurements with VSM magnetometry at applied magnetic field of 0.5T, showed that BXFO exhibit ferromagnetic behavior as displayed in Figure 1. Non-zero remanent magnetization (*Mr*) and coercive field (*Hc*) were observed and BXFO exhibited the apparent coercivity (0.4T) and remanent magnetization (0.05 emu/g). At the same time, this novel composition exhibits excellent dielectric properties and shows potential for electronic applications demonstrating that high-entropy approach can expand the compositional range of rare earth multiferroics and improve the multifunctional properties in multiferroic applications. The morphological, structural, and electrical measurements are underway to completely understand the intricate magnetic/electric dynamics at play in BXFO.
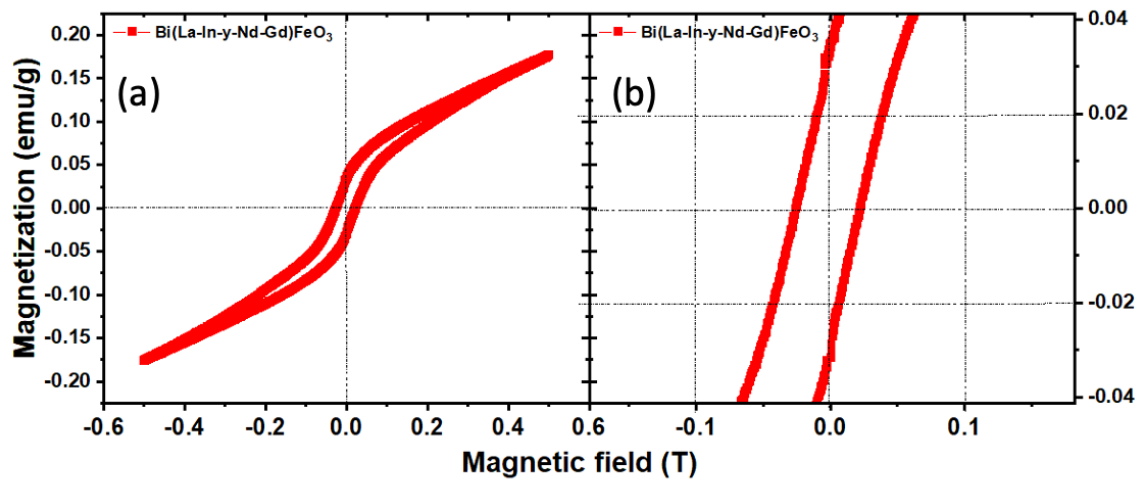


**Fig**. 1: *(a)* Room temperature Magnetic hysteresis (M-H) of $B_{0.5}(X_5)_{0.1}FO_3$ high-entropy perovskite oxide at 0.5T applied field **(b)** Zoom of M-H hysteresis of (a)

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# In-Operando Evaluation Of Tunable Heusler Compounds For Application In Thermomagnetic Harvesting Of Low-Grade Waste Heat

**Francesco Cugini[1,2], Giovanni Garulli[1], Lorenzo Gallo[2], Fabbrici Simone[2], Franca Albertini[2], Massimo Solzi[1,2]**

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Approximately 70% of the world's energy consumption is lost as heat released into the environment. Of this, a substantial 60% originates from sources operating at temperatures below 100°C [1]. Harvesting and converting this low-grade waste heat into electrical energy is a pivotal objective in the transition to a sustainable and circular economy. The thermomagnetic power-generation, based on magnetic materials, emerges as a promising technology that can contribute to achieve this goal. The concept of this technology was initially proposed in the late 19th century, but its potential for heat harvesting near room temperature has only been recognized in the past decade, in the wake of the intense research on magnetocaloric materials for magnetic refrigeration. Nevertheless, a substantial gap persists between fundamental material research and the practical implementation of these materials in efficient devices [2,3].

In this talk we present an evaluation of the thermomagnetic performance of representative Ni,Mn-based Heusler compounds. The magnetic proprieties of NiMnIn, NiMnSn e NiMnCuGa Heuslers were tuned, through a fine control of the composition, for optimal use in low-grade waste heat recovery applications. Each of the chosen alloys ($Ni_{48}Mn_{36}In_{16}$, $Ni_{48}Mn_{36}Sn_{16}$, $Ni_{50}Mn_{19}Cu_6Ga_{25}$) exhibits a second-order Curie transition slightly above room temperature, accompanied by substantial magnetization changes during the transformation. Their thermomagnetic potential was derived from magnetization measurements as a function of temperature and applied magnetic field. Furthermore, we directly measured their performance using a small-scale prototype of thermomagnetic generator (Figure 1, on the left), purposefully designed as an in-operando evaluation platform for thermomagnetic materials under real operating conditions. This device enables the characterization of small materials masses allowing for direct testing and performance comparison.

The correlation between the maximum mechanical output of thermomagnetic generator (Figure 1 on the right) and the work of thermomagnetic cycles calculated from magnetization data is investigated to provide a unique framework for evaluating magnetic materials intended for heat harvesting applications. Furthermore, our findings highlight the remarkable potential of Heusler compounds in the context of thermomagnetic thermal energy harvesting. The wide tunability of their magnetic properties, intrinsically linked to the strong correlation between structural, magnetic and electronic degrees of freedom, enables the fine optimization of Heuslers functionalities for specific application.
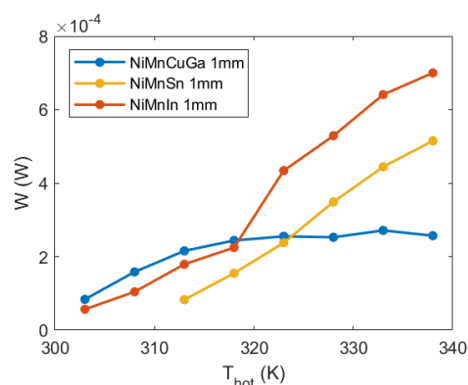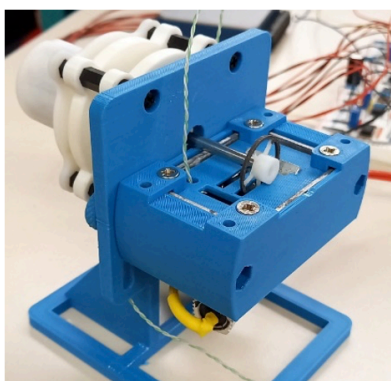


**Fig. 1** On the left: small-scale prototype of thermomagnetic generator for in-operando testing of thermomagnetic materials. On the right: maximum mechanical power of the thermomagnetic generator as a function of temperature of the hot reservoir obtained by using NiMnIn, NiMnSn and NiMnCuGa Heusler compounds as active magnetic material.

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# Top Performance of a Magnetocaloric Cooler/Heat Pump Working with Different Magnetocaloric Materials

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In recent years, the assembly and a complete experimental campaign of the large-scale AMR heat pump called MagQueen have been completed at DTU [1]. This prototype was designed and built within the ENOVHEAT project, and it is a magnetocaloric heat pump designed to meet the heating needs of a typical Danish house, having as design performance a COP of 5, heating power of about 1500 W at a temperature span of 25 K.

In the machine, the magnet rotates on a vertical axis, and 13 active magnetic regenerator (AMR) beds are arranged circumferentially on top of evenly spaced iron teeth bonded to an iron ring with outer and inner diameter of 580 mm and 380 mm, respectively. The magnetocaloric material (MCM) used in the regenerators consists of 10 layers of packed spherical $La(Fe,Mn,Si)_{13}H_y$ particles. Each regenerator bed contains 265 g of MCM, with a porosity of around 0.5. The spheres are bound together by a small amount of epoxy resin. A centrifugal pump circulates the fluid into the system and the blow periods are controlled via 26 solenoid valves synchronized to the position of the magnet via an encoder. The permanent magnet has a total volume of 10.5 l and consists of 56 sintered NdFeB segments glued together in two poles connected by an iron yoke. The maximum magnetic field is 1.6 T, and it is quite uniform in the circumferential direction. The maximum working frequency of the AMR is 2 Hz, while the flow rate can go up to 2000 l/h.

After initial validation tests and debugging of the system, we were able to obtain the experimental results that will be shown in this presentation.

As top performance, at a cycle frequency of 1.2 Hz, the device generated a maximum cooling power of 815 W over a reservoir temperature span of 5.6 K with a cooling COP of 6.0. A peak second-law efficiency of 20.5% (COP = 5.7) was obtained at a cooling power of about 290 W and a temperature span of 10.3 K while operating at a cycle frequency of 0.5 Hz [2].

After replacing the first order material with Gd, even higher performance was obtained.

At a temperature span of 14 K and a frequency of 1.4 Hz, the magnetocaloric refrigerator prototype using 3.8 kg of gadolinium provided a maximum cooling capacity of 452 W with an appreciable coefficient of performance of 3.2, corresponding to a second-law efficiency of 15.5 %. At partial load operating conditions, the device can produce a cooling capacity of 245 W with an increased second-law efficiency of 29.7 %, and a coefficient of performance of 6.2, making it more competitive with traditional vapor compression systems [3].

The performance demonstrated in this work could be an important milestone in the development of future magnetocaloric devices.



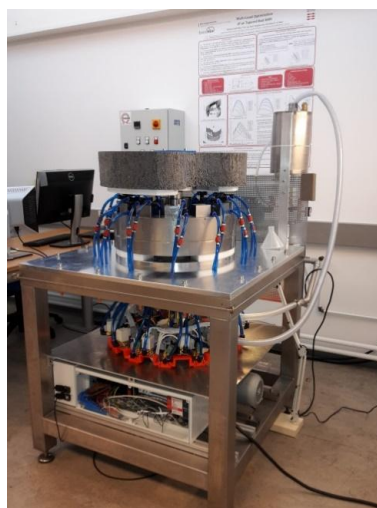**Fig. 1.** Picture of the AMR built at DTU.

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# Mössbauer Spectroscopy Insights into GeFe$_2$O$_4$ as a Potential Electrode for Lithium and Sodium Ion Batteries

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Based on the recoilless resonant absorption and emission of gamma rays by nuclei in a solid, Mössbauer spectroscopy (MS) combines an outstanding sensitivity to the coordination environment of the investigated atom with the possibility to probe magnetization dynamics over timescales in the ns regime.

With an energy sensitivity down to $10^{-7}$ eV, this technique allows to retrieve information about the magnetic, electric, structural and chemical properties of the environment surrounding the Mössbauer-active nuclei thanks to the analysis of the local hyperfine interactions [1]. Therefore, especially when dealing with molecular complexes made of non-equivalent Fe ions, information retrieved by MS are valuable and represent an essential complement to results obtained from other techniques, namely EPR or absorption/fluorescence spectroscopies [2].

MS and EPR spectroscopies are employed in our laboratory in order to investigate novel electrode materials [3]. Currently, our research is focused on the **investigation of a novel GeFe$_2$O$_4$-based material** for potential **applications in lithium and sodium ion batteries**. GeFe$_2$O$_4$, also known as Brunogeierite or GFO, can be included in the crystallographic class of spinels, which are well-known low-cost materials with an impressive range of applications. Fully characterizing these materials is a fundamental step towards achieving better energy storage solutions [4]. A **MS investigation** on GFO was performed **at temperatures as low as 5 K**, which has never been done before. At this temperature, a "**sextet**" signal appears, providing useful information about a remanent iron oxides phase, thereby enhancing synthesis knowledge.

For all samples (doped and undoped), we found a **previously undetected Fe$^{2+}$ contribution to the spectra**, that we have preliminarily attributed to the GFO sample and that could be the indication of a spinel partial inversion. Furthermore, a signal previously attributed to Fe$^{2+}$ within the existing body of literature, appears to stem, upon closer investigation, from Fe$^{3+}$.

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# Design Of Novel PDMS Magnetic Nanocomposites

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Research into novel nanocomposites (materials composed of multifunctional components) has attracted great interest in recent years for the possibility of combining the properties of the structural materials with those of the nanoscale filler, to create ingenious and useful materials meeting the requirements of specific applications [1].

In this work, the synthesis of magnetic polymer nanocomposites based on spinel iron oxide nanostructures ($MeFe_2O_4$; Me: $Fe^{2+}$ and $Co^{2+}$), embedded on PDMS (polydimethylsiloxane) matrix has been optimized. interestingly, the synthesis of the proposed nanocomposite was carried out with the electrospinning technique, an innovative method that exploits a high electric potential to create a solid material out of viscous solutions. This process allows the creation of composite materials thanks to the possibility of embedding nanofillers directly within the polymeric solutions; fibers are subsequently withdrawn towards a metallic collector, which can be flat or rotating, creating a membrane with macroscopic flexibility and a three-dimensional, microscopic fibrous network (Fig. 1) [2,3].

A complete characterization is carried out by means of morpho-structural (X-ray diffraction, XRD, Transmission electron microscopy, TEM) and magnetic measurements (Vibrating Sample Magnetometer, VSM). In addition, other methods (Fourier Transform Infrared Spectroscopy, FTIR, Thermogravimetric analysis, TGA, and Dynamic light scattering, DLS) have been used to determine the presence of magnetic nanoparticles within the polymer matrix as well as their stability in the synthesis solvent.

The results of this study could provide valuable insights into the synthesis and optimization of magnetic hybrid nanocomposites for numerous applications (e.g., biomedicine, and catalysis).
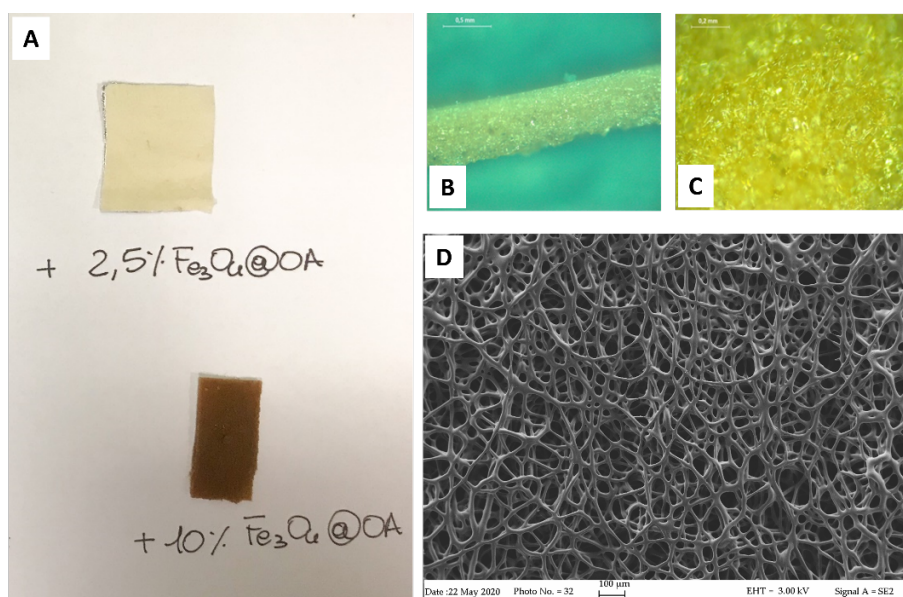


**Fig. 1** a) Macroscopic views of 2.5% and 10% $Fe_3O_4$@OA/PDMS composite; Optical image of: b) the material's section, c) the composite's fibers; d) scanning electron microscope image of the PDMS matrix.

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# BiFeO₃-based Systems for Pollutants Degradation in Water: a Piezo-photocatalytic Approach

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$BiFeO_3$ (BFO) has the typical $ABO_3$ formula of perovskites with a rhombohedral structure at room temperature. This material shows multiferroic properties, owing to the complex perovskite structure made of specific metal oxides: the ferro-electric behavior is due to the location of Bi in the A-sublattice, while the magnetic order is induced by the 3d cation in the B-sublattice. The ferroelectric polarization of BFO aligns along the 111 direction of perovskite unit cell and this makes him a potential piezophotocatalytic material [1]. The pure $BiFeO_3$ system was prepared by a simple one-pot sol-gel synthesis method with glycine as chelating agent, followed by an annealing step (first, at 300 °C for 30 min, then at 500 °C for 1h) [2]. The particles are agglomerated, with an average crystallite size of ~30 nm, as obtained by the analysis of XRPD pattern (Fig.1). To test the potential piezo-photocatalytic activity of this material, photocatalytic experiments were performed for the degradation of methylene blue, used as a model pollutant, in different conditions. A Xenon solar lamp (300 W) was used as the irradiation source while the mechanical vibration to highlight the piezoelectric features of the material was provided by an ultrasonic bath (35 kHz, 120 W); degradation tests were performed against 10 ppm dye solutions, with a concentration of $BiFeO_3$ equal to 0.5 g/L. The experiments were performed for 2 hours while the temperature was kept around 25 °C. Both photocatalytic and piezo-photocatalytic experiments have been carried out to show the effect of ultrasonic vibration and to specifically address the experimental outcomes of the materials' features (Fig. 1). Moreover, different effects such as volume and US frequency effect, have been investigated.
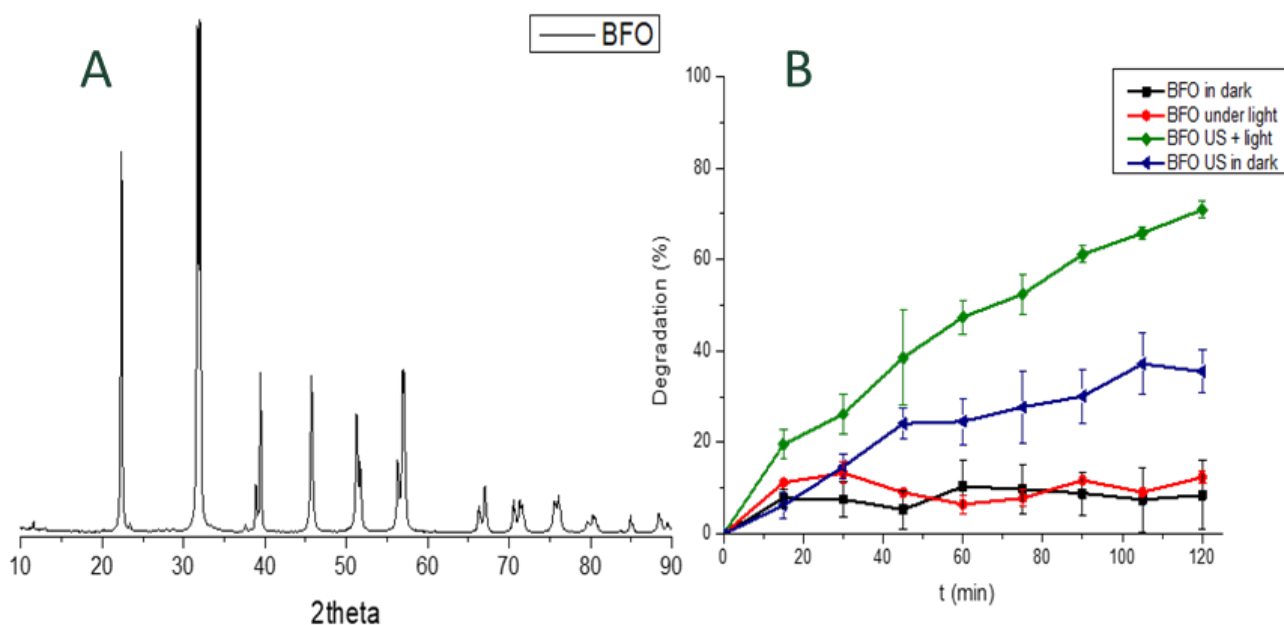
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# Magnetic Properties of Amorphous Fe-Si-Cr-B-C Alloy by Melt-spinning and Selective Laser Melting for Electrical Machines

**Purbasha Sharangi**[1], **Gabriele Barrera**[1], **Enzo Ferrara**[1], **Paola Tiberto**[1], **Isabella Gallino**[2], **Amirhossein Ghavimi**[2], **Ralf Busch**[2], **Marcos Rodriguez**[3], **Maria Teresa Pérez-Prado**[3]

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Amorphous soft-magnetic materials play an important role as core constituents in improving the energy transformation efficiency of electrical machines and passive electrical components [1].

Although the melt-spinning process remains one of the main techniques for obtaining amorphous soft-magnetic ribbons, new and efficient production methods based on additive manufacturing have been developed in recent years. These techniques allow to overcome technical limitations characteristic of casting processes and also to print complex 3D geometries.

In this work, room temperature hysteresis properties have been studied in Fe-Si-Cr-B-C alloy obtained in ribbon shape and in 3D printed cubic-shape by different casting techniques.

Ribbons were obtained by a conventional melt-spinning process, in which the pre-alloy was first inductively melted in a quartz tube equipped with a nozzle under vacuum and then injected onto a rotating copper wheel by insufflating high-purity Ar. The produced ribbons have thickness around 40 μm.

On the other hand, the 3D printed cubic samples were obtained by additive manufacturing via Selective Laser Melting using powder of the same alloy as precursor. The effect of changing printing parameters, such as laser power (20-60 W) and scan speed (350-650 mm/s), has been investigated. The processing conditions in the Selective Laser Melting have in fact a crucial role on the microstructure of the printed parts and therefore on their magnetic properties.

This can be observed in the optical images reported in Figure 1 a) where the dependence of morphology (surface roughness, porosity, density, ...) on the processing parameters is evident. The sample having the higher homogeneity is KS12 obtained with a scan speed of 350 mm/s and a power of 50 W.

Room temperature quasi-static hysteresis loops of all printed samples and as-cast ribbon were measured by VSM magnetometry. The corresponding magnetic polarization J (T) values are reported in Figure 1 a). The highest value of J, around 1.34 T, has been measured in the ribbon (dotted line), while in printed samples it is seen to increase with increasing sample homogeneity. Hysteresis curves of $Fe_{72.5}Si_{11.05}Cr_{2.23}B_{11.14}C_{3.09}$ ribbon and KS12 printed sample are compared in Figure 1 b). The ribbon displays a magnetically softer behavior with respect to the 3D KS12 printed sample: in the inset, the coercivity appears to be around one order of magnitude larger, and initial susceptibility lower in the 3D printed KS12 sample with respect to the amorphous ribbons.

A digital wattmeter has also been exploited to measure hysteresis losses behavior of ribbons as a function of frequency in the range 1Hz-1kHz at peak induction J = 0.5 T.
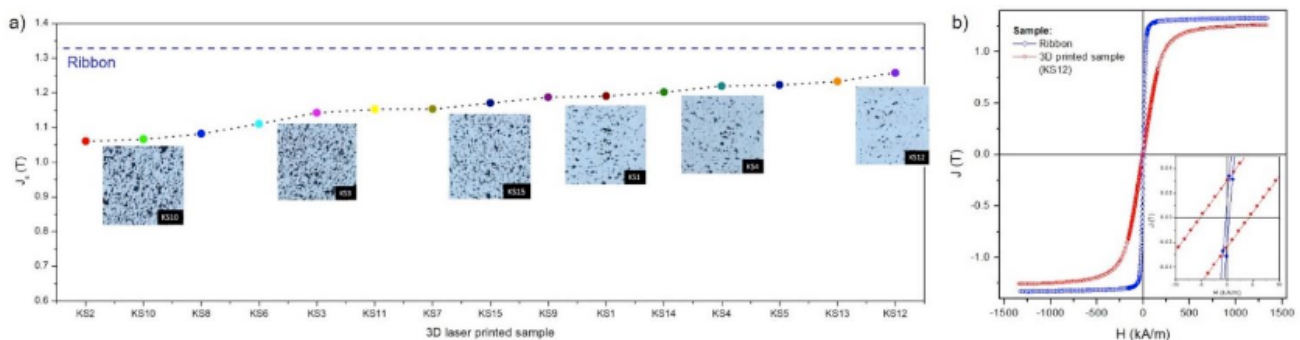


**Fig. 1** a) Saturation magnetization behavior of 3D printed samples (circles) and ribbon (dotted line). Optical images of the printed sample surface are shown. b) Quasi-static hysteresis curves of KS12 printed sample and ribbon. In the inset, an enlargement of the low field region.

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# Dependence of the Nernst Effect on the Structure and the Magnetic Properties of MnBi Samples

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The design of a thermoelectric device whose working principle is based on the Seebeck and Peltier effects has strict geometrical limitations. Instead, a device working with transverse thermoelectric effects like the anomalous Nernst effect can be shaped in thin film form for the production of integrated heat sensors or energy harvesters [1]. The Anomalous Nernst effect has been widely studied in various systems including ferromagnetic binary alloys and Heusler compounds [2]. However, most of these studies do not take into account the parameters that determine the properties of a real device, as the need to design planar structures or the opportunity to exploit the hard magnetic properties in order to have a system that does not require the application of an external magnetic field. In this framework, MnBi represents a promising material thanks to the ease of producing samples by powder metallurgy [3], with a value of the anomalous Nernst thermopower that is comparable to the one observed single crystal materials [4].

In this study we present the measurement of the Nernst thermopower by an experimental setup based on the detection of heat currents by means of calibrated Peltier sensors [5]. In particular, we measure -1.1 µV/K on samples annealed under a static magnetic field of 1 T, which develop a preferred orientation of the MnBi grains with their c-axis along the applied field direction [6].

As a further step, we will compare the Nernst thermopower of MnBi thin films prepared by means of sputtering deposition and thermal evaporation, with subsequent annealing, with the aim of establishing a preparation route optimized to obtain a Nernst efficient MnBi material in thin film form.
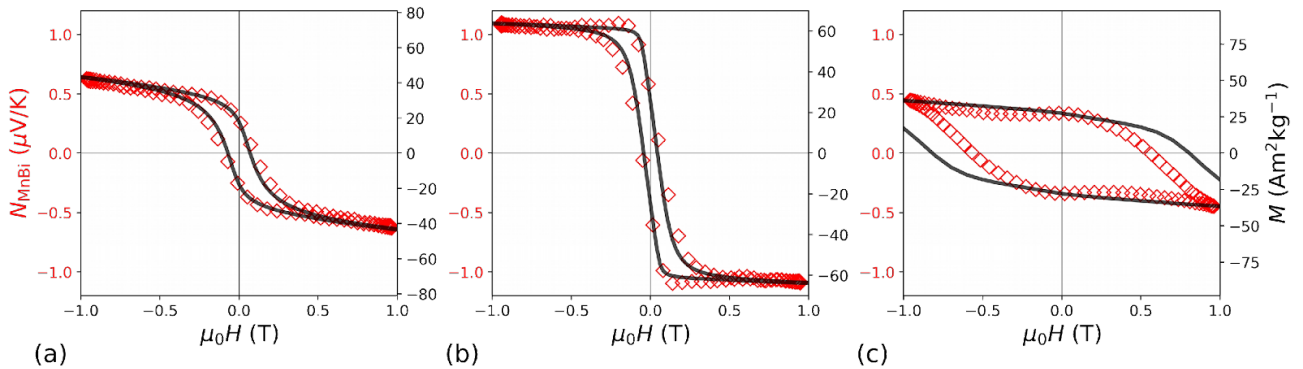


**Fig. 1** Comparison between magnetization curves (black line) and Anomalous Nernst thermopowers of MnBi (red diamonds). The bulk polycrystalline samples are prepared by following three different procedures: (a) zero-field annealing, (b) annealing under a static magnetic field of 1T and (c) milling of the material obtained by the zero-field annealing

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# POSTER SESSION 1/B
# MAGNETIC RECORDING AND SENSOR

# A micromagnetic study of the fractional resonance response driven by voltage-controlled magnetic anisotropy

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Spintronic diodes (STDs) exhibit potential advantages over semiconductor. They are compact (nanoscale size), CMOS-compatible, energy-efficient [1][2]. In particular, the STDs allows to use many driving forces to tune their rectification response, such as the voltage controlled magnetic anisotropy (VCMA) [3]. Here, we have predicted a fractional parametric resonance response driven by the simultaneous excitation of VCMA and ac spin-transfer torque for spintronic diodes working in the passive regime.

This resonance is characterized by the ferromagnetic resonant frequency, the standard parametric excitation at twice the resonance frequency and several other sub-harmonic peaks, all of which are an integer fraction (1/2,1/3, etc.) of the main resonance frequency. We have performed a systematic study of the resonance response of the MTJ as a function of VCMA amplitude. The dynamics is driven by the presence of VCMA and simultaneity by spin-transfer-torque driven by an ac in-plane spin-polarized current density (Jac =0.1MA/cm), and both current density and VCMA have the same frequency.

The figure 1 shows the results that are obtained by considering the current value fixed and varying only the value of VCMA (KVCMA =0, 50, 100 mT). In absence of VCMA, we obtained a frequency resonance of 4.88GHz. With adding of VCMA, not only the same frequency, we obtained other frequencies minor, until to 7for the value of VCMA higher and in this case is present also a peak at twice the ferromagnetic frequency (labelled -1). This work opens a new direction for the use of spintronic diodes in the field of communication, as a single device would have the ability to detect more information carriers.
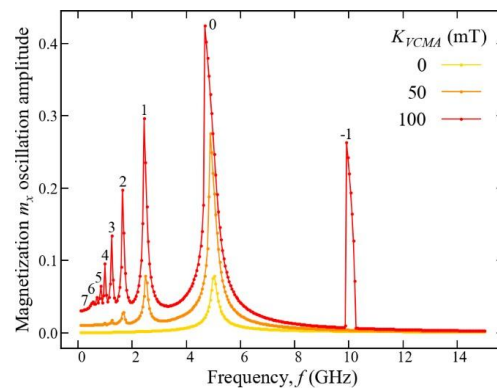


**Fig. 1** Oscillation amplitude of the $x$-component of the magnetization $mx$ as a function of the frequency of the ac current density $Jac$ with different values of the VCMA coefficient $KVCMA$.

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# Integrated coplanar waveguide coil on diamond for enhanced NV magnetometry

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Nitrogen-vacancy (NV) centers in diamond (Fig. 1a) constitute an increasingly favored quantum sensing platform, especially for magnetic field sensing [1]. The sensing protocol is based on optical initialization and detection of their spin states (Fig. 1b) with a technique referred to as Optically Detected Magnetic Resonance (ODMR, Fig. 1e). Homogeneously addressing large ensembles of NV centers offers clear benefit in terms of sensitivity, being the last one scaling as $1/\sqrt{N}$ with N the number of interrogated centers. Such experiments require a spatially uniform, intense, and broadband microwave (MW) field that can be difficult to generate. Previous approaches, such as copper wires, loop coils, and planar structures, have shown limitations in field homogeneity, bandwidth, and integration in compact devices. Here [2], we present a coplanar waveguide (CPW) gold coil patterned on a 3 × 3 mm² diamond substrate (Fig. 1c). The proposed CPW coil offers a highly homogeneous (coefficient of variation of less than 6%) MW field over a large area of 0.5 mm², full integration with a diamond NV center sensor, broad bandwidth from 1.5 to 4GHz, and ease of testing and operation through the proposed PCB and holder designs (Fig. 1d). It offers several advantages for magnetometry with NV centers ensemble, including enhanced heat dissipation, seamless integration, scalability, and miniaturization potential. The fabrication process flow is detailed and experimental results, confirming the simulated performance of the proposed CPW coil, are presented. Finally, the developed sensing platform, together with an open source data acquisition/analysis code, is used for determining the orientation and magnitude of an applied magnetic field.
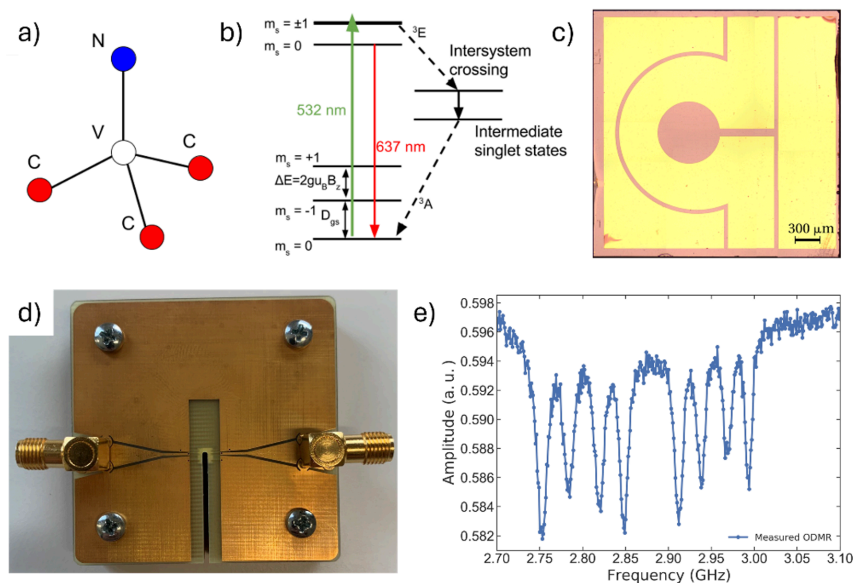


**Fig. 1** a) 3D structure of the NV center in diamond. b) electronic structure of the NV center c) optical image of the antenna patterned on the diamond chip, d) Assembled device: the diamond with the patterned CPW coil is sandwiched between the PCB and the 3D-printed holder e) example of ODMR spectrum acquisition for magnetic field sensing

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# POSTER SESSION 1/C
# MAGNETISM IN MEDICINE AND BIOLOGY

# Star Shaped Magnetic-Plasmonic Au@Fe$_3$O$_4$ Nano-Heterostructures for Photothermal Therapy

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Here we synthesize Au@Fe$_3$O$_4$ core@shell system with a highly uniform unprecedent star-like shell morphology with combined plasmonic and magnetic properties. An advanced electron microscopy characterization allows assessing the multifaced nature of the Au core and its role in the growth of the peculiar epitaxial star-like shell with excellent crystallinity and homogeneity. Magnetometry and magneto-optical spectroscopy revealed a pure magnetite shell, with a superior saturation magnetization compared to similar Au@Fe$_3$O$_4$ heterostructures reported in the literature, ascribed to the star-like morphology, as well as to the large thickness of the shell. Of note, Au@ Fe$_3$O$_4$ nanostars loaded cancer cells displayed magneto-mechanical stress under a low frequencies external alternating magnetic field (few tens of Hz). On the other hand, such a uniform, homogeneous, and thick magnetite shell enables the shift of the plasmonic resonance of the Au core to 640 nm, which is the largest red-shift achievable in Au@Fe$_3$O$_4$ homogeneous core@shell systems, prompting application in photothermal therapy and optical imaging in the first biologically transparent window. Preliminary experiments performed irradiating a stable water suspension of the nanostar and Au@Fe$_3$O$_4$ loaded cancer cell culture suspension at 658nm, confirmed their optical response and their suitability for photothermal therapy. The outstanding features of the prepared system can be thus potentially exploited as multifunctional platform for magnetic-plasmonic applications.
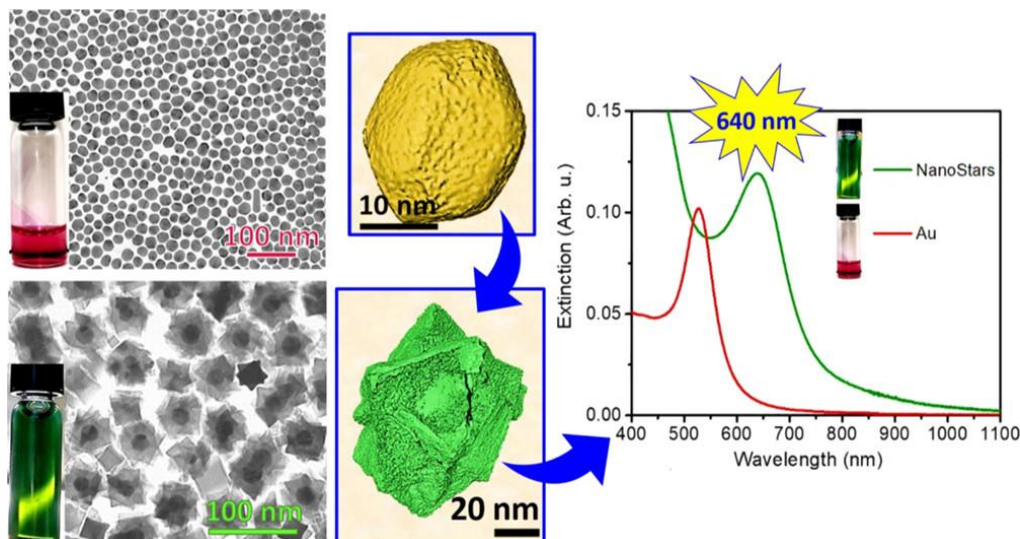
**Fig. 1** Au@Fe$_3$O$_4$ nanostars for photothermal therapy

# Magnetic Particles Imaging: Solving the Inverse Problem with Machine Learning Approaches

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Magnetic Particles Imaging (MPI) is a technique where magnetic nanoparticles with a typical diameter in the 10-20 nm range are driven in correspondence of tumour masses and are triggered with a static magnetic field gradient to form a sensitive region that is excited to produce a measurable signal by an external, low intensity ac electromagnetic field. By scanning with a suitable device (an antenna) over the patient's body, maps of the magnetic response of the magnetic nanoparticles can be obtained, which can be used to identify the cancer masses and characterise some of their properties. With respect to other imaging diagnostic techniques, MPI does not use ionising radiation or intense magnetic fields, and is therefore attracting much attention.

The maps acquired during scanning report the real and imaginary components of the third harmonic of the signal detected by an antenna that is capturing the magnetic response of the magnetic nanoparticles excited by the rf field. For each point of the map, the signal does not come only from the particles immediately underneath the antenna, but it is the integral of the contribution of all the particles, according to their distribution and their distance from the antenna. The solution of the direct problem, i.e. the calculation within the sensitive region of the real and imaginary parts maps given the initial nanoparticles distribution and their magnetisation vs. field curve, is straightforward (although time consuming), whereas the inverse problem, i.e. the calculation of the nanoparticles distribution from the real and imaginary parts maps, is not trivial and may be severely affected by incomplete or inaccurate knowledge of the physical properties of the nanoparticles [1]. Nonetheless, it is the inverse problem that is mostly relevant for diagnostic applications.

In this work we approach the solution of the inverse problem of MPI exploiting a machine learning model. First, nanoparticles with different size and magnetic properties (blocked or superparamagnetic), distributed in one or more clusters, with different shape and size, are randomly generated with a numerical approach (an example of nanoparticles distribution is given in Fig. 1(a)). Then, by using the cyclic magnetisation associated to the considered nanoparticles, the complex third harmonic response (system function, Fig. 1(b)) is calculated for each point of the map, and numerically integrated (Fig. 1(c) and (d)). A large dataset is therefore compiled, whose entries are the real and imaginary parts of the signal, used as inputs, and the initial nanoparticles distribution, used as output, of a convolutional neural network. After training the machine learning model, it is possible to test its predictions by comparing the true (numerically generated) nanoparticles, distribution, and the calculated one (Fig. 1(e)). The model is shown to efficiently reconstruct isotropic and anisotropic nanoparticle distributions (including bimodal or multimodal classes) without the need of entering the details of the magnetic properties of the particles themselves (which are often difficult to check and control in a living environment). Different machine learning models, all exploiting convolutional neural networks, are tested and compared.
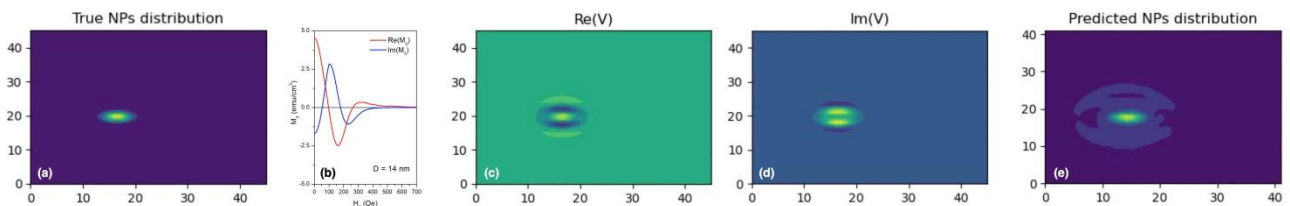


**Fig. 1** (a) Simulated distribution of magnetic nanoparticles. (b) Calculated third harmonic response at the peak of the distribution. (c) Real part and (d) imaginary part of the integrated third harmonic maps. (e) Recalculater magnetic nanoparticles distribution by a convolutional neural network.

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# Silk Fibroin Films with Embedded Magnetic Nanoparticles for Regenerative Medicine Applications

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The use of magnetic nanoparticles in regenerative medicine is a thriving research field aimed at remotely manipulating cells and/or conditioning their behavior [1]. At the same time, tissue engineering using silk-based materials is gaining increasing interest. In fact, silk fibroin protein possesses high biocompatibility with low inflammatory and immunogenic responses, tunable biodegradability and mechanical strength, permeability to water and oxygen [2]. By combining these two elements, we have created a biomaterial for prospective applications as bioactive coating in regenerative medicine [3]. In fact, it consists of a silk fibroin matrix in the form of film (~ 10 μm thick), with embedded iron oxide nanoparticles (mean size ~10 nm).

Films with different load of magnetic nanoparticles are produced (nanoparticles/silk fibroin nominal ratio = 5, 0.5 and 0 wt%) and the structural, mechanical and magnetic properties are studied. The nanoparticles form aggregates in the silk fibroin matrix and the film stiffness, as tested by nanoindentation, is spatially inhomogeneous, but the protein structure is not altered.

In vitro biological tests are carried out on human bone marrow-derived mesenchymal stem cells cultured on the films up to 21 days, with and without an applied static uniform magnetic field. The sample with the highest nanoparticles/silk fibroin ratio shows the best performance in terms of cell proliferation and adhesion. Moreover, it promotes a faster and better osteogenic differentiation, particularly under magnetic field, as indicated by the gene expression level of typical osteogenic markers.

These findings are explained in light of the results of the physical characterization, combined with numerical calculations. It is established that the applied magnetic field triggers a virtuous magneto-mechanical mechanism in which dipolar magnetic forces between the nanoparticle aggregates give rise to a spatial distribution of mechanical stresses in the silk fibroin matrix. The sample with the largest nanoparticle load, under cell culture conditions (i.e. in aqueous environment), undergoes matrix deformations large enough to be sensed by the seeded cells as mechanical stimuli that favor the osteogenic differentiation.

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# Advances in Gluten Detection: A Rapid Colorimetric Approach Using Core-Satellite Magnetic Particles

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The aim of this study is to develop a rapid and highly sensitive colorimetric immunosensor for detecting gluten in flour-based food products [1]. We focus on monitoring gliadin, a key component of gluten, which trigger the immune response in genetically predisposed individuals with celiac disease, an autoimmune disorder affecting about 0.5% of the general population [2]. To meet the legal limit of 20 ppm of gluten in foods labeled as gluten-free [3], we need to address the challenge of gliadin extraction. Gliadin, being insoluble in water, typically requires extraction with organic solvents. Our approach offers a faster, safer alternative using 60% ethanol, avoiding the complexities and potential hazards of traditional methods. ELISA [4], commonly employed for gluten monitoring, is known for its high costs and resource-intensive nature. To overcome these challenges, we propose a colorimetric immunosensor featuring core-satellite magnetic particles (CSMPs), characterized by magnetic cores with gold nanoparticles on their surface. These CSMPs are functionalized with anti-gliadin antibodies, facilitating binding to the gold surfaces [5]. Through the use of an optimal concentration of the surfactant Tween-20, we create a stable colloidal solution of clusters formed by weakly interacting CSMPs. The presence of extracted gliadin induces cluster fragmentation, causing a change in the solution's color (resulting in an increased extinction value). Additionally, we've observed a "hook effect" at concentrations exceeding 50 ppm of gluten, which we address through serial dilutions, extending the biosensor's application range up to $10^4$ ppm. In summary, our proposed colorimetric immunosensor offers a promising solution for the rapid and sensitive detection of gluten in flour-based products, effectively addressing the limitations of traditional methods.
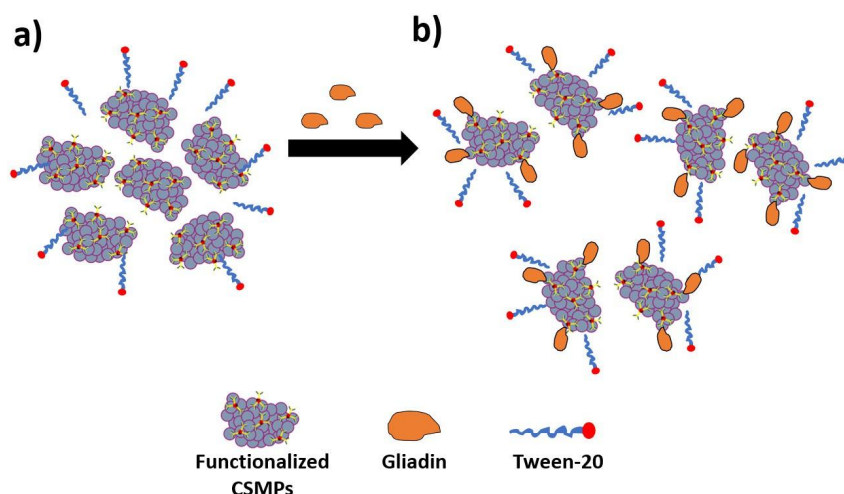


**Fig. 1** Operating principle of the sensor: (a) Formation of clusters of weakly interacting CSMPs achieved using an appropriate concentration of surfactant Tween 20. (b) Introduction of gliadin, leading to the fragmentation of CSMP clusters.

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# Exploring Radiomics features reliability by comparing different software and CT-MRI lung cancer images

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Currently, Magnetic Resonance Imaging (**MRI**) of the lung has not yet reached Computed Tomography (**CT**) quality. This is due to the lung tissue structural properties, like the scarce proton density and the presence of cardiac-respiratory movements, and to the lack of standard protocols. Despite so, there is a great interest in enhancing lung MRI images quality as such technique, unlike CT which uses ionizing radiation, is non-invasive [1]. For image analysis, **Radiomics** has recently gained more and more attention: it is a quantitative technique that allows to extract mineable data from medical images. The aim of Radiomics is to improve clinical decision-making effectiveness by defining novel imaging biomarkers, named *radiomic features*, able to reflect tissue static and dynamic properties [2]. However, Radiomics nowadays suffers from a lack of standardization and reproducibility of results. This primarily stems from data quality and variability, as well as from the choices made within various radiomics software, like the interpolating algorithms selection or the voxel resampling method, which can impact the results.

In this context, our goals are to explore the impact of imaging modality on radiomic features and to assess how different radiomic software influence the data analysis and interpretation. To achieve that, the statistical reliability of CT and MRI lung cancer radiomics features, and the agreement between two freeware radiomics software, **Pyradiomics** and **LIFEx**, has been considered.

This study concerned CT and MRI images from 35 patients, analyzed by using 3 different voxels resampling and 66 selected features. Features have been chosen based on their stability following the Image Biomarker Standardization Initiative (**IBSI**) guidelines, and their consistent mathematical definitions across both software. Pyradiomics-LIFEx correlation for each imaging technique, and CT-MRI data correlation for each radiomics platform, have been investigated through the Intraclass Correlation Coefficient (**ICC**). Considering the agreement between the two software (investigated for each technique separately), good/excellent ICC values have been obtained by nearly 90% of MRI features and by nearly 92% of the CT ones. This demonstrates the effectiveness of the IBSI guidelines, and the two software compliance. When focusing on CT, the agreement among software is minimally affected by the resampling method, whereas for MRI, the number of features exhibiting good/excellent ICC is more dependent on the resampling technique. That can be related to the fact that MRI images are noisier than the CT ones.

On the other hand, by comparing the CT and MRI techniques, less than 10% of features of both radiomics software showed a good/excellent ICC. This is a well-known result as the two modalities (CT and MRI) rely on different physical principles, and thus they are expected to provide complementary information to be used in a multi-modal diagnosis approach.

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# POSTER SESSION 1/D
# MOLECULAR MAGNETISM

# Preliminary EPR Studies on Single Molecule Magnets Aimed to be Used for the Detection of Particles in the NAMASSTE Experiment

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The development of new devices for the detection of particles based on the use of single molecule magnets (SMMs) is one of the aims of the NAMASSTE experiment (funded by INFN-Group V).

SMMs are crystalline materials made of identical isolated magnetic molecules [1] that, at very low temperatures and in an external magnetic field, show a metastable state that can be adjusted to be highly sensitive to an external perturbation, such as the one due to the interaction with an impinging particle. Therefore, SMMs can be potentially employed as quantum sensors, resulting at the base for new detection techniques, eventually applicable in the design of innovative experiments, for example for the dark matter research [2].

In NAMASSTE, the effect of low activity radioactive sources on the SMMs is investigated by Electron Paramagnetic Resonance (EPR) and Nuclear Magnetic Resonance (NMR) spectroscopies, as well as by SQUID magnetometry. The innovative approach employing EPR and NMR is expected to be more sensitive than the detection techniques currently under investigation [2,3], based on the variation of the magnetization over the entire volume of the sensor that is related to an "avalanche effect". A comparative study among the different detection methods is ongoing using the well-known $Mn_{12}$ SMM.

Moreover, from the collaboration with theoreticians of the field, the development of a model for the SMM-particle interaction, which is currently absent in literature, is in progress.

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# Spin Electric Effects Revealed by Electric Field Modulated EPR

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Magnetoelectric and multiferroic materials have the potential to disclose new technological concepts [1,2] with possible benefits for humankind. The microscopic understanding of the properties of these materials is fundamental for their development to a more mature stage and application.

The Electric Field Modulated Electron Paramagnetic Resonance (EFM-EPR, Figure 1), a recently implemented technique in our lab, which allows performing EPR under an electric field, has been proven to be very effective for the in-depth comprehension of the spin-electric effects in magnetic molecules. For an application perspec- tive, spin-electric effects are relevant for quantum technologies as an electric field can control the spin state of magnetic molecules, with several advantages with respect to the standard control based on magnetic fields.

An overview of the EFM-EPR based studies realized so far on different magnetic molecules [3-5] will be presented with a particular emphasis on how the electric field can affect the exchange interaction.
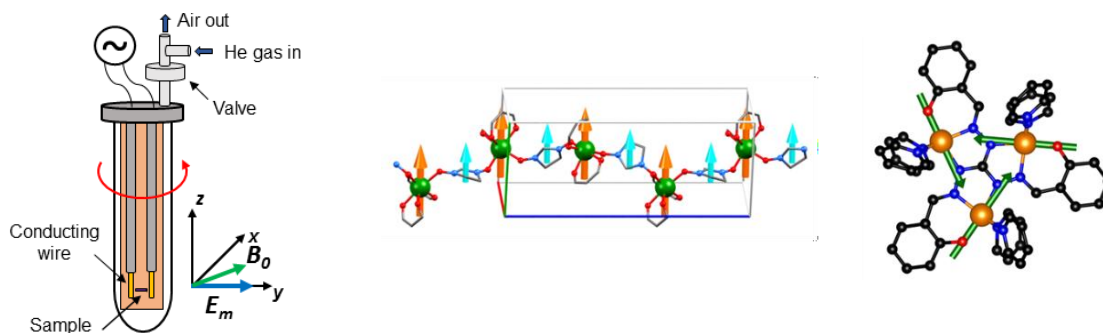


**Fig. 1** Left: schematic view of the modified version of the sample holder used for the EFM-EPR measurements. The electric field (Em) is obtained by applying an alternating voltage $V = V_0\cos(\omega t)$, with $V_0 = 170$ V over a distance of 1.5 mm, and $\omega = 2\pi \times 30$ kHz; Right: crystal structure of a molecular helix [3] and molecular structure of a spin trimer [5] studied by EFM- EPR.

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Manuscript in preparation.

# Anomalous Spin Dynamics of Tb-based Molecular Nanomagnets

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Over the past decades, molecular nanomagnets (MNMs) or single-molecule magnets (SMMs) [1] have increasingly become one of the research hostspots in molecular magnetisms due to their rich novel quantum phenomena. Accordingly, MNMs have garnered substantial attention as promising candidates for both applications in spintronics and quantum information processing. Currently, mononuclear lanthanide SMMs (Ln-SMMs) complexes usually identified as single-ion magnets (SIMs) [2] are reported to be one of the best candidates for realization of this technology. SIMs own large magnetic anisotropies which can generate high energy barrier and magnetic blocking temperature characterized by slow magnetic relaxation. However, even though with such ambitious applications, it is believed that fast spin-lattice relaxation and quantum tunneling of magnetization (QTM), dipolar or hyperfine interactions can reduce the energy barrier, thus limiting the ceiling of the relaxation time. Therefore, it is necessary to investigate and control the variables determining the dynamic magnetic properties of these systems and the role that each interaction plays in driving the relaxation dynamics. This requires studying and disentangling the relevant relaxation mechanisms at play like Quantum Tunneling of the Magnetization (QTM), direct, Raman and Orbach mechanisms. They are directly or indirectly affected by the presence of concomitant interactions (spin-orbit, crystal-field, hyperfine, exchange and spin-phonon coupling) which span several orders of magnitude of the energy scale.

In the present work, we investigate the magnetic properties and spin dynamics of $Tb(DTBSQ)(HBPz_3)_2$ (in short Tb-SQ) and $Tb(Trp)(HBPz_3)_2$ (in short Tb-Trp) (DTBSQ=3,5-di-*tert*-butylsemiquinonato, Trp=tropolonate, $HBPz_3$=hydrotrispyrazolyl-borate) by means of ac susceptibility and longitudinal field muon spin relaxation (LF-µSR) measurements. The reason for choosing these ligands is justified by the *paramagnetism* of semiquinonato (SQ), thus giving an effective Ln-radical exchange interaction, while tropolonato (Trp) is *diamagnetism.*

For Tb-SQ (paramagnetic ligand) the longitudinal muon relaxation rate $\lambda(T)$ peak qualitatively follows a Bloembergen-Purcell-Pound (BPP)-like behavior, according to a thermally activated correlation time. However, this law is not followed quantitatively, especially for low fields, probably because of the non-zero additional internal field, possibly of the order of 1 kG, insurging in the blocked regime for T —> 0. Remarkably, the Tb-trp (diamagnetic ligand) shows a qualitatively opposite behavior to the BPP scaling vs field, with a sizeable increase of the relaxation peak when the field is increased. This is at odds with the behaviour typically followed by most of the molecular nanomagnets. A qualitatively similar behavior has been recently found in the Dy-trensal (diamagnetic ligand) [3]. These results indicate that the spin dynamics of these SIMs is intrinsically more complex than usual and highly affected by the ligand, mainly via the exchange coupling, and possibly by the rare-earth ion (e.g. via its parity and or total electrons).

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# Thermal switching of the magnetic anisotropy in a molecular layer assembled on surface

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Magnetic anisotropy represents a crucial property for the development of novel magnetic materials and this is also the case of molecular systems. [1] The control of the magnetic anisotropy on surface might enable the development of molecular-based spintronic devices. Here, we show the temperature driven control of the magnetic anisotropy of a monolayer of molecules assembled on surface.

The present study was carried out on the trigonal lanthanide complex Nd(III)*trensal* (H$_3$*trensal* = 2,2',2''-tris(salicylideneimino)triethylamine), deposited via sublimation on highly oriented pyrolytic graphite (HOPG), obtaining a 2 nm thick film. The molecules in analogy with the earlier studies on the isostructural Er*trensal* complex [2,3] self-assemble with a preferential orientation on surface as confirmed via an X-ray Natural Linear dichroism experiment. The magnetic properties of the film were determined performing a variable temperature X-ray Magnetic Circular Dichroism (XMCD) spectra at the SOLEIL synchrotron exploring several orientations of the sample in a 6 T magnetic field. Our study flanked by chemical and morfphological characterizations, proves that this system retains their intact chemical structure, organizes on a regularly dense film and maintain their capability of reversibly switching their magnetic anisotropy down to the nanoscale.[4]

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# Effects of Magnetic Center Substitution on Magnetic Properties and Spin Dynamics in Ln-based complexes

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The investigation of molecular nanomagnets (MNMs) [1] provided model systems to study new quantum phenomena at the nanoscale level in low–dimensional systems. In single molecule magnets (SMMs) [2] and, recently, in single ion magnets (SIMs) [3], adjacent molecules can be considered as quasi-non-interacting magnetic units. These systems have been thoroughly investigated both for their peculiar quantum properties [4] and for their possible technological applications [5]. In this study, within the italian INFN NAMASSTE Project, we studied spin dynamics [6] and magnetic properties of two lanthanide-based complexes $(Ln(DTBSQ)(HBPz_3)_2$ with Ln = Tb, Dy [7], Tb-SQ and Dy-SQ in short) as a function of temperature (1.9K < T < 300K) and magnetic field applied ($\mu_0H$ = 0.5; 1.5; 3.42; 3.46T) through ${}^1H$ NMR and dc/ac susceptibility measurements. The investigation of these two systems allowed us to: (i) obtain, in the paramagnetic regime, the correct order of magnitude of the squared hyperfine dipolar coupling constant; (ii) extract the value of a high–T energy barrier corresponding to the gap among the ground state and the excited states in accordance with the calculated energy levels obtained from the susceptibility data; (iii) prove the complementarity of ac susceptibility and NMR techniques for the study of the spin dynamics in different timescales.
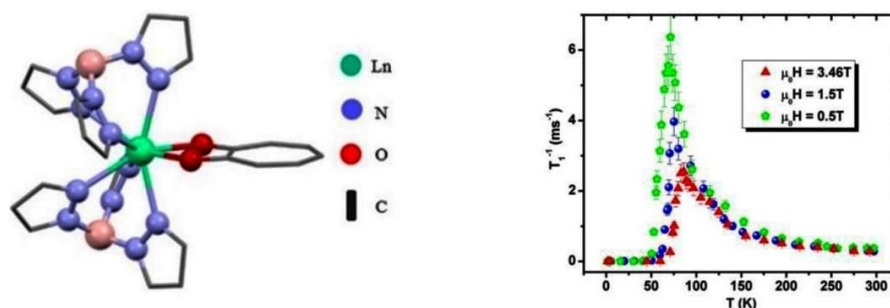


**Fig. 1** Molecular Structure of Ln – SQ complexes (left); (T1)-1 vs T curves at different applied magnetic fields in DySQ (right)

In conclusion, this research activity allowed us to point out how a different Ln magnetic center, bound to the paramagnetic semiquinone ligand, can influence the physical properties due to different magnetic anisotropy, crystal field and Ln - radical ligands interaction.

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# A Proficient Multivariate Approach for Iron(II) Spin Crossover Behavior Modelling in the Solid State

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Iron(II) *bis*-pyrazolilpyridyl (bpp-R) complexes with general formula $[Fe(bpp-R)_2](X)_2 \cdot solv$, where R = substituent on the bpp ligand (mainly on the central pyridyl ring), $X^-$ = anion, and solv = co-crystallized solvent molecules, can undergo spin transition from high spin ($S = 2$, HS) to low spin ($S = 0$, LS) upon cooling showing the spin crossover (SCO) phenomenon in the solid state [1], or they can be blocked in one of the to spin states [2]. The magnetic behavior is mainly influenced by the degree of distortion of the octahedral coordination environment around the metal center. This is in turn governed by the crystal packing, i.e. the intermolecular interactions among the substituent R of the bpp ligands, the anion $X^-$ and the co-crystallized solvent, if present.

In this contribution, an innovative multivariate approach, through the combination of the chemometric tools Principal Component Analysis (PCA) and Partial Least Squares (PLS) regression, will be presented. This approach was applied on the coordination Fe–N distances and N–Fe–N angles and selected torsional angles of the available HS structures in the literature, and the obtained results can efficiently model and rationalize the structural data distinguishing between SCO-active and HS-blocked complexes bearing different R groups, $X^-$ anions, and co-crystallized solvents (**Fig. 1**), and help predict the spin transition temperature $T_{\frac{1}{2}}$ [3].

The use of these models for gaining information on isostructural cobalt(II) complexes $[Co(bpp-R)_2](X)_2 \cdot solv$ with single-molecule magnet behavior [4] will be also discussed.
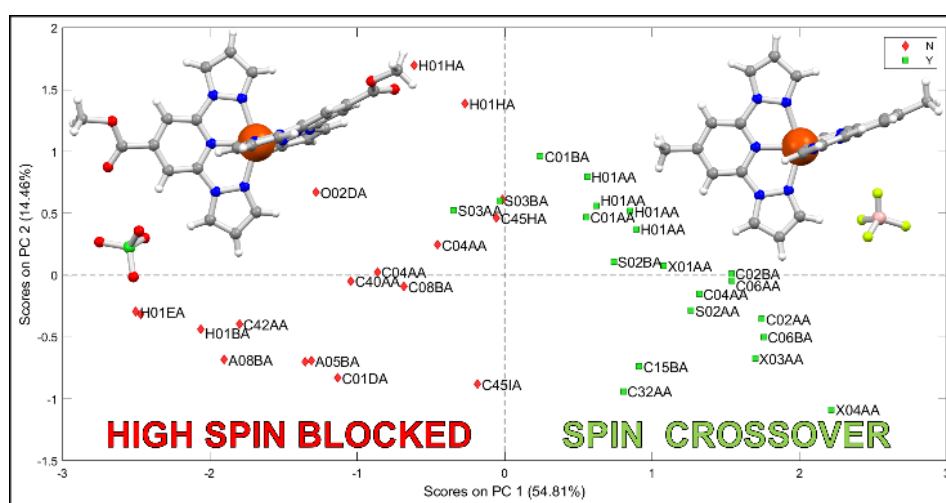


**Fig. 1** PCA model for solvent-free complexes and their division in HS-blocked and SCO-active complexes.

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# Investigating the magnetic properties of the [Cu(dttt)$_2$] qubit in different environments: moving from the bulk-phase to the surface

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The state-of-the-art in extremely coherent spin-based molecular qubits are dithiolene-based coordination compounds comprising $Cu^{2+}$ and $VO^{2+}$ ions [1,2]. In this paper, we present the almost unexplored hydrogen-free mono-negative **1,3,2-dithiazole-4-thione-5-thiolate** (**dttt$^-$**) ligand, reporting for the first time the synthesis and structural characterization of its $Cu^{2+}$, $Ni^{2+}$, and $Pt^{2+}$ neutral complexes in square-planar coordination (Fig.1) [3]. A combined DC magnetometry-ab initio approach was used to explore the magnetism of pure substances. This revealed AF interactions of 108 cm$^{-1}$ and 36 cm$^{-1}$ for the two pure [Cu(dttt)$^2$] crystalline phases, which are mediated by S···S intermolecular VdW interactions and propagate along 1D chains of paramagnetic sites.

When $Cu^{2+}$ spin centers are diluted in diamagnetic host frameworks (e.g., $Ni^{2+}$ and $Pt^{2+}$ analogs), [Cu(dttt)$_2$] units lose long-range interactions and behave as potential qubits. The static characteristics and spin dynamics of solid-state magnetically diluted samples were investigated using X-band and Q-band EPR techniques. The observed $T_m$ = 2.3 µs at 30 K is less than the predicted one > 100 µs, demonstrating that the diluting matrix may have a significant impact on the coherence duration of $Cu^{2+}$ electron spin. We propose that the contributions of nearby $^{14}N$ nuclei and the non-completely controlled production of radical impurities are the primary drivers of decoherence in this system.

These systems are also ideal for surface deposition by thermal sublimation due to their neutral character. The XPS investigation of [Cu(dttt)$_2$] thermal depositions under UHV conditions shows that films of intact molecules can be deposited on non-metallic surfaces via sublimation. Magnetic characteristics are also retained, according to EPR characterization of a thick deposit on Kapton. The magnetism and organization properties of single- and multi-layers of [Cu(dttt)$_2$] were also investigated using XMCD and XNLD, indicating that when a monolayer is grown on graphene/SiC(1000), both planar ordered structures and magnetic properties typical of an exchange coupled system are likely to be maintained. Thermal sublimation will permit dispersion in other matrices more suited for coherent spin manipulation due to the possibilities provided by these systems' thermal stability.
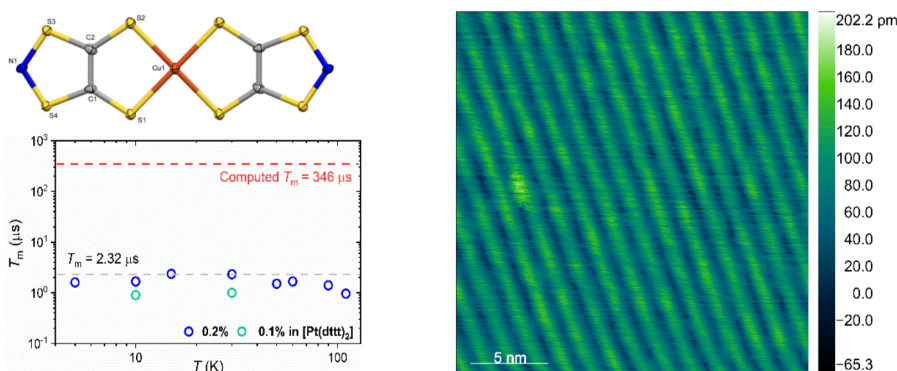


**Fig. 1** On the left, molecular structure of [Cu(dttt)$_2$] and plot of $T_m$ vs. $T$ extracted from EPR measurements. On the right, STM image of [Cu(dttt)$_2$] deposited on graphene/SiC(1000).

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# POSTER SESSION 1/E
# NANOMAGNETISM, NANOPARTICLES AND NANOSTRUCTURE

# Hardening of magnetic nanoparticles by solvent-mediated local strain release

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In this work, we demonstrate that a solvent mediated annealing process in mild condition is an effective post-treatment tool for improving the magnetic properties of chemically synthesized nanoparticles.[1] To this aim, non-stoichiometric cobalt ferrite particles of average size of 32(8) nm (see Fig. 1a) were synthesized by thermal decomposition [1] and further subjected to solvent mediated annealing at variable temperatures between 150 °C and 320 ºC in inert atmosphere. The post-synthesis treatment produces a 50% increase of the coercive field (see Fig. 1b), without affecting neither the remanence ratio nor the spontaneous magnetization. As a consequence, the energy product and the magnetic energy storage capability, key features for applications as permanent magnets and magnetic hyperthermia, can be increased by ca. 70%.

A deep structural, morphological, chemical, and magnetic characterization reveals that the mechanism governing the coercive field improvement is the reduction of the concomitant internal stresses induced by the mild annealing post-synthesis treatment (see Fig. 1c). Furthermore, we show that the medium where the mild annealing process occurs is essential to control the final properties of the nanoparticles, since classical annealing procedure performed on a dried powder does not allow the release of the lattice stress, leading to the reduction of the initial coercive field (see Fig. 1c). The strategy here proposed, therefore, constitutes a new method to improve the magnetic properties of nanoparticles, which can be particularly appealing for those materials, as is the case of cobalt ferrite, currently investigated as building blocks for the development of novel rare-earth free permanent magnets. [1-3]
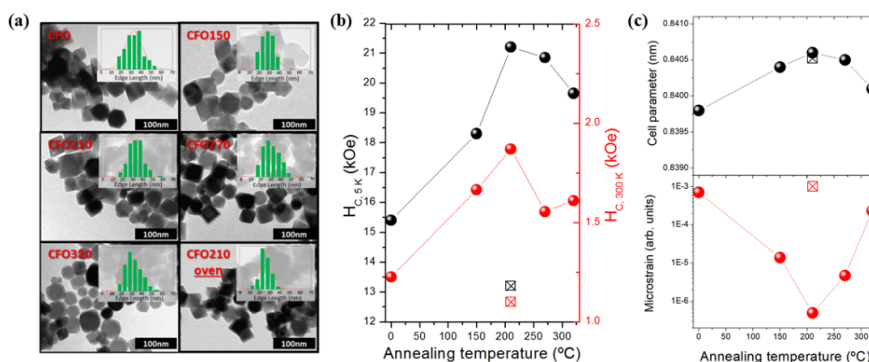


**Figure 1.** (a) Selected TEM images and corresponding particle size histograms for as-prepared and annealed nanoparticles. (b) Coercive field (HC) dependence measured at 5 K and 300 K as a function of the annealing temperature (empty dots refer to the oven annealed sample). (c) Cell parameter and microstrain dependence on the annealing temperature (empty dots refer to the oven annealed sample).

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# Magnetic Hyperthermia and Hadron Therapy Applied to 3D Cellular Scaffolds

**Francesca Brero**[1,2], **Martin Albino**[3,4], **Paolo Arosio**[5,2], **Luca Bocchino**[5], **Federica Carnevale**[6], **Mario Ciocca**[6], **Angelica Facoetti**[6], **Marta Filibian**[7], **Salvatore Gallo**[5,2], **Flavia Groppi**[5,2], **Claudia Innocenti**[4], **Anna Laurenzana**[8], **Cristina Lenardi**[5,2], **Silvia Locarno**[5,2], **Simone Manenti**[5,2], **Manuel Mariani**[1,2], **Francesco Orsini**[5,2], **Marco Piazzoni**[5,], **Margherita Porru**[1,2], **Camilla Recordati**[9], **Claudio Sangregorio**[3,4], **Francesca Scavone**[8], **Ivan Veronese**[5,2] and **Alessandro Lascialfari**[1,2]

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Utilizing nanoparticles (NP) in the biomedical field holds the promise of revolutionizing healthcare by enabling precise drug delivery and targeted therapies. In particular, magnetic nanoparticles for magnetic fluid hyperthermia (MFH) are an innovative avenue in oncology, providing a highly localized method to treat tumors.

The ongoing project aims to assess the antitumor efficacy of proton therapy and magnetic hyperthermia, applied to 3D scaffolds. Building upon the *in vitro* results obtained with the BxPC-3 cell line [1,2], transitioning to the use of scaffolds will enable a closer approximation to *in vivo* conditions.

Within this framework, the hyperthermia efficiency (Specific Absorption Rate, SAR) of 19 nm maghemite-based NPs, with different polymeric coatings, was evaluated at various alternating magnetic field strengths and frequencies to determine the optimal conditions for hyperthermia treatment, considering the patient safety guidelines as well.

Moreover, in order to determine if the investigated NPs could be good candidates for being theranostic systems (carrying out the dual-function of improving the MRI contrast and releasing heat for MFH therapy) we assessed the MRI contrast efficiency by acquiring NMRD profiles at room temperature (longitudinal $T_1$ and the transverse $T_2$ relaxation times from 10 kHz up to 60 MHz).

Furthermore, non-destructive localization of tumor cells and NPs within the 3D scaffolds, was accomplished through $T_1$-Weighted and $T_2/T_2$*-weighted 7 Tesla MRI acquisition protocols.

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# Magnetocrystalline Anisotropy of Heavy Rare-Earth Atoms on Graphene: from DFT to Crystal Field Theory

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Motivated by experimental advancements in the field of rare-earth (RE) atoms adsorbed on surfaces and 2D-materials [1,2], we propose a first-principles Density Functional Theory (DFT) study on a selected set of heavy rare-earths atoms (Dy, Ho and Tm) deposited on a graphene monolayer, where the primary objective is to unveil their ground-state electronic and magnetic properties. The choice of graphene as a 2D-material is closely linked to various theoretical and experimental studies where graphene is frequently employed as a decoupling layer between the rare-earth and the substrate [3-5]. This serves to reduce potential scattering processes, often source of magnetic instability. The focal point of this study [6] involves the application of the DFT+U method [7,8] to calculate the magnetic anisotropy of the RE/graphene complexes, which allows for identification of the easy-axis of magnetization and to fit the magnetic anisotropy constants. The significant magnetic anisotropy energy, amounting to several meV, arises from the inherent strong spin-orbit coupling interaction combined with the influence of crystal field effects on the localized _4f_ electrons. The angular dependence of this anisotropy energy is determined by the $C_{6v}$ symmetry of the graphene monolayer and the orbital moment of the _4f_-shell. An approach is introduced for "reverse-engineering" the crystal field parameters starting from the classical anisotropy constants. This permits to determine the splitting of the magnetic multiplets $J_z$, a critical factor in detecting potential quantum tunneling of magnetization effects and, by extension, assessing magnetic stability. Additionally, we investigate the effects of perpendicular mechanical deformation on the system by conducting simulations at various strain levels. Remarkably, the large spin and orbital moments of open _4f_-shells generate a strong magneto-elastic coupling, providing opportunities for flexible manipulation and control of the magnetic state in rare-earth systems.
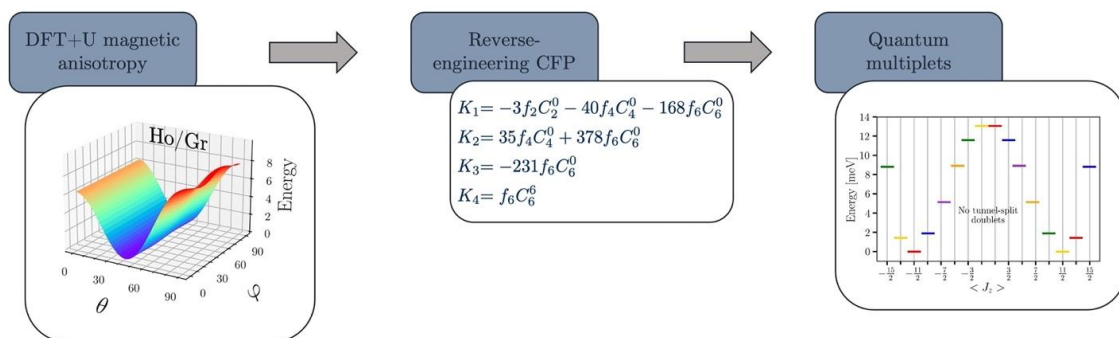
**Fig. 1** Reverse-engineering the crystal field parameters (CFP) from ab initio DFT calculations. The classical magnetic anisotropy curves of rare-earth/graphene systems are fitted to extract the anisotropy constants Ki. Using a first-order perturbational approach, the CFP are computed and employed to diagonalize the crystal field matrix for the multiplets.

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# Understanding The Effects of Cation Exchange On Magnetic Oxide Nanoparticles By Combining Electron Microscopy and DC Magnetometry

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The concept of tuning the magnetic behavior of a given population of nanoparticles (NPs) by mixing diverse magnetic phases is a longstanding and challenging research topic, since complex multi-component structures can provide radically different magnetic response with respect to typical single-phase nanostructures. However, unravelling how different contributions impact in the final magnetic features is a non-trivial task, given the strict bond between fine structural features and physical properties. In this context, synthetic approaches based on cation exchange (CE) of iron oxide-based NPs have been reported in recent years to offer a valuable tool to disentangle the contributions to magnetic response given by structural features, since CE modifies the NPs composition while maintaining their original shape and size unaltered. Indeed, this synthetic strategy is a quite popular tool to modify the composition of many semiconductor nanomaterials but was seldom applied to iron oxide NPs, where the substitution of iron with diverse transition element cations is expected to modify their overall magnetic response. In fact, the few studies devoted to this kind of approach assumed a CE over the whole volume of the NPS, but were quite discordant.

We combined TEM-based deep structural and compositional studies with DC magnetometry to different iron oxide-based NPs to clarify the discordances reported in literature and a gain a consistent and complete view of the effects of CE on this class of materials. The results of our studies point unequivocally to the fact that CE reactions start at the NPs surface and lead to core/shell structures, with only the newly-formed shell being affected by the CE. In fact, we discovered that pushing the conditions for CE to the limit lead to the formation of nanoflowers and a loss of initial shape and size. [1] Also, we expanded the scope of our studies by using elongated NPs as starting points for CE and showed that this process is not driven by factors of shape or size, but is drastically influenced by the iron oxide starting phase. [2] Indeed, stoichiometric phases, like magnetite, are structurally free of vacancies and provide a low number of iron cations to be replaced at the surface; conversely, wüstite, which is structurally prone to vacancies, showcases a boosted cation exchange reactions for iron, leading to quite thicker shells displaying different composition and a related change in magnetic behavior. [3]

The resulting materials exhibit interesting and complex magnetic properties, whose interpretation was possible by combining structural and compositional analysis with DC magnetometry. This led to realizing that the complex NPs formed by CE approach actually feature multiple magnetic shells, with a first thin intermediate one that cannot be directly observed by TEM, but whose presence is evident thanks to its magnetic response.

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# Study of the temperature dependence of the coercive field of Cobalt-ferrite nanoparticles

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We have investigated the reversal processes of magnetization of Cobalt ferrite(CFO) nanoparticles that exhibit high magnetic anisotropy and coercive field ($H_C$). CFO is between the spinel ferrites the one that exhibits larger magnetic anisotropy. However, the coercive field of bulk oxide is in general small due to the cubic symmetry of the magneto-crystalline anisotropy. Recently, several studies [1-6] have observed high $H_C$ in CFO nanoparticles at room temperature being potentially considered as materials to develop rare-earth free magnets [1-7]. In particular, we have demonstrated [3] that NPs of 40 nm of diameter exhibit $H_C$ and (BH)max competitive with those of commercial M-type hexaferrites.In addition, a solvent mediated annealing allow to improve further the $H_C$ [7]. However, in most of these studies a strong decreasing of the Hc from low temperature to room temperature was observed. This affects to the potential application of these materials as permanent magnets. The understanding of the physical mechanisms that give rise to the temperature decrease of the $H_C$ is necessary to design nanomaterials applied as permanent magnets.

We have investigated the magnetic properties of non-stoichiometric cobalt ferrite ($Co_{0.6}Fe_{2.4}O_4$) particles of an average size of 30nm synthesized by thermal decomposition and further subjected to solvent mediated annealing at variable temperatures between 150 ºC and 320 ºC in inert atmosphere [7]. The post-synthesis treatment produces a 50% increase in the coercive field. The temperature dependence of the hysteresis was measured from 5 K to 400 K. All the samples exhibit a continuous decrease of the $H_C$ and specific magnetization while remanence remains almost constant until 200°C and it drops at larger temperatures. We have analyzed these results considering the effect of the thermal activation process and the temperature dependence of the magnetic anisotropy which are not enough to explain the reported results. Also we will consider the effect of different reversal modes. Finally, we will discuss on the possible guidelines to improve the coercive field of these nanomaterials

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# Magnetic response of Nano/Microparticles into Elastomeric Electrospun Fibers

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The combination of magnetic nanoparticles (MNPs) with high-voltage processes to create ultra-thin magnetic nanofibers (MNFs) holds great promise for advancing next-generation technologies. In this research, we employed the electrospinning technique to produce nanofibers made of polycarbonate urethane, incorporating magnetic particles.

Two types of magnetic payloads were utilized in our study. The first type consisted of iron oxide nanoparticles (IONPs) with an average size of 7.2 nm and a polydispersity index of 3.3%. The second type involved nickel particles (NiPs) with a bimodal size distribution, featuring average sizes of 129 nanometers and 600 nanometers, and corresponding polydispersity indexes of 27.8% and 3.9%.

Due to the varying particle sizes, we observed significant differences in their aggregation and distribution within the nanofibers. The magnetic behavior of the fiber mats loaded with IONP and/or NiP was consistent with their respective morphology and polydispersity index. IONPs exhibited superparamagnetic behavior since their average size falls below the typical upper limit for superparamagnetic behavior, which for IONPs is in the range of 20-30 nm. This was evident from both the remanence ratio ($M_r/M_s$) and the coercive field ($H_c$) measurements, which were zero.

Conversely, NiPs exhibited a remanence ratio of 22% with a coercive field of 0.2 kOe, consistent with the behavior expected for particles in a single or pseudo-single domain state interacting through dipolar forces
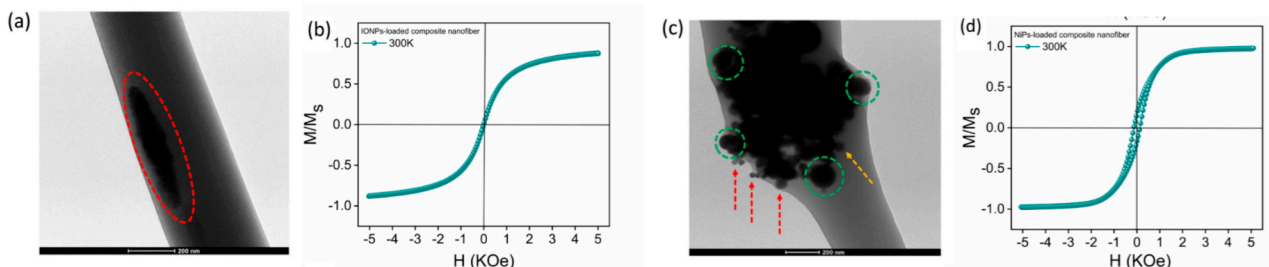


**Fig. 1** TEM Images and Hysteresis Loops of Loaded Composite Nanofibers. (a) typical TEM image of an IONP-loaded composite nanofiber. The red circle highlights well embedded MNPs within the fiber; (b) hysteresis loop of an IONP-loaded nanofiber mat; (c) typical TEM image of a NiP-loaded composite nanofiber. Green circles indicate the presence of large agglomerates with different sizes/ morphology, while yellow arrow points to small particles inside the fiber. Smaller NiPs near the fiber's edge are marked with red arrows; (d) hysteresis loop of NiP-loaded nanofiber mat. Both cases feature the same nominal volume fraction of magnetic particles (IONPs or NiPs) set at 15% by volume.

In conclusion, we have demonstrated that the magnetic properties can be modulated by controlling the average size and polydispersity index of the magnetic particles integrated into fiber mats. This approach allows for the design of magnetically active systems tailored for various applications, including wound healing and drug delivery.

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# Emission and Absorption Magneto-optical properties of Lead Bromide Perovskite Nanocrystals

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Lead halide perovskites are emerging materials for optoelectronics and have driven a steep increase in the performance of solar cells and light emitting diodes during the past 10 years.[1] Lead halide nanocrystals (NCs) have shown impressive emissive properties, with quantum yield approaching 100%, and tunable absorption and photoluminescence.[2] However, the origin of the exciton fine structure in lead halide perovskite NCs is still matter of debate. Indeed, several works explain the exciton fine structure with crystal field anisotropy,[3] while other works claim the occurrence of Rashba effect.[4] The determination of the exciton binding energy and exciton effective mass is another challenging task.[5] To this aim, the most established technique is represented by magneto-absorption measurements performed at high magnetic fields (10-30 Tesla). This approach has been applied to bulk single crystals,[6] thin films[7] and single NCs[8] of halide perovskites.

In this contribution, we propose the use of Magnetic Circular Dichroism (MCD) and Magnetic Circularly Polarized Luminescence (MCPL) to characterize the effect of magnetic fields on the exciton energy levels both in absorption and emission in ensembles of ≈10 nm $APbBr_3$ NCs (with A=Cs, formamidinium or methylammonium) with cubic morphology. Differently from high magnetic field measurements, here we work in a perturbative regime (applied fields of the order of 1 Tesla). Moreover, we take advantage of polarization modulation and phase-sensitive detection that enable to measure very small differences in absorbance or luminescence with high sensitivity. This approach avoids the need for high magnetic fields to directly visualize the field-induced energy shift of the optical response. A fitting approach was employed to extract fundamental parameters of the exciton from the MCD and MCPL spectra of the perovskite NCs.

The approach could be potentially applied to different perovskite NCs and could represent a precious tool to extract exciton parameters, as well as their variation with the environmental conditions such as humidity, temperature and UV excitation power.

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# Size Dependence of Surface Spin Disorder in Ferrite Nanoparticles

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Surface spin disorder or canting arises from the breaking of exchange bonds and the breaking symmetry of the lattice, and thus crucially determines the performance of magnetic nanoparticles (NPs) and their potential technological and biomedical applications [1,2]. Despite an enormous interest and technological relevance of magnetic NPs, there is still a lack of knowledge on the magnetic NPs spin structure. Due to the surface-to-volume ratio, surface effects will be closely related to the particle and coherent domain size. However, it is difficult to isolate the surface contribution from the bulk effects using macroscopic magnetization techniques, such as magnetization measurements, ferromagnetic resonance, Mössbauer spectroscopy [3], x-ray magnetic circular dichroism [4], and electron energy loss spectroscopy [5]. A spatially resolved magnetization is required to unveil and disentangle the surface contribution. Half-polarized small angle-neutron scattering (SANSPOL) enables us to investigate the magnetization on the nanometer scale [6]. Our previous study has proven that the magnetic volume in ferrite NPs is not fixed at the coherent domain size but increases with the applied magnetic field [7]. This implies that the applied magnetic fields polarize the disordered surface spins, leading to an increase in the magnetic size of the NPs [7].
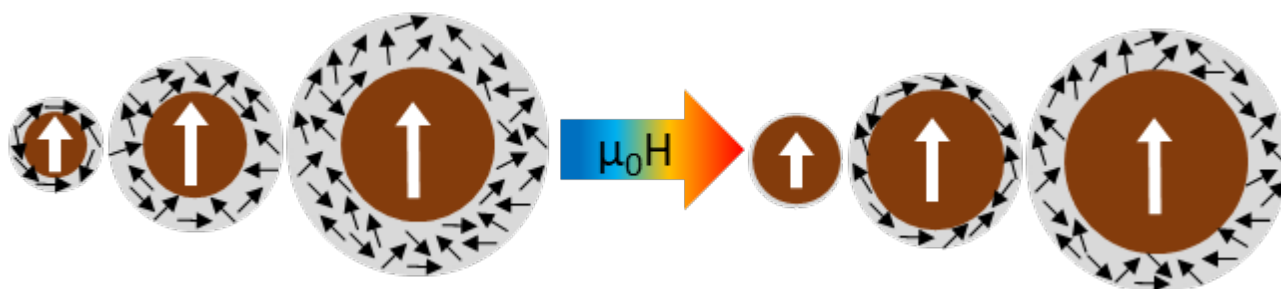


**Fig. 1** Schematic presentation of the size dependence of magnetized volume growth in applied magnetic field. Grey and brown particle part corresponds to the disorder and magnetized volume of nanoparticles.

In this contribution [9], we will present the size dependence of the disorder energy and the surface anisotropy in spherical $CoFe_2O_4$ NPs with different coherent domain sizes range of 3.1(1), 6.3(2), and 8.6(1) nm synthesized using the oleate-based solvothermal method [8] with narrow size distribution confirmed by transmission electron microscopy (TEM) and small-angle x-ray scattering (SAXS). Rietveld's analysis shows that coherent domain size is smaller than mean particle size, suggesting a possible presence of a spin disorder or canting. The spatial magnetization distribution obtained from SANSPOL reveals significant magnetic field dependence of magnetized volume for each sample, but with different degrees of the total magnetized NP volume. Ultimately, we will discuss the particle and coherent size dependence of the surface anisotropy constant.

## Acknowledgements

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# Seeing an old synthesis through a new lens: coprecipitation-based ultrasmall and ultrastable SPIONs as MRI contrast agents

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Magnetic Resonance Imaging (MRI) is a non-invasive imaging technique for clinical diagnosis and research purposes. The diagnostic efficacy of MRI is greatly enhanced by contrast agents, which improve image contrast mainly by locally shortening the longitudinal ($T_1$) and transverse ($T_2$) relaxation times of water protons. Gadolinium-based contrast agents considerably shorten the $T_1$ relaxation time, leading to a marked positive contrast in $T_1$-weighted images. However, Gd-based contrast agents entail a series of health risks. Superparamagnetic iron oxide nanoparticles (SPIONs) are increasingly studied as alternative contrast agents, as they are biocompatible and can be detected in smaller concentrations. Nonetheless, most SPIONs act as $T_2$ contrast agents, hence they provide a negative contrast in $T_2$-weighted images [1]. Remarkably, several recent papers reported their potential use as $T_1$ contrast agents when their size is sufficiently small (ca. <4 nm) [2]. These Ultrasmall SPIONs, or USPIONs, can be synthesized by iron salts reduction, thermal degradation, and co-precipitation. The co-precipitation approach has the lowest synthetic requirements, as it can be performed at room temperature and environmental conditions, in aqueous solvent and using low-cost chemicals with the least amount of time. However, this method generally produces larger and more polydispersed nanoparticles compared to other synthetic routes and it requires careful operational precision.

In this work, a new and robust coprecipitation method was developed for the synthesis of USPION aqueous suspensions characterized by high monodispersity and colloidal stability for applications as $T_1$ contrast agents.

The general procedure adopted involved the base-induced co-precipitation of iron oxides from a $FeCl_3$ and $FeSO_4$ mixture, followed by the addition of citric acid as stabilizing agent. Citric acid was selected due to its high biocompatibility and the ability to enhance electrostatic repulsion between nanoparticles, thus preventing aggregation over a wide range of pH at low to moderate ionic strength. Samples were characterized to study their morphology, dimension, chemical composition, magnetic properties and stability towards water and physiological buffer solutions. Despite coprecipitation is very well known for a long time, our synthesis retains the potential to further decrease the SPION size while retaining high crystallinity of the core.

The nuclear relaxation properties of the synthesized iron oxides nanoparticles coated with citrate were investigated by ^{1}H-NMR-D profiles, collected in the frequency range 0.01-57MHz. The range of frequency was selected to allow the investigation of the physical mechanisms responsible for nuclear relaxation through the analysis of the $r_1(v)$ and $r_2(v)$ relaxivity curves, and to cover several frequencies associated to the fields used by most common clinical imagers, i.e., $\mu_0 H$ = 0.2, 0.5, and 1.5 T (corresponding to ~8, 20, and 64 MHz). The NMR data show that the prepared nanoparticles have adequate longitudinal and transverse relaxivities to be used as diagnostic probe in MRI with both $T_1$ and $T_2$ Contrast Agent (CA) modalities. Preliminary MRI data obtained using phantoms filled with different concentration of proposed USPION aqueous suspensions at 1.5 Tesla static magnetic field were also performed.

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# From Nanoscale Magnetic Features to Macroscopic Properties: the Case of Bi-Magnetic Spinel Ferrite Nanoparticles

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Nanoparticles, exhibit unique physical properties that significantly differ from their bulk counterparts [1]. These properties, especially magnetic features , are highly sensitive to particle size and are influenced by both core and surface effects. The collective magnetic behavior of nanoparticle ensembles is also strongly affected by interparticle interactions, which can be dipole–dipole or based on exchange coupling between surface atoms [2].

The magnetic spinel ferrite nanoparticles are especially relevant for biomedical purposes, such as biosensing, imaging, and hyperthermia cancer treatment owing to their tunable magnetic properties and moderate cytotoxicity [3]. Understanding the origins of magnetic properties in these spinel ferrite nanoparticles is a key step to designing materials with optimized properties for specific applications. In this talk we summarize our current understanding of magnetism in spinel ferrite nanoparticles, with a focus on the interplay among the single particle anisotropy and interparticle interactions in nanoparticle ensembles, connecting nanoscale magnetic features to macroscopic properties.

This talk will focus on our current understanding of the importance of surface spin disorder, interface exchange interaction, magnetic anisotropy, and magnetic interparticle interactions in governing the collective magnetic behavior of spinel ferrite nanoparticle assemblies. We emphasize the interplay between intrinsic magnetic anisotropy of individual spinel ferrite nanoparticles, including those with bi-magnetic core/shell morphologies, and their interaction intensity and collective magnetic response [4, 5].

Specifically, the research delves into the magnetic properties of bi-magnetic core/shell nanoparticles composed of cobalt ferrite (CFO) and nickel ferrite (NFO), including investigations into the inverse configuration. The growth of a magnetically soft NFO shell affects the hard properties of the CFO seeds with a decrease of $\mu_0 H_C$ from ~1.3 to 0.8 T. On the contrary, the magnetically harder shell increases the coercivity of the NFO seeds from ~0.025 to 0.03 T. These changes cannot be explained quantitatively by a classical additive rule: a strong influence of the architecture was revealed in a clear interplay among intraparticle (i.e., proximity effects) and interparticle interactions. This effect has been investigated by the remanent plot technique (i.e., ΔM-plot). Then we applied the Monte Carlo simulation method to better understand the effect of different factors and for the first time in the core/shell system, the contribution of proximity effects in ΔM-plot has been highlighted. Implementation of this model allows one to design the material with desired magnetic properties.

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# Effects of Superstructure on the Magnetic Properties of Magnesium-Doped Maghemite Nanoparticles

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Magnetic iron oxides maghemite ($\gamma$-$Fe_2O_3$) and magnetite ($Fe_3O_4$) nanoparticles (NPs) attracted enormous attention due to their potential biomedical application. This interest is first of all caused by their tunable magnetic properties and moderate cytotoxicity. Both iron oxides have an inverted cubic spinel structure, however, the maghemite has cation vacancies in octahedral positions [1]. Missed $Fe^{2+}$ cations make maghemite more biocompatible because the $Fe^{2+}$ ions play a crucial in the catalytic activity of the spinel ferrite NPs. The cationic vacancies can be distributed randomly or form a superstructure with space group P4132 [2]. The effect of this superstructure on the magnetic properties of NPs still poorly documented in literature because usually the smallest particles do not reveal the superstructural features. Nevertheless, understanding this phenomenon will allow better control magnetic properties of NPs. For example, recently it was discovered that systematical doping of $Mg^{2+}$ into vacancy sites may significantly improve magnetic properties that allowed increase magnetic heat induction during magnetic hyperthermia for cancer treatment [3].

This work sheds light on the interplay of the superstructural and magnetic properties of maghemite-based NPs. A set of maghemite and maghemite doped with small amounts of $Mg^{2+}$ was prepared with the sol-gel auto- combustion method. Manipulation of reaction kinetics through the setting of temperature regime allowed preparation of NPs of the same size (~20 nm) and variating superstructural properties. Effects of doping and superstructure on magnetic properties were investigated with SQIUD magnetometry and Mössbauer spectroscopy in wide temperature and field ranges.

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# Iron Oxide-Based MNPs: Shape, Size and Coating Effect on their Hyperthermic and ^{1}H-NMR Relaxation Properties

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In nanomedicine the study of iron oxide-based magnetic nanoparticles (MNPs) is of great interest: they can be exploited as contrast agents for MRI and/or hyperthermic agents for tumor treatment (Magnetic Fluid Hyperthermia, MFH). Due to their magnetic nature, they shorten the nuclear relaxation times ($T_{1,2}$) of the hydrogen nuclei, enhancing the image contrast according to their bio-distribution, and, under alternate magnetic field conditions, they can release heat within the unhealthy tissues. The relaxation mechanisms involved in these processes are correlated to the shape, dimensions and coating of MNPs [1,2,3], characteristics on which this study is based. The optimization of their morpho-structural peculiarities (shape, dimensions, kind of core, magnetic ion, and coating), is an open challenge aimed to obtain more efficient therapeutic and diagnostic nanoelements.

This study is focused on two differently shaped sets of MNPs: nanospheres and nanoflowers with different sizes (from 11 to 25 nm), and coated with different biocompatible molecules (DMSA, PAA, and CM-dextran).
The samples are morpho-structurally and magnetically characterized by TEM, XRD, IR, TG, AFM and SQUID analysis. The relaxation properties of the colloidal MNPs dispersions are investigated by ^{1}H-NMR measurements of the longitudinal ($T_1$) and transverse ($T_2$) nuclear relaxation times as a function of frequency. The relaxivity ($r_i$, i=1,2) vs frequency (*i.e.*, static magnetic field), determines the MNPs' efficiency as MRI contrast agents. The relaxation times below 7.2 MHz have been measured utilizing the Fast-Field-Cycling (FFC) technique, which resorts to Pre-Polarized (PP) acquisition sequences (Saturation Recovery SR and Spin-Echo SE), while higher frequencies were explored by means of an electromagnet, using SR ($T_1$) and Carr-Purcell-Meiboom-Gill (CPMG, $T_2$) sequences. The hyperthermic efficiency was evaluated by measuring the Specific Absorption Rate (SAR), at different alternating magnetic field amplitude (4-50 mT) and frequency (102.2-971.2 kHz).

The morpho-structural and magnetic characterization confirmed the superparamagnetic nature of the cores and the presence of the coatings surrounding them. The behavior of the ^{1}H-NMRD longitudinal and transverse relaxation profiles are explained in terms of the different relaxation mechanisms and associated spectral densities, and are influenced sizeably by MNPs' shape, size, and coating. Similar conclusions can be traced for the heating release mechanisms and values.

By concluding, different size, coating, and shape lead to different spin dynamics, which depends on the physical mechanisms responsible for the nuclear relaxation dominating in a specific frequency region. By unravelling such mechanisms, we aimed at optimizing the morpho-structural and magnetic parameters for obtaining the best efficiency in MRI contrast and MFH heat release. Through the present study, we suggest some possible ways to tailor the investigated MNPs' microscopic characteristics for MRI and MFH use.

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# POSTER SESSION 1/F

# SUSTAINABLE MAGNETS AND MAGNETIC APPLICATIONS

# Facile and fast synthesis of highly ordered L1$_0$-FeNi nanoparticles

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The L1$_0$-FeNi binary alloy is a candidate for next generation rare earth-free permanent magnets (PMs) [1], which can revolutionize the high-performance PM market currently dominated by the Nd-Fe-B. However, the fabrication of the L1$_0$ phase is extremely challenging owing to the low atomic mobility below the chemical order/disorder transition temperature that kinetically limits the formation of the L1$_0$ phase [2]. Despite many efforts, the experimental results are still far from the theoretical predictions and the proposed approaches mainly involve complex and expensive protocols, which cannot be easily scaled-up for bulk production and/or result in a low amount of the L1$_0$ phase [2].

To overcome current limitations, we exploited an effective and easily scaled-up chemical synthesis method, already successfully used for other L1$_0$ alloys [3,4], to obtain highly ordered L1$_0$ FeNi nanoparticles by low-temperature reduction in a H$_2$ atmosphere (Fig. 1a) of two crystalline Ni-Fe complexes (Ni-nitroprussides or Fe-tetracyanonickelate) consisting of an ordered arrangement of Fe and Ni atoms with a 1:1 ratio on alternating planes [5,6]. The intrinsic order of the precursors, resembling the atomic arrangement of the L1$_0$ structure, allows reducing the energy (and then temperature and time) required to order the Fe and Ni atoms thus driving the formation of the L1$_0$ phase. Carbon coated (2-7nm) (Fig. 1c) FeNi alloy nanoparticles (20 – 120 nm) with a L1$_0$ phase percentage > 55% , high coercivity (up to 65 mT) and large saturation magnetization ($\sim$ 140 Am$^2$/kg, close to the bulk value) ) (Fig1b) were obtained  at low temperature (< 290 K) and reasonable time (< 24 h). Despite the coercivity is still far from optimal for a high-performance permanent magnet, the results clearly prove the effectiveness and high potential of the developed strategy, which can be exploited, after further optimization, for mass production of highly ordered L1$_0$-FeNi nanoparticles for next generation critical-element-free permanent magnets.
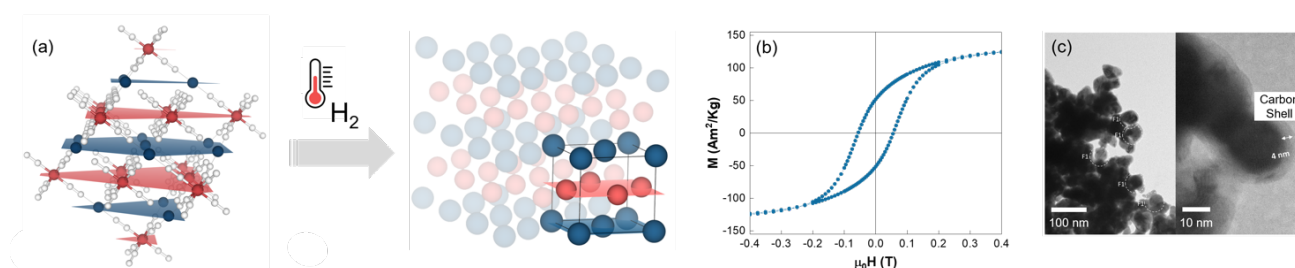


**Fig. 1** (a) Schematic representation of the synthesis process: from Ni/Fe crystalline complex (left) to L10-FeNi alloy (right). (b) Room temperature M(H) loop and (c) corresponding TEM image.

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# POSTER SESSION 2/A
# FUNDAMENTAL MAGNETISM

# Anomalous Cascade of Transitions in 5d[1] Re-based Double Perovskites $Sr_2ZnReO_6$ with Strong Spin-Orbit Coupling

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Recently, 5d-based DPs ($A_2BB'O_6$) have been the focus of a huge research interest in the condensed matter physics community due to the presence of exotic quantum phases such as the $J_{eff}$ = 1/2 Mott insulators, quantum spin liquids, field-induced quantum transitions, topological Mott insulators, and Weyl semimetals [1], which results from the comparable energies of strong spin-orbit coupling (SOC), on-site Coulombic (U) and crystal-field interactions.

Here we have determined the magnetic ground state of a high-quality high-pressure synthesized $Sr_2ZnReO_6$ polycrystalline sample by using magnetization, susceptibility, specific heat, dielectric and muon-spin rotation/ relaxation (µSR) measurements. In contrast to earlier measurements [2], with macroscopic probes we detect a more complex phase diagram, with three anomalies at 15, 35 and 60 K associated to three possible phase transitions. Magnetization hysteresis loops at different temperatures are consistent with a FM-like behavior below 15 K and with a weak ordered magnetic moment (~0.03 $\mu_B$) and a coercive field of 20 kOe at 2 K, an order of magnitude higher than previously reported [2]. Microscopic investigations by µSR confirm a long-range magnetic ordering below 15 K and indicates a weak magnetic glassines below about 35 K, while no specific magnetic signature is observed around 60 K. The possible origin of this cascade of transitions is discussed.

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# Unraveling the Magnetic Ground State and Microscopic Exchange Interactions in Na$_2$PrO$_3$

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The investigation of Kitaev spin liquids are of extensive interest owing to their intriguing potential for novel exotic magnetism, particularly the realization of quantum spin liquids in more than one-dimensional lattice geometries [1,2]. Dominant Kitaev interactions have been proven to be hosted typically by compounds with partially 5$d$ and 4$d$ states in the low-spin d$^5$ electronic configuration following the Jackeli-Khaliullin mechanism [1,2]. However, beyond this mechanism, dominant Kitaev interactions are also proposed to be hosted in Ce$^{3+}$ and Pr$^{4+}$ compounds with f$^1$ electronic configuration [3]. For instance, Na$_2$PrO$_3$ has been theoretically proposed [4] to host antiferromagnetic Kitaev model featuring anisotropic bond directional interactions, with J=1/2 Kramers spin-orbit-entangled local moment of the Pr$^{4+}$ cation 4f electrons.

In this presentation, we will show the results of muon spin spectroscopy and neutron scattering measurements accompanied by DFT and model Hamiltonian simulations, aimed at investigating the magnetic ground state properties and the underlying microscopic exchange interactions that characterize Na$_2$PrO$_3$, in search of signatures of Kitaev's interactions. A Néel AFM structure with an unusual small effective magnetic moment on Pr that are collinearly aligned along the c-axis with K= (0,0,0) propagation vector has been established with the muon data analysis. Analysis of the neutron scattering data together with non-linear spin wave simulations results show that the microscopic interactions are characterized by a Hamiltonian with dominant isotropic Heisenberg interaction (J) and the presence of anisotropic symmetric pseudo-dipolar interactions ($\Gamma$), excluding the presence of Kitaev interactions. This is further supported by point charge crystal field analysis which shows that the ground state of the Pr$^{4+}$ ions in Na$_2$PrO$_3$ deviates from the expected J=1/2 limit. The findings of this study could have significant implications for a more in-depth understanding of the exotic quantum states of matter and the development of quantum technologies.

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# Monopole-Limited Nucleation of Magnetism in $Eu_2Ir_2O_7$

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Iridium oxides with characteristic chemical formula $R_2Ir_2O_7$ – $R$ being a rare-earth ion – host a wide variety of exotic electronic phases arising from the combined effect of the spin-orbit interaction, Coulombic correlations and the peculiar geometrical properties of the pyrochlore lattice. Particular interest has been devoted to the metal-insulator transition developing for $R$ = Eu, Sm, and Nd, where a low-temperature magnetic insulating phase evolves into a non-magnetic metallic state upon increasing the average ionic size at the $R$ site. In the magnetic state, for $T \leq T_N$, the iridium magnetic moments are forced along the local <111> directions pointing all inwards or outwards the tetrahedron defining their crystallographic sites, realizing the topologically non-trivial all-in–all-out order.

Here, we present an in-depth analysis of muon-spin spectroscopy measurements of $Eu_2Ir_2O_7$ under the effect of the $Eu_{1-x}Bi_x$ isovalent and diamagnetic substitution [1,2] as well as of external pressure [3]. Our results evidence an anomalously slow increase of the magnetic volume fraction upon decreasing temperature only for stoichiometric $Eu_2Ir_2O_7$, pointing towards highly unconventional properties of the magnetic phase developing therein [1]. We argue that magnetism in $Eu_2Ir_2O_7$ develops based on the nucleation of magnetic droplets at $T_N$, whose successive growth is limited by the need of a continuous generation of magnetic hedgehog monopoles on the pyrochlore lattice (see Fig. 1).
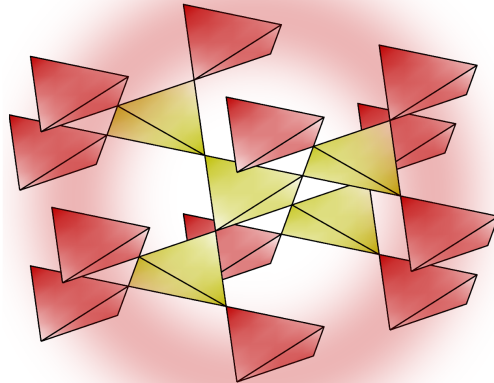


**Fig. 1** During the expansion of the magnetically ordered volume, represented by the yellow tetrahedra, new hedgehog monopoles must be generated corresponding to the red tetrahedra on the surface of the droplet. The associated energy cost acts as a limiting factor for the growth of small droplets [1].

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# Spin Dynamics in a High Temperature Ferromagnetic Metal-Organic Framework

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The crystalline structure of metal-organic frameworks (MOFs) is composed of metal centres connected by organic polytopic ligands. In turn, MOFs are characterized by ultrahigh internal surface areas and degrees of porosity that can be tuned flexibly depending on the practically unlimited choice of the structural elements. The high degree of chemical tunability of MOFs is reflected in a controlled wide variability of their electronic properties. In particular, MOFs have recently attracted attention as a possible platform to implement magnetic ground states. However, the main drawback against the realization of stable, long-range ordered magnetic phases with high critical temperatures is the weak magnetic coupling between the metal centres typically provided by the organic ligands.

The recent report of itinerant ferromagnetism with record critical temperature $T_C$ = 225 K in the mixed-valent $Cr(tri)_2(CF_3SO_3)_{0.33}$ (Htri, 1*H*-1,2,3-triazole) MOF pictured in Figs. 1a and 1b is an exciting development of this field of research [1]. However, a local investigation of the microscopic magnetic properties of this material is still missing. Here, we report on our extensive investigation of two nominally identical samples of $Cr(tri)_2(CF_3SO_3)_{0.33}$ by means of ^{1}H and ^{19}F nuclear magnetic resonance (NMR) and muon-spin rotation (µSR) [2]. Based on our experimental results, we highlight the lack of any critical dynamics associated with the magnetic transition despite the conventional nature of the long-range ordered configuration detected by muons. In particular, the dependence of both the ^{1}H and ^{19}F spin-lattice relaxation rates on temperature is consistent with the development of activated slow dynamics around the magnetic transition. A further, independent activated relaxation process of possible structural origin is detected only by ^{1}H nuclei within the paramagnetic regime. We interpret our results in terms of a disordered phase of segregated magnetic domains akin to what is realized in mixed-valent manganites.
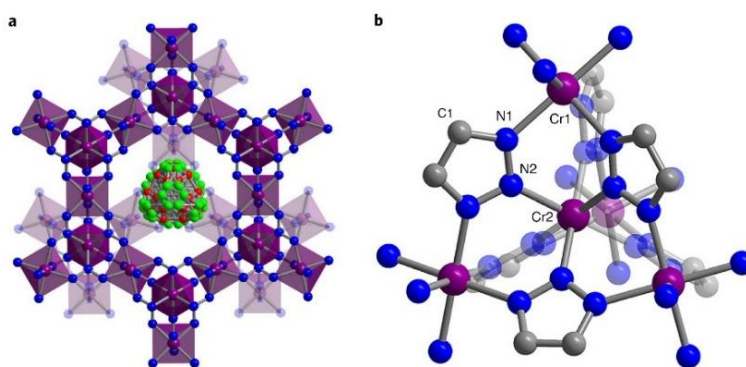


**Fig. 1** a, portion of the Cr–N sublattice of the investigated MOF with chromium–triazolate chains forming a diamondoid lattice (with a disordered charge-balancing anion in the pore cavity). b, Structural repeating unit. C, grey; Cr, purple; O, red; F, green; N, blue. Reproduced from [1].

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# POSTER SESSION 2/B
# LOW DIMENSIONAL MAGNETISM,THIN FILMS

# Micromagnetic modeling of Ni$_2$MnGa Thin Films with X-type microstructure

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Magnetic shape memory compounds are among the most promising classes of materials for multiple-stimuli actuation and energy harvesting, thanks to the multifunctionality arising from their distinctive magnetostructural transformation. Ni$_2$MnGa is a model system within this class of compounds; it shows a martensitic phase transformation from a cubic phase (austenite) to a lower symmetry phase (martensite) by decreasing temperature. We grow Ni-Mn-Ga films with thickness up to 400 nm by sputtering on MgO(100) or Cr/MgO(100). The L2$_1$ austenitic phase grows epitaxial at high temperature and transforms to the 7M monoclinic martensitic phase when samples are cooled down to room temperature. The martensitic phase shows a complex twin microstructure, with characteristics that we can engineer by growth parameters, external stimuli (temperature, magnetic field, stress) and patterning on the micron scale [1 and references therein]. Thanks to electron and scanning probe microscopies and to magnetic characterization, we have deepened the correlation between microstructure and magnetic/magnetothermal properties, also imaging the films while varying temperature and applying a magnetic field.
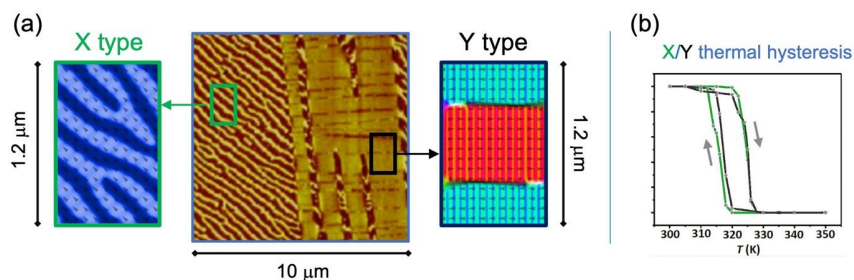


**Fig. 1** a) MFM image of a Ni-Mn-Ga film and corresponding micromagnetic configurations of X/Y microstructures; b) thermal hysteresis of X/Y microstructures across the martensitic transformation

Each twin microstructure imposes a specific geometrical arrangement of the easy-magnetization axes, giving rise to distinctive magnetization patterns and magnetization processes. Consequently, Ni-Mn-Ga films display a unique versatility of the magnetic properties, which can be modified by choosing a specific twin microstructure (X- or Y-type), combining the two microstructures, or modifying their spatial arrangement on the scale of tens of microns. The support of a micromagnetic model, built on the film microstructure and experimental characteristics, has been essential for modifying the magnetic properties by microstructure engineering [2]. Each twin microstructure also shows characteristic magnetothermal properties, i.e., thermal hysteresis and sharpness, which can be improved by choosing a specific microstructure (Fig. 1).

We will here show the most recent results obtained by applying the micromagnetic model to films with X-type microstructure. We have in fact considered films with variable thickness, twin size and different kinds of interfaces (conjugation and non-conjugation interfaces, ref. 3).

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# Magnetic properties of Fe-Ga/Kapton for flexible electronics

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Flexible electronics have manifested exploration and development of potential energy efficient technologies like ultrathin sensors, actuators, wearable electronics and new generation straintronic devices in recent years. The ability of these electronics to bend, stretch and wrap makes them advantageous over conventional electronics. Due to magnetic devices being important parts of electronic devices, it is essential to study the magnetic properties of magnetic thin films and devices fabricated on flexible substrates [1, 2]. Tuning of magnetic properties by changing the curvature of devices has significant impact in the new generation of sensor-based technologies. In this work, magnetostrictive  Fe-Ga thin films have been deposited on a flexible Kapton ($Fe_{70}Ga_{30}$ (28 nm)/Kapton and $Fe_{80}Ga_{20}$ (28 nm)/Kapton ) sheet to exploit the magneto-elastic coupling effect and modify the magnetic properties of the sample. We have investigated the structural and magnetic properties of as-deposited and stress-induced states. Tensile or compressive strain generated by the convex or concave states influence the uniaxial magnetic anisotropy of the system. The schematic of the deformation in samples is shown in figure 1(a). The flat state, the concave state and the convex state corresponds to no strain, compressive strain and tensile strain, respectively. Figure 1(b) shows the in-plane hysteresis loops measured with SQUID-VSM at room temperature for flat (red), concave (green) and convex (blue) configurations. In Fig. 1(c) the anisotropic magneto-resistive behaviour is reported, for different curvatures. Low temperature measurements show a hard magnetic behaviour and the presence of exchange-bias effect after field cooling to 2 K.
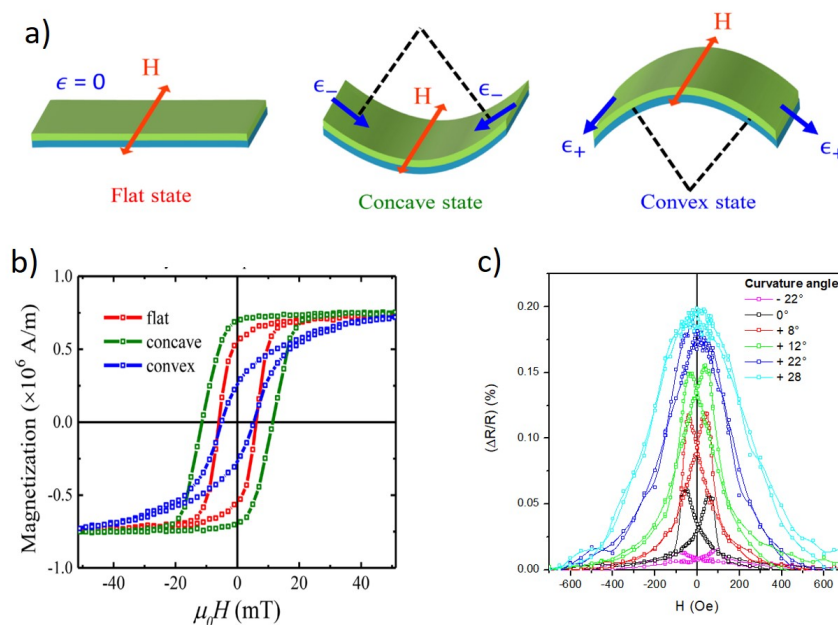
**Fig. 1** (a) Schematic of FeGa (28 nm)/Kapton for flat (no stress), concave (compressive stress) and convex states (tensile stress) by bending of samples. (b) Magnetic hysteresis curves at room temperature (300 K). (c)  Normalised anisotropic magneto-resistance curves as a function of curvature angle.

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# Character change of Dzyaloshinskii-Moriya interaction in 2D VO2 films with P4̄m2 symmetry

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2D magnets have been attracting increasing attention in the scientific community because of their high degree of tunability of magnetic properties. In this work we aim to explore the manipulation of chiral magnetic interactions in the 2D magnet VO2 which displays strong anisotropic Dzyaloshinskii-Moriya interaction [1] because of the presence of spin orbit coupling and its broken inversion symmetry being part of the P4̄2 space group (D2d point group). In particular, we elaborate on the theoretically predicted [2] switch from an anisotropic DMI to an isotropic DMI by means of the controlled motion of the oxygen species on the top and bottom interfaces of the system. The system is of particular interest because by breaking the symmetry along the z-axis, the point group symmetry is lowered from D2d to C2v, which is a multichiral point group which in principle allows to stabilize both skyrmions and antiskyrmions: the details of the electronic structure are responsible for the choice of one particular type of DMI. We compute the structural and magnetic properties of the material via ab-initio calculations performed with the VASP code [3], exploiting the 4 state method to compute the exchange matrix elements of the material as a function of different oxygen displacements along the z-axis. We discover that the predicted character change of DMI indeed takes place, but is dependent on the type of oxygen displacements we operate. We attribute this behavior to the specific orbital hybridization patterns of the V-3d orbitals and the O-p orbitals we obtain by performing different displacements of the oxygen atoms [4].
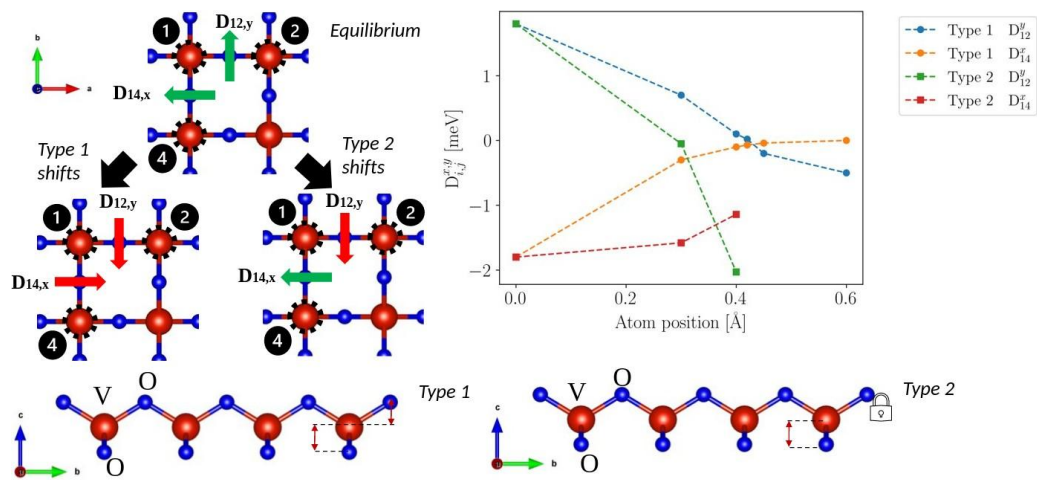
**Fig. 1** DMI manipulation as a consequence of different types of oxygen displacement in the VO2 2D system. On the left panel we show a schematic representation of what we mean with character change of DMI. The DMI obtained with Type 1 shifts of the oxygen can only stabilize antiskyrmions while Type 2 displacements can change the character of DMI and stabilize skyrmions. On the bottom panel we can show the Type 1 and Type 2 shifts. Finally, on the top right we show the values of DMI computed with the 4 state methods in a 3x3 supercell of VO2.

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# Metal-TetraPhenyl-Porphyrins Adsorption on Atom-Thick and Bulk Magnetic Oxides

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Metal tetraphenyl porphyrins (M-TPP) can host different metal ions within their tetra-pyrrole ring, providing exceptional flexibility in the molecular properties and functions. Molecular layers of M-TPP typically self-assemble on surfaces forming square-like superlattices of planar molecules with a high degree of structural order. That makes them an ideal benchmark for the study of their properties by surface science techniques and facilitates applications where well-defined hybrid interfaces are requested. Additionally, these ordered layers can pave the ground to the subsequent growth of 3D molecular architectures. Among supporting surfaces, oxides and oxidized layers raise interest because of their intrinsic properties (e.g., as antiferromagnetic substrates for organic spintronics [1]), or as protective layers.

We have combined experimental techniques and ab initio methods based on density functional theory (DFT) to investigate Co-, Ni-, Zn-, and VO-TPP molecules adsorbed on an atom-thick oxide [namely Fe(001)-p(1x1)O] where the oxide layer is able to preserve the characteristic features of quasi-free molecules as we evidence by UV-photoemission/inverse photoemission spectroscopy and calculations.[2] Adsorption structures are characterized by well ordered 5x5 superlattices that can attain different orientations depending on the central atom, despite a moderately-dependent computed energetics points to a subtle influence.[3] DFT analysis also points to a dominant antiferromagnetic coupling between the molecular spin and the substrate one. VO-TPP, which further offer an additional degree of freedom through the V=O bond orientation, also form square ordered superstructures with both upwards and downwards cases possible.[4]

The interaction of a selected cases (Co-TPP) at the surface of antiferromagnetic NiO substrate is then studied as a prototypical case for perspective antiferromagnetic spintronics applications.[1] Calculations allow us to identify the adsorption site for Co atop Ni, facilitating magnetic coupling between the molecule and the surface despite the absence of a net substrate magnetization.
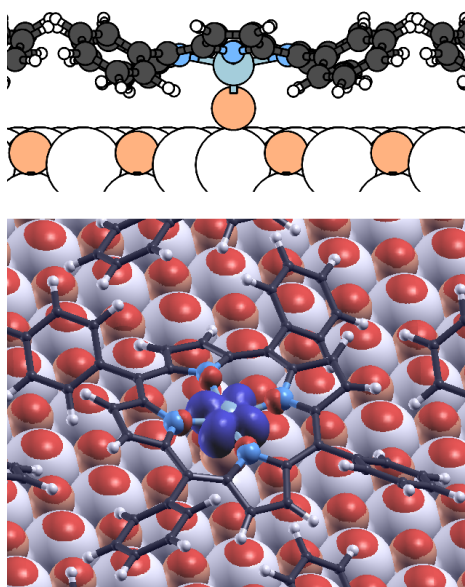


**Fig. 1** Structural model of VO-TPP adsorbed on Fe(001)-p1x1O (top) and corresponding spin density (red/blue=spin majority/minority).

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# *Ab initio* studies of hybrid organic–antiferromagnetic interfaces: the cases of Iron-phthalocyanine (FePc) on NiO(001) and Cr2O3(0001)

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In the production of spintronics devices (i.e. systems combining spin and electronic degrees of freedom) antiferromagnetic materials represent a reference point in the transport of high frequency (THz) coherent spin excitations, avoiding dissipative couplings with external magnetic stimuli. To modify interface properties, produce low energy-loss and light-tunable spin-transport devices, organic molecules are adsorbed on these materials [1][2].

In our research, we are interested in organic molecules adsorbed on transition-metal oxide substrates [3-7]. Among transition-metal oxides the ones with high Neel temperature and insulating behaviour, as the late transition-metal oxides, are valuable choices in order to build room-temperature spin-excitation-transport devices [8]. Here, we consider NiO(001) and Cr2O3(0001), that have a charge-transfer and Mott-Hubbard insulator character, respectively. Among organic molecules, the organo-metallic molecules such as metal phthalocyanines are optimal candidates to produce electronic and magnetic interface states, due to their tunability following the choice of the central metal (magnetic) core in combination with the external organic macrocycle properties.

By applying Hubbard-corrected density-functional theory (DFT+U) (with Van der Waals xc-functionals), we determine the adsorption configurations of FePc molecule on NiO and Cr2O3 and we investigate the electronic hybridization between molecular and surface states, highlighting the changes to their magnetic structures. We further evaluate the optical spectra of free and adsorbed molecules at the IP-RPA+U order. In particular, we find that the minimum energy configuration on NiO and Cr2O3 is the one with the Fe atom on the O, with a super-exchange interaction emerging in the former case. The optical spectra instead show a movement of charge from the substrate toward the molecule and the metal center, where a different filling in the two spin-channels suggests a change in the magnetic configuration of the molecule.
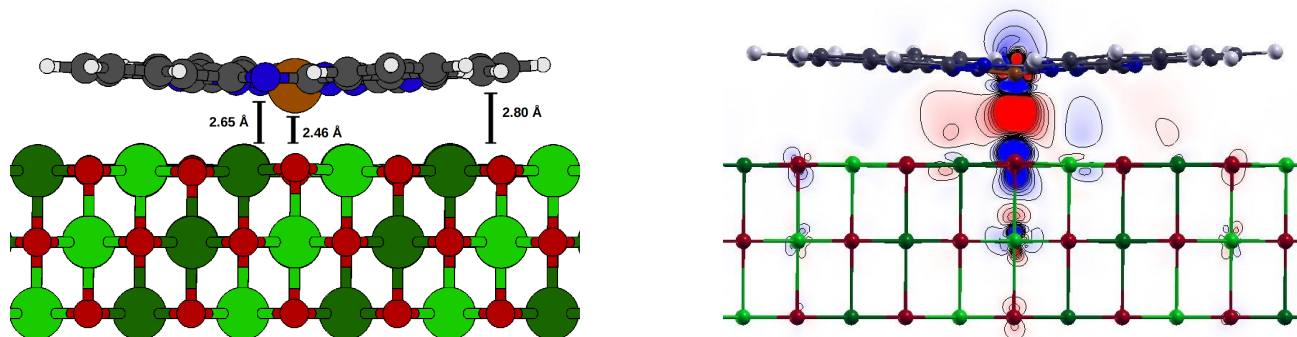


**Fig. 1** Side-view of the FePc-NiO(001) system in its minimum energy configuration (left) and the respective spin density difference (right) (Isovalues in a range from -0.003 to 0.003 bohr3).

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# *Ab initio* studies of hybrid organic–antiferromagnetic interfaces: the case of pentacene on NiO(001)

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Organically functionalized solid surfaces are a very active field of research, thanks to the tunability of molecular electronic properties, which can, in turn, modify the properties of the substrate. In "spinterfaces" the molecular overlayer can tune the spin polarization of the magnetic substrate surface, with potential applications in spintronics. We perform first-principles studies on the structural, electronic, magnetic and optical properties of interfaces between organic molecules and antiferromagnetic substrates, i.e. both bulk and ultrathin transition metal oxides, within the joint computational/experimental SINFONIA project ("Selectively activated INFOrmation technology by hybrid Organic Interfaces") [1]. The project is aimed at exploring the possibility of developing devices that enable the conversion of an optical stimulus applied to an organic molecule adsorbed on a solid surface to a propagating magnetic perturbation (spin wave) within the substrate and backwards with extreme spatial and temporal resolutions. Here I will report on a monolayer of pentacene adsorbed on the nickel oxide (001) surface.

In our density functional theory (DFT) calculations with Hubbard correction (DFT+U), we considered surface unit cells and molecule orientations based on low-energy electron diffraction (LEED), angle-resolved photoemission (ARPES) and scanning tunneling (STM) measurements. The Ni-Ni bridge adsorption sites are found to be energetically favored. On the most stable pentacene/NiO(001) adsorption configurations, we compute electronic and magnetic properties. The effects on surface and molecule magnetization for molecule adsorption on the (001) surface of bulk NiO are mild and depend on the orientation of the molecule with respect to the magnetically anisotropic surface (Fig. 1). Preliminary results suggest instead much larger effects for molecule adsorption on ultrathin NiO. We also investigate the optical properties of the adsorbed system, focusing on spectral features due to molecule adsorption.
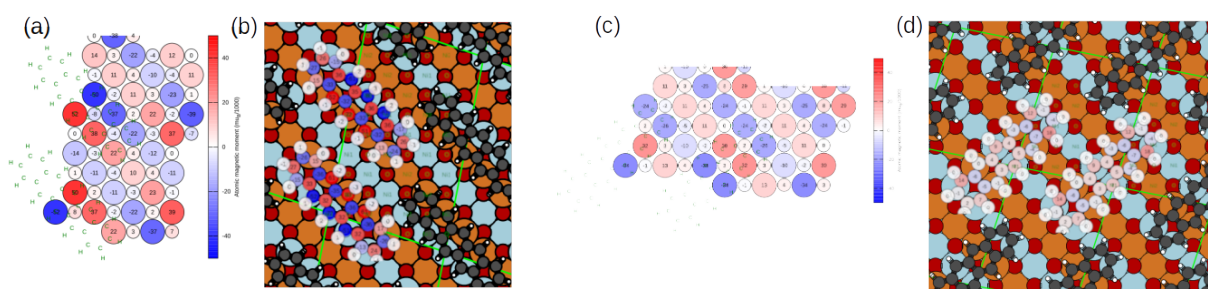


**Fig. 1** Most stable pentacene/NiO(001) configurations: modifications to the magnetic moments of the surface (a,c) and magnetic moments induced on the molecule (b,d) upon adsorption. Color scale from -0.05 µB (blue) to 0.05 µB (red).

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# Electronic and Magnetic Properties of monolayers of Vanadyl porphyrin Molecules

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Due to their unrivalled tunability properties, molecular qubits represent a reliable breakthrough approach to improving quantum information (QI) technologies.[1] Indeed, crucial objectives in QI sciences can be achieved by acting on the molecular structure with targeted synthetic approaches.[2] In this scenario, porphyrin-based systems are attracting interest thanks to their unparalleled chemical versatility, optical features, and stability properties, making them widely appealing for on-surface processing and integration into quantum circuits.[3]

Vanadyl(IV) 5, 10, 15, 20-tetraphenylporphyrin (VOTPP) is a $S = 1/2$ molecular system with remarkable spin qubit properties. Its structure offers a higher chemical tunability with respect to archetypal molecular qubits, such as Vanadyl(IV)Phthalocyanines (VOPc), and a less rigid organic scaffold where peripheral phenyl rings could promote spin decoupling from the substrate. Here we reported the properties of a VOTPP monolayer on the Ag(100) surface by photoemission spectroscopies and synchrotron radiation.

The results suggest that both the electronic and spin structures are retained in the monolayer if compared to the massive phase. Additionally, X-ray photoelectron spectroscopy evidenced the presence of two species characterized by different molecule−surface interaction strengths.[4] Resembling VOPc, they could arise from molecules having the vanadyl group pointing upward or towards the surface allowing a controlled tuning of the interaction and opening perspectives for future studies addressing spin features at the single-molecule level.
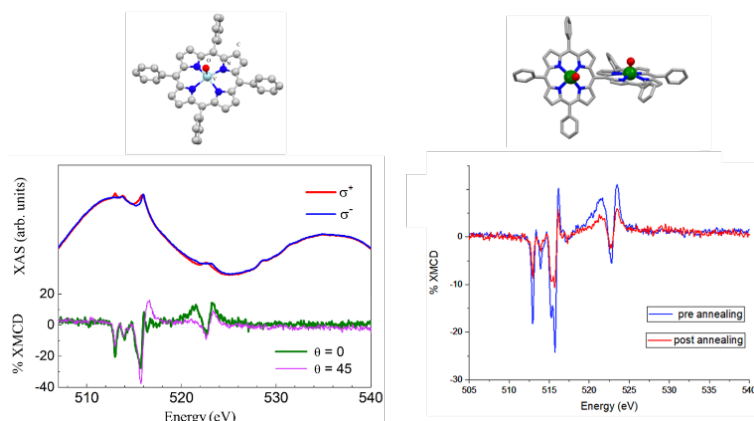


**Fig. 1** Left: top molecular structure of VOTPP, bottom XAS (top) and XMCD (bottom) of VOTPP on Ag(100) spectra recorded at θ = 0° and XMCD at θ = 45°, B = 6 T, and T = 2.0 K; Right: top molecular structure of TL-{VO}₂ bottom XMCD (T=2K) spectra of pre and post annealed m-m{VO}₂ deposited onto Au(111).

Recently has been reported that *meso-meso* (m-m) linked porphyrin dimer containing two vanadyl(IV) ions m-m{VO}₂ suitable for implementing two-qubit quantum logical operations.[5] Indeed, exchange coupling interactions between the two metal ions fall in the perfect range ($J_{ex} \approx 10^{-3}-10^{-2}$ cm$^{-1}$) to guarantee the correlation and individual addressability of the two units while unaltering their coherence properties. As suggested by DFT calculations and confirmed by experimental evidence, their antiferromagnetic (AF) exchange interactions can be tuned by acting on the dihedral angle between the two porphyrins' planes.[5] Experimentally proved in the bulk phase,[6] here we report our findings on dimers deposited on Au(111) surfaces.

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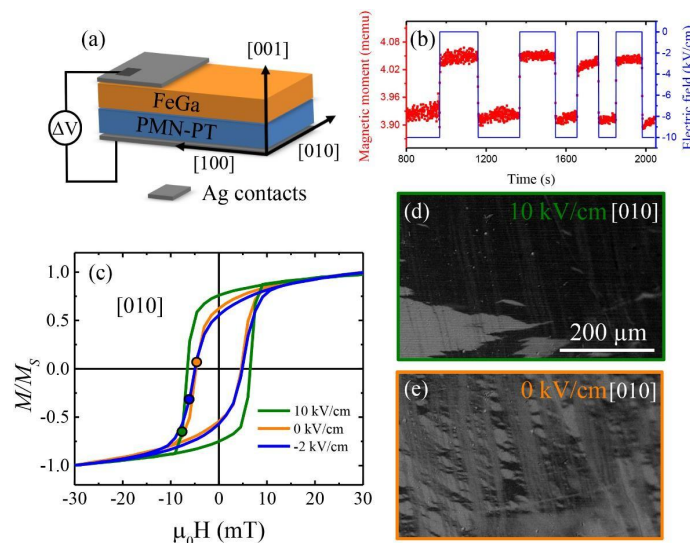# Electric Field Control of Magnetization Reversal in FeGa/PMN-PT

**Gajanan Pradhan[1,2], Federica Celegato[1], Alessandro Magni[1], Marco Coisson[1], Gabriele Barrera[1], Paola Rizzi[2], Paola Tiberto[1]**

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The recent era of information technology devices largely focusses on energy and cost efficiency. Magnetoelectric (ME) materials possess huge potential to be used in these technologies due to its coupling between magnetization and electric-field induced strain which therefore consumes less power and significantly reduces heat losses [1,2]. The application of voltage generates strain at the interface and this strain transfer to the magnetic layer from the piezoelectric layer induces change in magnetic anisotropy and domain structures [3].

In the framework of artificial multiferroic heterostructures and their interfacial magnetoelectric interplay, here we propose to investigate the properties of Iron Gallium (FeGa)/PMN-PT heterostructures (Figure 1(a)) using magnetometers and magnetic imaging techniques. FeGa thin films have been deposited by sputtering on PMN-PT substrates. The study of magnetic domains using Magneto-Optic Kerr effect (MOKE) revealed the presence of in-plane magnetic domains in the samples. Under the application of voltage, stress is generated at the interface of FeGa and PMN-PT which is measured using a strain gauge. The remanent magnetic moment is observed to be have a cycling behavior in an ON-OFF electric field process as observed in a vibrating sample magnetometer (VSM) (Figure 1(b)). The magnetic hysteresis also observes a change as a function of electric field applied which is reversible in nature as represented in Figure 1(c). The hysteresis curve at the compressive state at 10 kV/cm (green curve), has the highest magnetic remanence (Mr) and coercive field (Hc). The magnetic domain are large forming zig-zag domain walls, as shown in Figure 1(d). Near the zero electric field state, the hysteresis has lower Mr and Hc (orange curve). The magnetic domain contrasts show a very different behavior as compared to the state at +10 kV/cm. The domains have a vertical segregation between them indicating bright-dark-bright patterns in some and linear grey contrast in others (Figure 1(e)). This can be directly linked to the underlying ferroelectric domains that are forming at the remanent polarized state.



**Fig. 1** (a) Schematic of electric field system for FeGa/PMN-PT. (b) Magnetization switching with ON-OFF electric field. (c) Change in magnetic hysteresis with electric field and corresponding magnetic domains during magnetization reversal (d,e).

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# POSTER SESSION 2/C
# MAGNONICS

# Coherent and Dissipative Coupling in a Magneto-Mechanical System

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Understanding low energy magnetic excitations and their coupling to other degrees of freedom require performing experiments both in time and frequency domains. Hybrid quasi-particles in condensed matter systems are observed at the degeneracy points between different degrees of freedom exhibiting non-zero coupling. These solid-state chimeras could be exploited in a wealth of applications, ranging from transducers to sensors, to memory and logic units [1]. In particular, when the dispersion relation of acoustic waves and of spin waves are degenerate, magnetostriction can allow for efficient crosstalk between lattice and spin reservoirs in the few gigahertz and inverse micron range [2].

We report on the hybrid magneto-mechanical properties of a 1D magnonic crystal composed of Fe(10 nm)/Py(10 nm) bilayered nanowires. An infrared laser pump triggers both acoustic and spin waves, and the two modes can be driven into resonance by proper tuning of an external magnetic field. The system then behaves as a magneto-mechanical cavity, and the coupling between magnon and phonon is investigated by analysis of time-resolved reflectivity and Magneto-Optical Kerr Effect (MOKE). The observed magnetic modes are in agreement with Brillouin Light Scattering and micromagnetic simulations. We compare the results to acoustic-wave-driven ferromagnetic resonance in Ni thin films [3-4]: here the pump pulse, in Transient Grating configuration, only triggers the acoustic dynamics, and the magnetization precession is completely acoustically-driven, giving clear difference in the spectral phase dependence of the resonance.
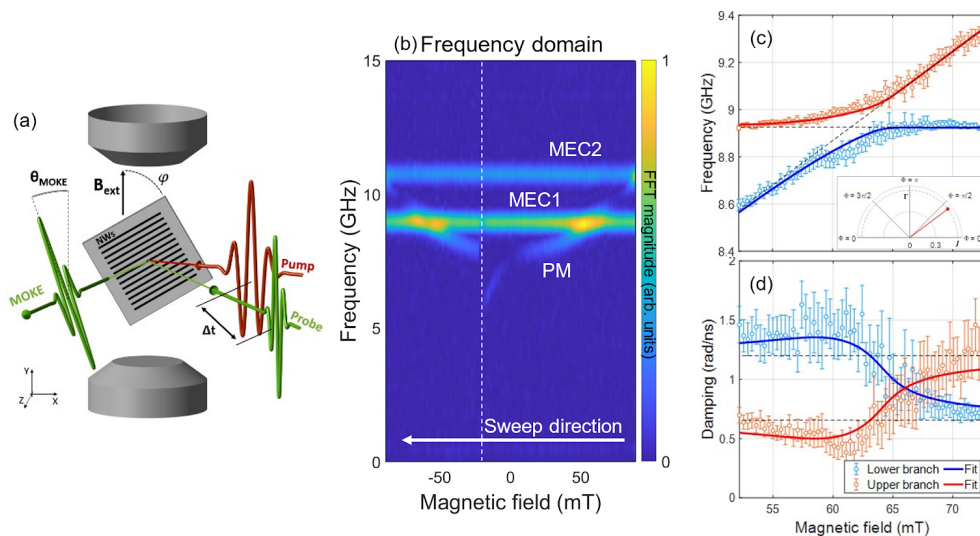


**Fig. 1** (a) Sketch of the experimental end-station for time-resolved MOKE. (b) FFT magnitude of the MOKE transients, as a function of the applied magnetic field. (c-d) Analysis of frequency and damping at the magnon-phonon crossing.

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# Thermal Laser Patterning of YIG Structures for Magnonics

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The fabrication and integration of high-quality structures of Yttrium Iron Garnet for spin waves processing is of overwhelming importance for magnonics. Films with excellent properties are grown only on single crystal Gadolinium Gallium Garnet substrates kept at high temperature, largely exceeding the maximum allowed thermal budget for CMOS electronics. Furthermore, the physical fabrication of magnonic conduits via conventional lithography requires a tight control of the edge roughness to avoid extrinsinc magnon scattering and dedicated planarization to be integrated in a real device. In this work we describe a novel approach based on laser induced local crystallization of amorphous YIG films deposited at room temperature on GGG by pulsed laser deposition. On this system a 405 nm laser with nominal spot size of 1.2 µm is used for patterning an arbitrary shaped region by inducing crystallization. To fully characterize the dynamic magnetic properties of crystallized structures in this contribution we report on Spin Wave (SW) propagation in conduits patterned with different laser doses on YIG films with 160 and 80 nm nominal thickness. Due to the different thermal budget in the thicker films the strain induced during laser patterning leads to a morphological corrugation, associated to a modulation of the local magnetic properties, as seen in the AFM and MFM images of figure 1.a and 1.b. This reflects in a non-uniform propagation of SWs for just a few microns in a 10 $\mu$m wide conduit, where Damon-Eshbach waves are excited and observed by Brillouin Light Scattering (BLS), as reported in figure 1.c. While the morphological corrugation almost disappears in structures patterned on 80 nm thick YIG and its potential impact is further minimized in narrower conduits (1 $\mu$m wide), thus leading to a continuous propagation of SWs over 10 $\mu$m (see Figure 1.d). In order to increase the magnetic properties of the patterned films and to overcome the limitations induced by the laser machining we have started to exploit a single laser scan and to fabricate suspended YIG structures which can be transferred virtually on any kind of substrate thanks to a dedicated pick and place system exploiting PDMS viscoelasticity properties. These results reveal the potential of our patterning approach for magnonic conduits with arbitrary shape. Preliminary results on single laser scan and suspended structures will be presented at the conference.

**Figure 1:** a,b) Topography and MFM signal from a square pattern with writing direction as the dashed line, from a 160 nm thick YIG film; c) and d) BLS intensity map recorded for a 10 m wide conduit patterned on 160 nm YIG, and of a 1 m wide conduit patterned on a 80 nm thick YIG conduit, respectively. In the panel c and d, we could add an arrow to indicate the direction of the magnetic field, as in the sketch in panel c.

# Magnetic Nanopatterning of YIG Films via Direct Laser Writing for Magnonics

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Spin waves (SWs) are propagating perturbations in the spin lattice of magnetic ordered materials. In magnonics, the low energy consumption related to their propagation as well as their rich phenomenology make SWs a promising candidate for next-generation data processing and transmission. Magnonic crystals represent the main building blocks for both digital and analog spintronic devices [1]. Among the systems which are currently under study in magnonics, Yttrium Iron Garnet (YIG) certainly plays a major role, mainly because of its peculiar optical and magnetic properties, such as the lowest Gilbert damping ever measured. That allows spin-waves (SWs) to propagate in YIG crystals up to few millimetres preserving their coherence, which is essential for computing devices based on interference and wave processing [2]. Notwithstanding, an actual exploitation of YIG-based technology is still prevented by the failure of standard lithographic processes in patterning YIG films, primarily due to the uncontrolled deterioration of its unrivalled magnetic properties.

In this work, we make use of direct laser writing (DLW) to achieve effective grayscale patterning of 1 µm-thick YIG crystals via local tunable modifications, according to a new paradigm in nanofabrication called phase nanoengineering [3]. By varying the exposure parameters, patterns having different structural, optical and magnetic properties have been obtained. The change in the static magnetic properties of such patterns has been studied by means of Magnetic Force Microscopy, revealing a tunable change in the magnetic configuration at remanence. In particular, above a laser power threshold (56 mW) magnetic stripe domains become thinner, indicating a sizeable change in the magnetic properties (Figure 1a). Raman spectroscopy has then been employed to correlate the change in the magnetic properties with a modification in the composition and structure of the film. The graphs in Figure 1b point out a left broadening in Raman spectrum recorded in patterns written with high laser power. This effect is compatible with the creation of oxygen vacancies in patterned areas [4]. Finally, micro-Brillouin Light Scattering measurements on arrays of patterned nanodots have revealed a tunable change in the spatial distribution of SWs intensity (Figure 1c).

These results prove how phase nanoengineering holds promise for the design and implementation of novel magnonic devices based on the crafting of the magnetic and structural properties of YIG films.
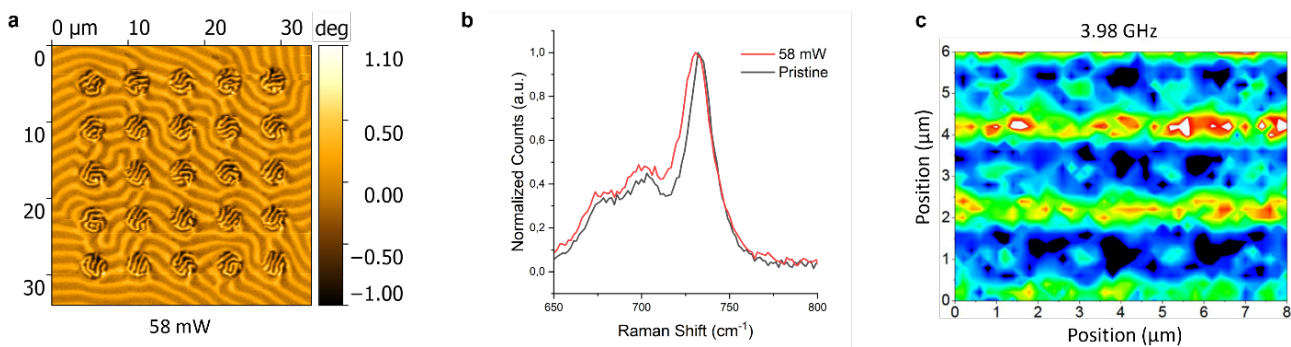


**Fig. 1** Phase nanoengineering of YIG film. a) MFM image of dots patterned with 58 mW shows thinner magnetic stripe domain with respect to pristine film. b) Raman spectrum of a pattern written with the same laser power as in (a) presents a left broadening compared the spectrum of the pristine film. c) µBLS measurement of a magnonic crystal made of an array of patterned nanodots reveals the spatial localization of SW mode at 3.98 GHz.

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# Magnetic Nanopatterning of Skyrmion Lattices via Direct Laser Writing

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Spin textures in magnetic materials, including magnetic domains, domain walls, and skyrmions, hold significant promise as active components in data storage and processing devices [1], due to their nanoscale scalability, resistance to external perturbations, and their high level of tunability. Tuning and manipulating the properties and the configurations of spin texture is relevant for building spintronic devices with selected properties and functionalities. In particular, magnetic skyrmions have attracted a lot of attention in the recent years for their peculiar properties. Magnetic skyrmions are local whirling of the magnetization that, with their nanoscale size and stability, have recently drawn attention as potential building blocks for nanoscale information processing [2,3]. However, controlling their nucleation and arrangement in a magnetic film has always been a challenge.

In this work, we introduce phase-nanoengineering [4], and in particular Direct Laser Writing (DLW) and thermal scanning probe lithography (tSPL), as effective methods for writing reconfigurable spin textures on CoFeB/Ta/Ru/IrMn and IrMn/NiFe/Co magnetic multilayers. These magnetic stacks are excellent candidates for stabilizing skyrmions at room temperature and zero field, although skyrmion stabilization occurs randomly [5]. We use a highly localized energy source to selectively heat the material in the presence of a magnetic field, resulting in localized magnetization pinning and the creation of arbitrary-shaped and reconfigurable spin textures. As depicted in Figure 1a, the magnetic patterning in presence of an external magnetic field allows to finely tune the shifting of the film exchange bias with the laser power: this demonstrates the potentiality of DLW for greyscale patterning. Figure 1b shows that a skyrmion lattice with arbitrary arrangement and minimum feature size of around 250 nm was successfully patterned with DLW. Moreover, the dimensions of the skyrmion is increasing with the laser power. The patterned spin textures show stability at remanence, and therefore they cannot be permanently erased with magnetic fields.

These results show that DLW emerges as a promising technique for precise and reconfigurable spin texture engineering, offering potential applications in nanoscale data storage and processing.
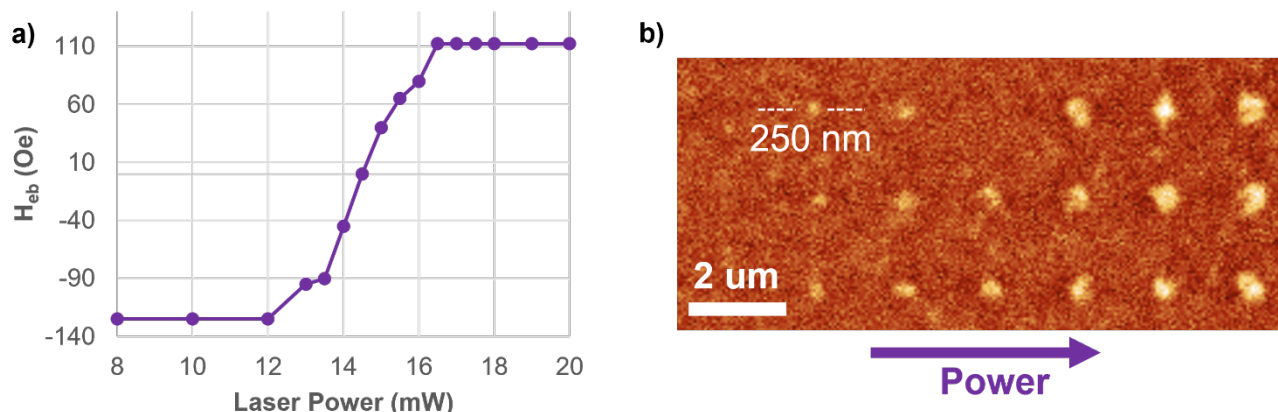


**Fig 1. a)** Local tuning of the exchange bias shift of patterned regions as a function of laser power.
**b)** Simple square skyrmion lattice patterned with DLW. The increase of the patterned skyrmion dimension as a function of the laser power is clearly visible.

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# POSTER SESSION 2/D
# NEW FRONTIERS IN MAGNETISM

# Collapse of the Magnetic Domain Structure in Co Thin Films Interfaced with Molecules

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The interface between 3d ferromagnetic thin films and molecular layers is known to alter key magnetic properties of the former, including such device-relevant parameters as magnetic anisotropy and magnetic moment [1,2]. The effect is originated by the hybridization between the FM surface d orbitals and the p orbitals of the molecule, inducing significant modifications to the effective surface Spin-Orbit Coupling and hence to the Magneto-Crystalline anisotropy term [3,4].

In this work, we investigate the hybridization effects of fullerene $C_{60}$ and Gallium-quinoline ($Gaq_3$) molecules on the magnetic properties of polycrystalline 5 nm thick Cobalt layers, performing MOKE, AMR and SQUID measurements. Among the most interesting results we shall mention a significant in-plane magnetic hardening of the cobalt layer, which at room temperature amounts to a factor of 2 with respect to bare or oxidized cobalt films, while moving to colossal enhancement at low temperatures (**Fig 1a**). The physics of this unusual behavior was further investigated via the minor loops (se **Fig.1b**), revealing an unusual magnetization dynamics with a clear deviation from the Rayleigh law [6,7].

These findings can be reasonably well explained and fitted on the basis of a new 2D phenomenological micromagnetic model, in which an additional in-plane anisotropy term $K_R$ is added. The term reflects the interface-induced modification of the surface Co atoms, it is constant in value but its axis **a(r)** is random but correlated over a distance $r_C$. It is shown that if $r_c$ is of the order of the domain wall length $\Delta$ then the *random anisotropy* term dominates over any present uniform term proper of the FM layer, thus inducing and enlargement and rounding of the hysteresis loops, as experimentally observed. Remarkably, the ground state of the system (zero net magnetization) is not more divided into domains but it is characterized by continuous, randomized directions of the magnetization vector – see **Fig 1c,d**). We believe that this new Ferromagnetic Glass State (FGS) state arises from the competition of the two length scales $r_c$ and $\Delta$ and reflects a more general property for various collective effects in solid state physics.
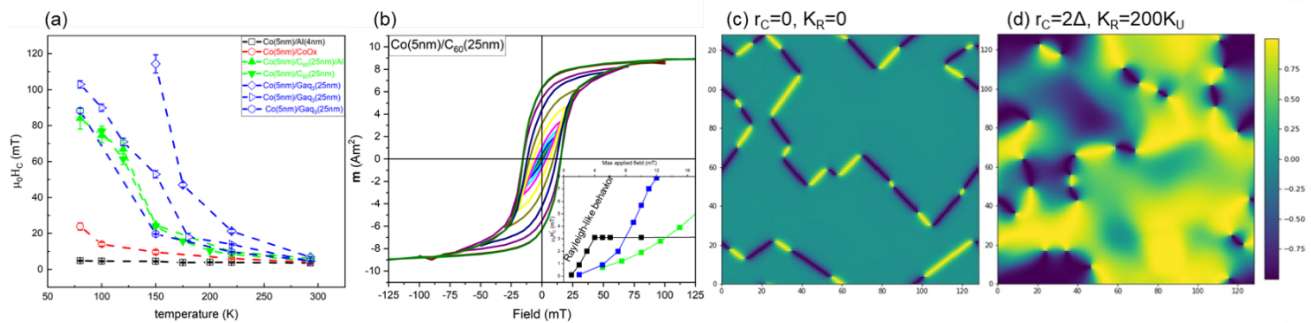


**Fig. 1** (a) Coercive fields as a function of temperature for Co interfaced with C60 and Gaq3 and compared with the reference Co/Al and Co/CoOx systems. (b) Minor loops of a Co/C60 thin film at 150K, inset shows the minor coercivity as function of the maximum applied field for Co/C60 (green), Co/Gaq3 (blue) and Co/Al(black). Micromagnetic simulation of the my component of the magnetization unit vector in the ground state of the system (c) with no Random anisotropy term, highlighting the domain walls of the system, is compared to (d) the case with a strong random term and a correlation radius two times the domain wall width.

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# POSTER SESSION 2/E
# SOFT AND HARD MAGNETIC MATERIALS

# Magnetic Bistability Induced by Bending Stress in Amorphous Microwires

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Magnetic and magneto-optical studies were carried out in amorphous microwires previously subjected to bending annealing.

We studied two glass-coated microwires with chemical composition of $Fe_{71.7}B_{13.4}Si_{11}Nb_3Ni_{0.9}$ (diameter of metallic nucleus d=103 µm, total diameter with glass covering D=158 µm) prepared by Taylor-Ulitovsky technique. The manufactured samples had a uniform distribution of magnetic properties along the microwire length. Then, the microwire was subjected to the annealing procedure. The samples were bended and annealed in the bended state ($T_{ann}$ = 300 °C (45 min)) (Figure 1). The annealing was carried out in air because insulating and continuous glass coatings protect microwires against oxidation. The radius R of the bending was 2 cm for the sample 1 and 1 cm for the sample 2. Then the samples were unbent and examined in the straightened state.

The hysteresis loops were obtained using the fluxmetric method. The magneto-optical Kerr effect (MOKE) technique has been applied as a method to acquire the contrast images of the surface magnetic domain structures [1]. The applied external mechanical bending stress induces the distribution of the internal stress inside the sample: from the maximum value of the tensile stress on the top surface to the maximum value of the compressive stress on the bottom surfaces of the sample [2].

The effect of bending annealing-induced magnetic bistability was discovered. Without annealing and after the annealing without bending, this effect was not observed. The effect of induced bistability was observed in a spatial region close to the length of the curved part of the sample. The longitude of this area varied with changes in the bend radius. The spatial disappearance of the effect of induced bistability occurred gradually as we moved towards the edges of the sample, which was not subjected to the bending during the annealing.

The induced bistability effect was accompanied by the rapid movement of a single longitudinal domain wall along the surface of the microwire that was not observed in the classical bistability effect. The existence of the longitudinal magnetic domain structure is the result of a particular distribution of the internal stress. This distribution represents a gradual transition from a compression to a tension across the microwire diameter.
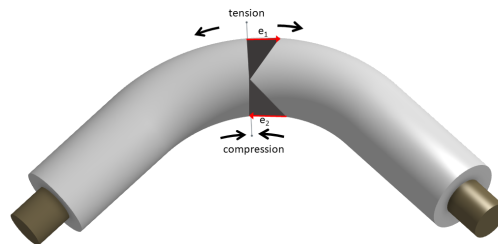


**Fig. 1** Distribution of the mechanical stress in bended microwire.

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# Microstructure and magnetic properties of post-processed Nd-Fe-B powders from Hydrogen-based recycling route

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We present a study on the structural and magnetic properties of NdFeB powders obtained by hydrogen processing of waste permanent magnets. The rare-earth (RE) permanent magnets, in particular the NdFeB ones, are key components of many technologies involved in the Green Transition like wind turbines and motors for electric mobility. On the other hand, Republic of China has the monopole in the supply of RE compounds and in the production of these magnets. For both reasons the REs, and hence the corresponding magnets, are considered between the most critical raw materials [1]. Recycling is a process oriented to recuperate REs from waste magnets with a vision of circular economy. The recycling process called "magnet-to-magnet" obtain magnetic powders directly from recycled magnets and these powders are employed to produce new magnets [2]. Hydrogen Processing (HP) is a key step in this recycling route. In fact, fine powders are obtained almost directly from waste magnets thanks to the hydrogen induced decrepitation [3,4]. However, there are several factors like the presence of the coating, the presence of different elements and oxides, and the particle size control, that affect to the further production of the magnet. [2,3]

In this work, we have investigated the properties and further mechanical processing of the NdFeB powders produced after the HP followed by a soft-oxidation. The oxidation process opens a different recycling route with respect to the conventional one: oxidized powders are not pyrophoric and can be easy managed and transported. Also, these powders were subject to a Jet Milling process to select and reduce the particle size (JM samples). Initial oxidized powders are composed of polydisperse particles of hundreds of microns of size. X-Ray diffraction studies show the main presence of the hydrided 2:14:1 phase (H-2:14:1) while the EDX studies show that also that Fe oxides, Nd, Pr and Dy oxides are present together to other elements like Al and Cu. The specific magnetization of OX sample, 130 Am$^2$/kg, is smaller than the bulk and its coercive field is negligible. The JM process gives rise to the particle size reduction to below hundreds of microns, the decreasing the specific magnetization (115 Am$^2$/kg) but the increase of the coercive field (0,15T). Susceptibility measurements as function of the temperature (up to 1000°C) were employed to investigated the presence of the different phases and the desorption process. The Curie temperature of the H-2:14:1 is around 330 °C, above of the NdFeB one. Two peaks in the susceptibility curves at 400° C and at 620 °C are tentatively associated to the gas desorption and the alloy decomposition to form α-Fe or Fe$_2$B, respectively. Further studies are in progress to clarify the nature of these processes. Also, high-energy ball milling was performed with the purpose of further reducing the size to the micrometric range. The influence of the different milling processes is discussed considering the ensemble of structural, morphological and magnetic properties.

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# The Magnetism of Hollow High-Entropy Spinel Oxide Nanofibers

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High-entropy oxide (HEO) nanofibers (NFs), based on equimolar (Cr,Mn,Fe,Co,Ni), (Cr,Mn,Fe,Co,Zn) and (Cr,Mn,Fe,Ni,Zn) combinations, were prepared by electrospinning followed by calcination up to 900 °C.[1] The NFs are hollow and comprise nearly strain-free, single crystallites (≈100 nm) with spinel structure (Fig. 1a). EDX proved homogeneous cation distribution within the NFs (Fig. 1b). Consideration of configurational entropy *vs.* cation octahedral stabilization suggested that the cations distribute between the octahedral and tetrahedral sublattices of the spinel structure to satisfy the energetic preferences for octahedral sites of each cation (enthalpy prevails) but are then randomly distributed within the two sublattices (entropy prevails).

The temperature dependence of both high-field and low-field (Fig. 1c) magnetization showed that the NFs undergo a paramagnetic-ferrimagnetic (PM-FIM) transition with relatively low critical temperature $T_C$. (Cr,Mn,Fe,Co,Ni) NFs have $T_C$ = 374 K and replacing Co or Ni with non-magnetic Zn decreases $T_C$ to 233 and 105 K for (Cr,Mn,Fe,Ni,Zn) and (Cr,Mn,Fe,Co,Zn), respectively. The Zn-containing NFs also have a low temperature transition to a spin-glass-like state. The low saturation magnetization (15-40 emu/g at 5 K) showed that the NFs are non-collinear FIMs and confirmed the above-mentioned cation distribution.

The temperature dependence of the magnetization isotherms $M(H)$ (Fig. 1d) highlighted the large coercivity $H_C$ of (Cr,Mn,Fe,Co,Zn) and the unexpectedly low $H_C$ of Co-containing (Cr,Mn,Fe,Co,Ni) NFs, due to the different Co distribution in the tetrahedral and octahedral sites. Furthermore, $M(H)$ data strengthened the conclusion that our HEO NFs have a low-$T$ FIM phase and a high-$T$ PM phase with transition temperature.

Magnetic data also provided evidence that thermal-activation effects and superparamagnetism are not important for the present NFs.
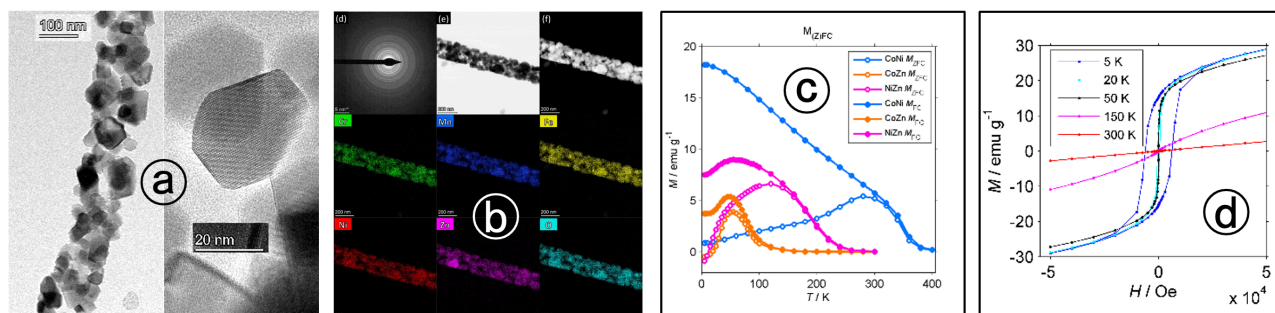


**Fig. 1** TEM images (a) and ED, STEM image and elemental maps (b) of a (Cr,Mn,Fe,Ni,Zn) NF. c) ZFC and FC magnetization of the HEO NFs. d) Magnetization isotherm M(H) at different temperature of (Cr,Mn,Fe,Co,Zn) NFs.

The largely different magnetic behavior between (Cr,Mn,Fe,Co,Ni) and the Zn-containing NF is due to the decreased magnetization of the tetrahedral sublattice and the lower average exchange coupling between cations in different sublattices ($J_{AB}$) caused by the presence of $Zn^{2+}$ cations in the tetrahedral sites. This enhances the role of magnetic frustration, leading to lower $T_C$ and spin collinearity, and the occurrence of a spin-glass-like-phase at low T.

Whereas (Cr,Mn,Fe,Ni,Zn) and (Cr,Mn,Fe,Co,Zn) were minimally characterized in the literature, (Cr,Mn,Fe,Co,Ni) had already been studied.[2] In all cases, our HEO NFs have similar saturation and remanent magnetization, comparable $T_C$ but consistently higher coercivity.

In conclusion, investigation of the magnetism of $(Cr_{1/5}Mn_{1/5}Fe_{1/5}Co_{1/5}Ni_{1/5})_3O_4$, $(Cr_{1/5}Mn_{1/5}Fe_{1/5}Co_{1/5}Zn_{1/5})_3O_4$ and $(Cr_{1/5}Mn_{1/5}Fe_{1/5}Ni_{1/5}Zn_{1/5})_3O_4$ NFs showed that the latter have a diverse and rich magnetic behavior, modulated by the cation distribution across and within sublattices. Magnetic structure and properties can then be engineered by changing the composition of the HEO NFs.

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# Magnetization Study of the Low Temperature Anomalies in the Substituted Dysprosium-Yttrium Iron Garnets

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Rare earth iron garnets with the general chemical formula $RE_3Fe_5O_{12}$ (REIGs) are a class of ferrimagnetic insulators desirable for their tunable magnetic properties. They exhibit a variety of magnetic interactions which show promise for spintronic and photonic applications [1]. Recently, the pure REIG films with RE = Dy and their mixed compounds, where the $Dy^{3+}$ ion has been replaced by the nonmagnetic $Y^{3+}$ ion, $Dy_xY_{3-x}IG$ with compositions in the range $0 \le x \le 3$, were used as a tri-layer heterostructure films for spintronic devices [2]. Our attention has again returned to the study some anomalous magnetic properties due to the occurrence of the so-called low-temperature point $T_B$, according to previous Belov' prediction for ferrimagnets which have a 'weak' sublattice characterized by a sudden change of the long-range magnetic order in the RE subsystem [3]. Recently, we have reported for bulk DyIG, anomalies near $T_B \approx 42$ K in the temperature variation of the magnetic and magneto-optical pertinent parameters related to specific heat, spontaneous magnetization, magnetic Faraday rotation and Cotton Mouton susceptibilities [4, 5]. However, such predicted $T_B$-points which have been observed in REIGs for the other RE heavy ions as Gd, Tb, Ho, and Er, should be well exhibited in bulk mixed $RE_xY_{3-x}IG$ compounds which have been less investigated.

We report in this work, isothermal magnetizations M(H) obtained in the 2-300 K range in high DC magnetic fields  H up to 16 T applied on $Dy_xY_{3-x}IG$ single crystals (x = 1.5, 2.0, 2.5, 3) which have a non-zero point $T_{comp}(x)$, respectively equal to 117, 133.6, 190.0, and 218.5 K. The measurements were performed on the samples which were allowed to rotate freely and oriented along the <111> direction which is the natural easy axis (EA) of magnetization below room temperature. In decreasing T, the well-known spontaneous spin reorientation (SR) phase transition of the first order-type between the <111> and the angular <uuw> phases was observed at a temperature-independent of the content x, $T_{SR}$ (H = 0, x) = 14.62 ± 0.5 K [6 and references therein]. Between 4.2 K and $T_{SR}$, it was found that M(H)<Free> curve is always greater than M(H)<111> curve and the low symmetry <uuw> angular phases (i.e. where the iron sublattice magnetization vector $\mathbf{M_{Fe}}$ lies on a low symmetry direction <uuw> and <111> ceases to be the EA of magnetization). The change of the EA of magnetization towards the <111> direction occurs for T > 14.62 K where no substantial difference exist between two M(H) curves up to 300 K. A line of the second-order-type, which characterizes the critical field due to the SR phase transition induced by the field between the canted coming from the low-symmetry angular <uuw> phase and the coaxial <111> high temperature phase, was found to increase linearly with T from $T_{SR}$ (H = 0, x) up to 44 K at 16 T in the ($H_{SR}$-T) magnetic phase diagram.

Between $T_{comp}$ and $T_{SR}$(H = 0,x), anomalies with minima and maxima appear at $T_B(x) = 42$ K ± few K in the temperature variations of the curves of the derivative $dM_S(T)/dT$ of the spontaneous magnetization $M_S(T)$ which is of the N-type predicted by Néel and paraprocess magnetic susceptibility $\chi_p(T)$. This value of the $T_B$-point which was found earlier for the pure DyIG [4, 5] seems practically independent of the content x. From the variation with T of the first derivative curve of the modulus of the magnetic moment vector of the $Dy^{3+}$ ion, $|d\mathbf{m}/dT|$ , the independent character with x of $T_B(x)$ is well demonstrated. These results seem to show a

certain continuity which appears well explained within the one-ion model. However, considering the anisotropy of the crystal field and exchange interactions where the two-ion model should be necessary, the Dionne' models [7] are used for a modified formula of $T_B$ which allows us to conclude that we are therefore in the presence of a strong contribution from the S spin as assumed by Belov for just 2/3, the remaining of 1/3 returning to the original orbital contribution L. All results are discussed in connection with the magnetodielectric effect revealed before in DyIG [8–10] together with some concomitant effects due to the Schottky anomaly which occurs around a similar region of the $T_B$-point [4, 5].

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# POSTER SESSION 2/F
# SPINTRONICS

# Tailoring of the ferroelectric and Rashba properties of GexSn(1-x)Te towards ultralow power spintronics devices

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The global demand for electrical energy in information and communication technology has increased exponentially and is on the verge of becoming unendurable. A thrilling spintronic solution for greener devices was outlined by Intel [1]. The proposed magneto-electric spin-orbit logic stores information in the magnetic state of a nanomagnet and processes such information by exploiting spin-to-charge conversion in materials with large spin-orbit coupling. However, the performances of existing materials are far from being satisfactory [2].

Ferroelectric Rashba semiconductors emerged as a feasible avenue to achieve non-volatile efficient devices: as demonstrated by some of us for GeTe [3], such materials can provide a spin-to-charge conversion controlled by their non-volatile ferroelectric polarization state. Unfortunately, the measured spin-to-charge conversion efficiency is rather limited and the operating voltage to switch the polarization is too large for applications. Nonetheless, other ferroelectric Rashba emerged (e.g. SnTe, WTe2 and PbGeTe) [4-6].

Here, we show an approach able to tailor the ferroelectric and Rashba properties of GeTe by alloying it with SnTe. The ternary compound GexSn1-xTe (x between 0.1 and 1) preserves the giant Rashba effect up to above room temperature (Fig. 1a and b).Moreover, Sn weakens the ferroelectricity with respect to that of bare GeTe, in turn lowering the coercivity of the film and significantly reducing the voltage required for the ferroelectric switching (Fig. 1c).

Endorsed by ab-initio density functional theory calculations, these results consolidate the strategy for the engineering and tuning of the ferroelectric and Rashba properties and could allow for the realization of low-consuming processing-in-memory devices.
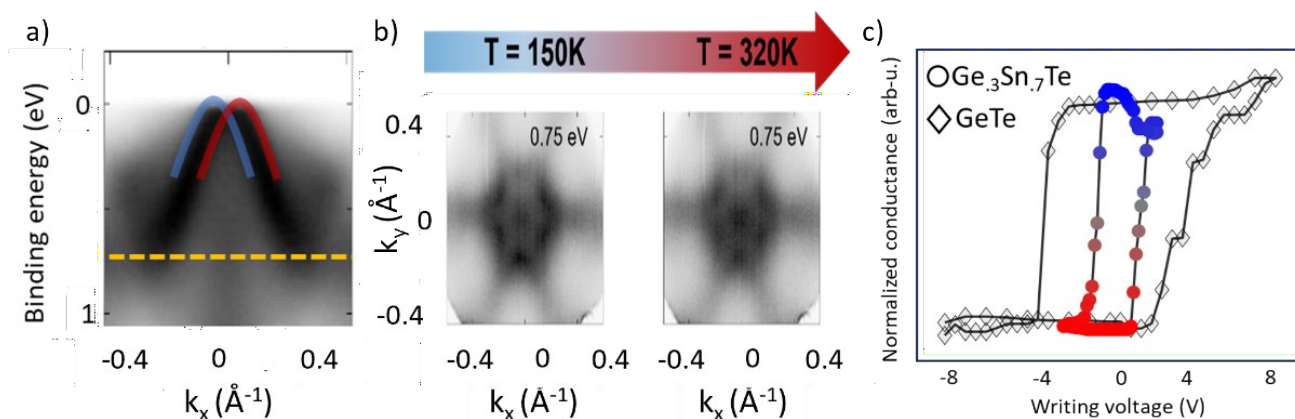


**Fig. 1.** (a) Band dispersion and Rashba splitting detected by angular-resolved photoemission. (b) The signature of the Rashba splitting persists up to room temperature, as evident from iso-energy maps at the energy identified by orange dashed line in panel a. (c) The ferroelectric hysteresis loops measured on GeTe and Ge.3Sn.7Te obtained by electro- resistive measurements indicates a reduction of the coercivity with Sn.

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# Spin-orbit readout in nanometric and micrometric heterostructures for magneto-electric spin-orbit logic

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Spintronics is considered among the most promising fields for overcoming the issue of energy consumption in information and communication technologies, this related the exponential increase of the number of transistors described by Moore's law [1].

The magneto-electric spin-orbit (MESO) logic was proposed by Intel back in 2015 [2,3] as a processing-in-memory unit beyond CMOS, with atto-joule switching and reading energies. The MESO architecture stores a bit of information in the non-volatile magnetization state of a nanomagnet. Such a bit can be flipped electrically through magneto-electric coupling with a multiferroic. The information processing instead exploits the magnetization-dependent current generated by spin-to-charge current conversion whenever a spin-polarized current injected from the nanomagnet flows into a suitable material with large spin-orbit coupling [4]. The MESO logic potentially allows for ultra-low energy devices, although many issues must be addressed. Among the most challenging issues are the reliable voltage control of the magneto-electric switching and the optimization of the overall device efficiency, especially for what concerns the spin-to-charge conversion process [5].

Here we study the capability to perform the readout of the magnetic state by inverse spin Hall effect (ISHE) in nanometric structures composed of a few-nanometers thick magnetic layer of NiFe on Pt (Fig. 1a), fabricated by e-beam lithography. We show the appearance of a transverse voltage upon injection of a spin-polarized current from the ferromagnet that mimics the hysteresis loop of its magnetization (Fig. 1b). The study of the output voltage as a function of the angle between the magnetization and the direction of the current allows to distinguish the contributions of the spin Hall, anomalous Hall and planar Hall effect (Fig. 1c).

The same study on much larger devices (on the micrometric scale, fabricated by optical lithography) revealed important differences. Counterintuitively, we show a much higher conversion efficiency for the spin-to-charge conversion mechanism, which we attribute to the predominance of the anomalous Hall effect within the ferromagnet. Therefore, we discuss the crucial role of the micromagnetic configuration of the ferromagnetic electrode, and we support our results by micromagnetic simulations.

In conclusion, these findings provide useful insights into the physics of the spin-orbit readout and represent a step forward toward a proper and conscious design of spin-orbit devices.
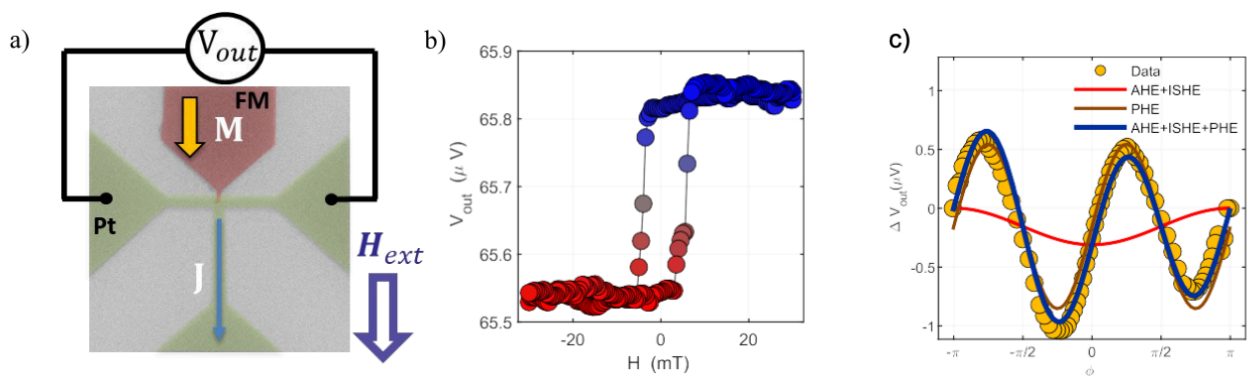


**Fig. 1** (a) Micrograph of the of the devices. The input current (of density J) is injected from the ferromagnet FM (in red) into a material (in green) with strong spin-orbit coupling (platinum, in our devices). An external magnetic field is used to set the direction of the magnetization and, in turn, the transverse output voltage (Vout) shows the hysteretic behaviour reported in (b). (c) The output voltage versus orientation of the in-plane magnetization (angle ϕ in the graph) can be decomposed in terms of spin Hall/ anomalous Hall (SHE/AHE) and planar Hall (PHE) contributions.

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# Inverse and Direct Edelstein Lengths in a Topological Insulator-Ferromagnet Heterostructure

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The possibility to optimize the conversion between electrical and spin currents (je, js) is fundamental to design efficient spintronic devices. In the case of heavy metal (HM)/ferromagnet (FM) heterostructures, the spin Hall angle $\theta_{SH}=j_s/j_e$ characterizes the spin-charge interconversion. Within the recent interest in the study of Topological Insulators (TI), the interaction channel between spin and charge currents in topologically protected surface states displaying spin momentum locking has opened up new possibilities to improve the efficiency of spintronic devices [1]. It has been observed that TI's are very promising candidates to replace HM's, in terms of their capability to induce switching in the FM layer by current densities even one order of magnitude lower than in the HM case. The relationship between charge and spin in TI-based devices relies on surface and/or bulk-driven processes. Their efficiency can be described by the Edelstein Effect (EE) length $q_{EE}$ that quantifies the charge-spin conversion or, based on Onsager reciprocity, by the inverse-EE length $\lambda_{IEE}$ quantifying the spin-charge conversion: both $q_{EE}$ and $\lambda_{IEE}$ can be related to the spin Hall angle $\theta_{SH}$ [2].

In this contribution, we report on the angle-dependent magnetoresistance (ADMR) [3] measurements performed on a Si(111)/Sb2Te3(30)/Au(5)/Co(5)/Au(5) system [4], to evaluate the charge-spin conversion efficiency, by following methodology reported in [5]. Fig.1 shows a typical measurement of the ADMR with the field rotating along the three main planes. By this method, we can successfully decouple the spin Hall magnetoresistance (SMR) [6] from the anisotropic magnetoresistance (AMR) effect generated by Co, thanks to their different symmetries. A remarkable charge-spin conversion effect is observed, with a spin Hall angle $\theta_{SH}\cong 0.3$. The spin Hall angle can be related to the $\lambda_{IEE}$ value previously measured on the same system by SP-FMR [4,5]. For TI thickness higher than the spin diffusion length $\lambda_S$, the parameter $\lambda_{IEE}$ can be approximated to $\lambda_S\theta_{SH}$ [4,7], which leads to $\lambda_S = 0.9$ nm, pointing towards a nearly interfacial spin-charge interconversion. Despite the relationship between the direct and indirect spin-charge conversion parameters being still under debate [2], the presented results suggest a high potentiality for using Sb2Te3 as both spin-charge and charge-spin converter devices. Being Sb2Te3 produced with metal-organic vapor deposition over large-area Si substrates, this could further boost the future technology transfer of spintronic devices based on this 3D-chalcogenide topological insulator.
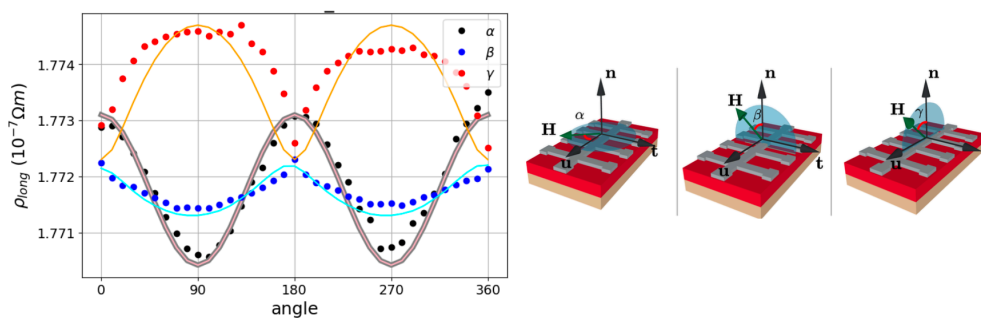


**Fig.1** (a) AMDR result under a H=1.30 T field (b) Reference angles for the experimental setup.

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# Temperature Dependent Raman Study and Mott Insulating Behavior of Antiferromagnetic Hexagonal Sr$_{0.5}$Ba$_{0.5}$MnO$_3$

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SrMnO$_3$ crystallizes into two structures cubic(*C*-) and hexagonal(*H*-). Both *C*-SrMnO$_3$ and *H*-SrMnO$_3$ exhibit G-type antiferromagnetic (AFM) behavior with Neel Temperature (T$_N$) ~230K and ~280K, respectively [1]. Strained *C*-SrMnO$_3$ is theoretically and experimentally established to be multiferrroic with ferroelectric *T$_C$* ~400K and large negative magneto-electric (ME) coupling at *T$_N$*[2]. Strained hexagonal SrMnO$_3$ is not explored extensively for its structural, magnetic or electronic properties. In this context, strain is applied on *H*-SrMnO$_3$ by 50% doping of Ba at A-site, Sr$_{0.5}$Ba$_{0.5}$MnO$_3$(SBMO). SBMO follows P6$_3$/mmc symmetry similar to its parent compounds. Structure of SBMO allows various exchange interactions between Mn and oxygen ions. In SBMO oxygen ions are present at two sites leading to caging of Mn ions in MnO$_6$ octahedra and Mn$_2$O$_9$ bioctahedra (formed by face sharing oxygen of two octahedras) stacked along c-axis. Such arrangement gives rise to linear 180$^0$ Mn-O-Mn superexchange interaction between two bioctahedra, non-linear Mn-O-Mn superexchange interaction within a bioctahedra and direct Mn-Mn interaction between two Mn ions in a bioctahedra. Magnetization versus temperature (M Vs T) shows a broad feature with maxima at ~336K and steep decrease in magnetization at ~241 K. M Vs T and magnetization versus applied field (H) indicates towards AFM behavior below 241K. Raman measurement at room temperature reveals five modes consistent with the P6$_3$/mmc symmetry of SBMO. Temperature dependent Raman measurements reveals emergence of a mode at higher energy side of face shared oxygen displacement mode (A1g) in the temperature window of 280K-270K. Appearance of extra modes indicates towards lowering of symmetry. However, reason for lowering of symmetry in such small temperature window is unclear. Further, Intensity versus temperature for Mn-displacement mode (E1g) shows anomalies at ~350K, ~280K and ~240K. As Raman intensity depends on polarizability associated with the mode, it indicates change in polarizability of SBMO across magnetic anomalies. This classifies SBMO as potential magneto-electric material. Theoretically, *H*-SrMnO$_3$ is classified as mix of charge transfer and Mott-Hubbard insulator at 0K[3]. We have performed resonance photoemission spectroscopy (RPES) at ~200K. It is observed that in the valence band spectra presence of oxygen is negligible near Fermi edge indicating towards Mott-Hubbard insulating behavior in AFM regime.



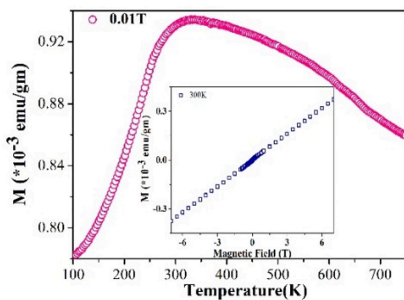**Fig. 1** M VsT. Inset shows M-H curve at 300K



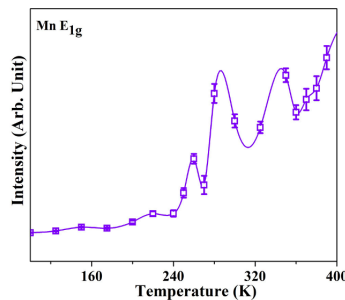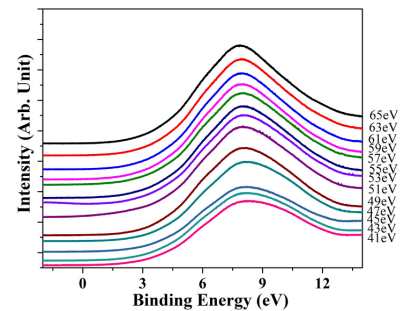**Fig. 2** Raman Intensity of MnE$_{1g}$ mode.



**Fig. 3** Valence band spectra with variable photon energy.

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# Wafer-scale Growth of Topological Insulator Sb2Te3 Films Using MOCVD

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Topological insulators (TIs) have emerged as a fascinating class of materials that exhibit unique properties enabling spin-charge conversions, making them promising candidates for future electronic and spintronic applications. Recently, our group developed a process employing metalorganic chemical vapor deposition (MOCVD) to grow nearly-epitaxial antimony telluride (Sb2Te3) thin films over Si(111) [1], which have been demonstrated to possess TI properties [2]. Moreover, efficient spin-charge conversion into MOCVD-grown Sb2Te3 has been found in (Fe,Co)/Sb2Te3-based heterostructures [3,4]. Here, we present a wafer-scale growth of Sb2Te3 thin films with nominal thicknesses of 30 and 50 nm using MOCVD along with their chemical, morphological, structural, and magneto-transport properties. As illustrated schematically in Fig. 1(a), we covered the diameter of a 4-inch (~10 cm) MOCVD reactor with two long stripes of intrinsic Si(111), on top of which the Sb2Te3 layers were deposited. Since we take advantage of a rotating disk MOCVD system, the quality of growth on these stripes will represent that of a full 4-inch wafer.

By conducting Scanning Electron Microscopy (SEM), we confirm the continuous growth of Sb2Te3 thin films over the whole substrate areas, for both 30 and 50 nm thickness, with Fig. 1(b) displaying a selected image for a 30nm sample. X-ray diffraction (XRD) patterns reveal the quasi-epitaxial growth of Sb2Te3 over the whole 4-inch area. Magneto-transport measurements are conducted in a Van der Pauw configuration on pieces from all over the stripes-length. We detect clear weak antilocalization effects for all samples, which are interpreted within the Hikami-Larkin-Nagaoka model to extract parameters $\alpha$ and $l_\varphi$, being connected to the number of 2D-conducting channels and spin coherence length, respectively [2]. In the case of 30 nm-thick Sb2Te3, $\alpha$ is found in the range from -0.16 to -0.57, while in the 50 nm-thick ones, we measured $\alpha$ from -0.23 to -0.3. In both cases, $l_\varphi$ is found to be in the range of 50 to 70 nm. We conclude about the successful growth of 30 and 50 nm-thick Sb2Te3 showing reproducible properties over the whole 4-inch area. In particular, the uniformity of the Sb2Te3 topological character marks an important step towards the technology scale-up of this material for spintronics.
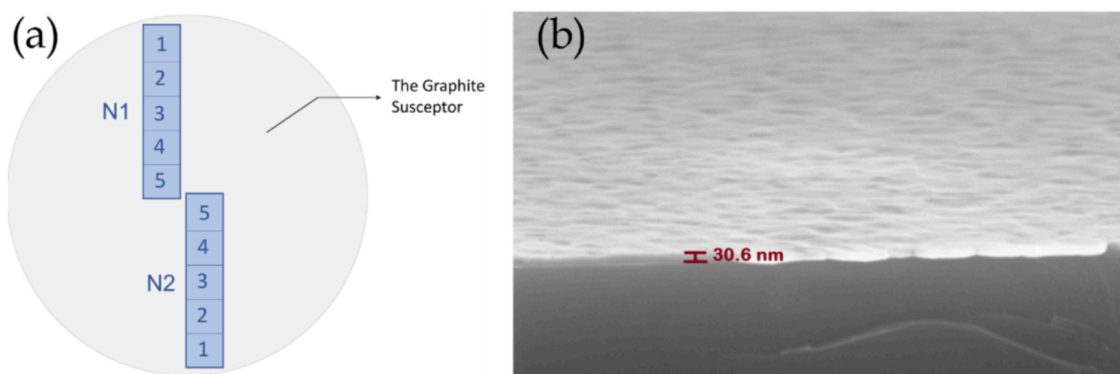


**Fig. 1.** (a) A schematic representation of the geometry used to place substrates into the reactor chamber. (b) Tilted cross-sectional SEM image of sample N2_4.

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# Thermal Treatments Effects On PMN-PT/Fe Heterostructures

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Multiferroic heterostructures exploit the interfacial coupling between a ferromagnetic layer and a piezo/ferroelectric one to modify and control the magnetic response of the latter through external stimuli that modify the piezo/ferroelectric properties. [1] This converse magnetoelectric interfacial coupling can be controlled by either strain, charge or ion migration [2] and is nowadays integrated in more-than-Moore voltage controlled MRAMs.

By using Pb(Mg1/3Nb2/3)O3-PbTiO3 (PMN-PT) as ferroelectric substrate in multiferroic heterostructures, our group showed how photostriction [3] and morphological modifications [4,5] are additional levers to reversibly modify the magnetic properties of interfacial thin films. In this framework, the ferroelectric properties of the substrate are crucial to determine the tuning of the magnetic properties. In particular for PMN-PT, its combination of relaxor ferroelectric, piezoelectric and photovoltaic properties, together with its complex phase diagram, still leaves open questions on their interconnection and optimization. [6] For instance, crystalline quality and ferroelectric domain thermal stability are almost neglected once coupled in heterostructures.

Here we show how, by annealing PMN-PT/Fe heterostructures in inert atmosphere over PMN-PT ferroelectric Curie temperature, the domain population significantly modifies once cooled back to room temperature, passing from a highly disordered, mostly out-of-plane domain population to a more defined crystallinity with majoritarian in-plane one. If further annealed, the domain population returns to be mostly out-of-plane, sign that intermediate annealing steps can freeze PMN-PT domain population in sort of metastable configurations. This structural information was obtained by combining micro-Raman and x-ray diffraction measurements. In correspondence to these three states, the magnetic properties of interfacial Fe thin film are affected by the ferroelectric modifications, passing from an isotropic to an anisotropic behavior, then back to an isotropic one. These results stimulate for further investigations, on both micro and macroscopic scales, on the domain population and thermal stability in ferroelectric materials and their coupling with magnetic layers.
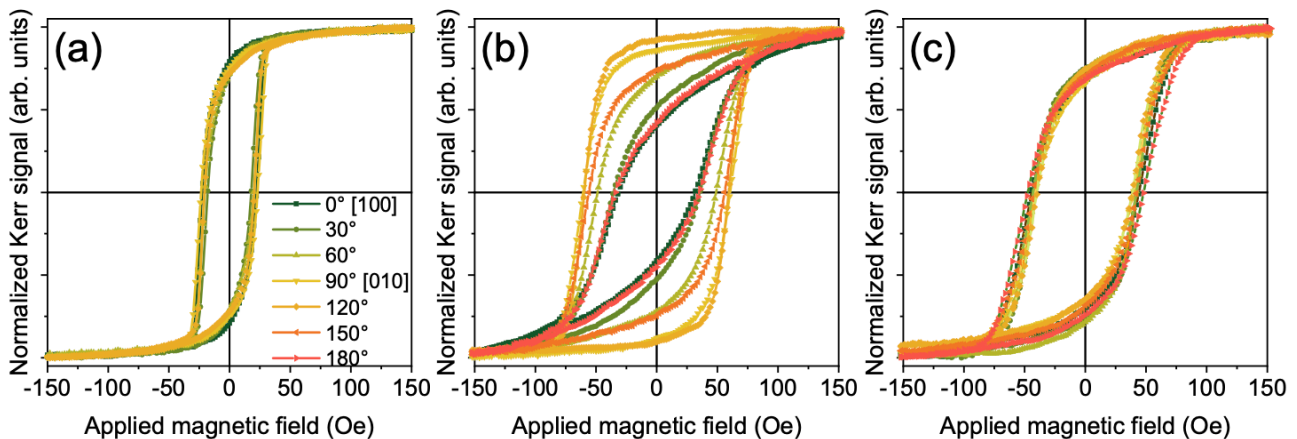


**Fig. 1** – Kerr effect hysteresis loops of PMN-PT/Fe heterostructure after different thermal treatment steps: (a) pristine, (b) annealed at 200°C, 15 min, (c) annealed at 200°C, 2 hours

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# POSTER SESSION 2/G
# SUPERCONDUCTIVITY AND MAGNETISM

# Time Reversal Symmetry Breaking transition in kagome superconductors

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Kagome compounds with formula $AV_3Sb_5$ (A = Cs, Rb, K) [1] are superconducting layered materials that display other two charge related transitions: a charge-density wave (CDW) order concomitant or followed by a time reversal symmetry breaking transition (TRSB) at lower temperature. The interplay between the two phenomena has been the subject of intense research, but while the nature of the CDW phase has been progressively refined [2], the details of the TRSB state are still debated. Here we present a study which combines Nuclear Magnetic Resonance (NMR) measurements, Muon Spin Rotation Spectroscopy and Density Functional Theory calculations to unveil the structure of the CDW and the TRSB state of the A=Rb and Cs samples. The results unambiguously identify the lattice and the electronic structure in the CDW phase and we introduce stringent constraints on the effective moments that break time reversal symmetry [3,4].

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# Weak Ferromagnetism and Metamagnetic Phase Transition in the Antiferromagnet PrBCO$_{6.95}$ Cuprate

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Among the REBa$_2$Cu$_3$O$_{6+x}$ series of cuprates (REBCO$_{6+x}$) with RE a rare earth ion or the yttrium, PrBCO$_{6+x}$ compounds are known to show from previous neutron-scattering experiments, antiferromagnetic (AFM) ordering of the Pr spins at the Néel temperature T$_N$ in the range of 14-20 K for the optimally (OP) (0.50 < x < 1) or over (OV) (x = 1) doped states. The same AFM structure observed in underdoped YBCO$_{6+x}$ was found near 300 K for the Cu(2) spins in the CuO$_2$ plane [1]. High magnetic-field effects have been observed recently [2] around T$_N$ = 14 K, and below T$_N$ at the well-known spin reorientation-point T$_2$ = 10.5 K, and close to the low-critical-point T$_{cr}$ = 4-5 K. Above the saturation field in the range 0.5 T < H$_S$ < 1 T, it was observed a zero-field extrapolated spontaneous magnetization deduced from the field-linear regime up to 2 T, M$_S$(T) equal to 206.39 emu mol$^{-1}$ at T = 1.35 K. This result was in favor that PrBCO$_{6.95}$ possesses a weak ferromagnetism-like contribution which settles into both AFM regimes where earlier precise investigations revealed noncollinear structures [1]. When T increases from 1.35 K, it was reported that M$_S$(T) survives above T$_N$ with a shape change in the differential susceptibility χ$_d$(T) on crossing T$_{cr}$ [2]. We report here isothermal magnetization measurements M(H) in DC magnetic field H up to 2.1 T in several temperatures from 1.6 to 100.5 K using a vibrating-sample magnetometer (VSM2T) with a high resolution (3.0 10$^{-7}$ emu). A second set of measurements were made in the limited range of 1.35-20 K, in DC magnetic field H up to 11 T produced by a magnetometer (BS2) based on superconducting coils (resolution of about 10$^{-3}$ emu). We observe in Fig. 1 that M$_S$(T) decreases with T exhibiting an exponential decay above T$_N$ and goes to 1.13 emu mol$^{-1}$ at 100 K and probably to zero above. The results are compared with previous investigations based on X-ray magnetic circular dichroism (XMCD) which have provided evidence of a field-induced out-of-CuO$_2$ plane Cu(2) spin moments in an OP YBCO$_{6+x}$ film with a superconducting temperature T$_c$ = 90 K [3]. At H = 4 T, the Cu(2) spins are canted out-of the CuO$_2$ planes at 9 K, and, as T increases, the **c**-axis spin moment, i.e., perpendicular to the CuO$_2$ superconducting layers, decreases with T exhibiting the same exponential decay and goes to zero well above T$_c$. The VSM data taken at H = 2 T, M$_{2T}$(T) displayed in Fig. 1, show the same variation in addition with the cupslike feature at T$_N$ and a change in slope below T$_{cr}$. Metamagnetic-like field-induced transitions are detected at a threshold field H$_t$ in the M(H) versus H curves in the whole range of T for H lower than 0.15 T, with an abrupt increase of the remanent magnetization below T$_N$ down to 1.6 K where M$_r$(T) reaches the value of 2.74 emu mol$^{-1}$. All results are discussed in terms of the significant role of the Pr-Cu(2) coupling.
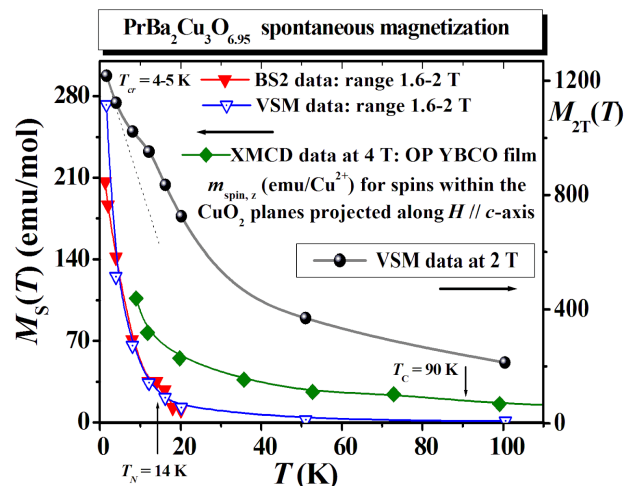


**Fig. 1** Temperature dependences of MS(T) and M2T(T) data of PrBCO6.95. The Cu(2) XMCD data at 4 T of an YBCO film in OP state related to the value of the Cu(2) spin projected along the c-axis [3 ] are reported for comparison.

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# KAgF$_3$, A Quasi 1-D Heisenberg Chain With Strong Spin Orbit Coupling

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Silver(II) fluorides compounds have electronic configurations analog to copper oxides and could exhibit similar physics, including low-dimensional magnetism and high-Tc superconductivity.

We present the results of our extensive NMR characterization of polycrystalline KAgF$_3$, a quasi one-dimensional antiferromagnet (ordering temperature $T_N$ = 29 K), whose magnetic structure and transitions, already investigated by neutron scattering and µSR [1], are still debated.

In the low temperature AFM phase, the broad $^{19}$F NMR spectrum gives direct access to the internal hyperfine fields at the two inequivalent fluorine sites (approx. 250 and 730 mT), also visible in zero external field. AFM order occurs at $T_N$ = 29.5 K in H = 0.8 T, confirming the muon zero field determination [1]. In increasing external fields, the static internal field vanishes at significantly higher temperatures, demonstrating the presence of a weak ferromagnetic coupling, due to the antisymmetric Dzyaloshinkij-Moriya (DM) interaction.
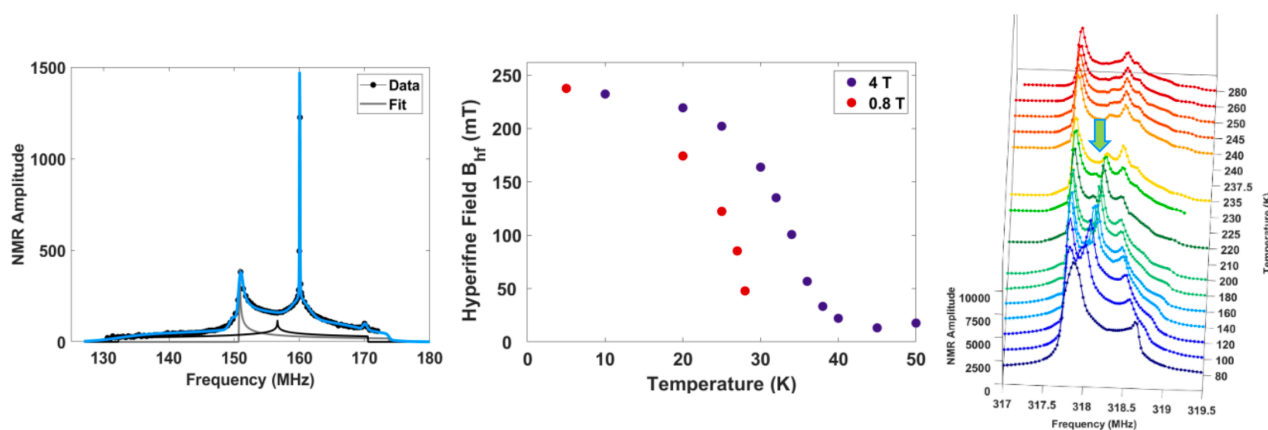


**Fig. 1** NMR results. (Left) Powder Spectrum in H = 4T at 10 K. (Center) Temperature dependence of the local field at one 19F site in the ordered phase. (Right) Temperature evolution of the NMR spectrum in the paramagnetic phase.

Above $T_N$ the fluorine nuclei give rise to the shift pattern shown on the right panel of fig.1, with two singularities visible at 80 K, only weakly temperature dependent. Unexpectedly, a third, strongly temperature dependent singularity emerges in the range 80 K ≤ T ≤ 235 K . This third contribution vanishes above 235 K, temperature corresponding to a structural transition, already detected by neutrons and susceptibility measurements [1,2]. These results will be discussed in the frame of the large Ag exchange coupling and of its DM component.

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# Magnetic Tunnel Josephson Junctions towards a Ferromagnetic Transmon Qubit

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Superconducting qubits have emerged as a prominent platform for realizing large-scale quantum processors [1-4]. However, going beyond the current size of today's quantum processor consisting of a few hundred qubits to a scalable quantum processor with thousands of qubits is far from a trivial challenge. Understanding and further mitigating sources of decoherence in superconducting qubits is a fundamental step for building scalable quantum computing architectures and for reducing resource requirements for quantum error-correction [5, 6]. For instance, the most widely adopted superconducting qubit design, the *transmon* [7], has led to spectacular progress, but it still presents certain architectural issues: frequency-tunable transmon allows fast two-qubit gates, but the susceptibility to flux-noise in SQUIDs results in typical phase coherence times of the order of a few $\mu$s [5].

So far, superconducting quantum circuits have relied almost exclusively on Superconductor/ Insulator/ Superconductor (SIS) Josephson Junctions (JJs) based on Aluminum technology. Recently, novel hybrid paradigms have been introduced demonstrating that devices integrating superconductors and exotic barriers can provide additional qubit frequency knobs and new routes to explore new physics [8]. In this framework, we have proposed a proof-of-concept of a hybrid ferromagnetic transmon qubit, namely the *ferro-transmon* [9]. The main idea of the ferro-trasmon consists in the use of tunnel magnetic JJs (MJJs) that allows digital control of the qubit frequency through magnetic field pulses. The memory properties of MJJs enable them to retain their state at the end of the pulse, thus eliminating the need for a static field during the qubit operation that can be detrimental for coherence. This proposal may have a strong impact on the scalability of superconducting quantum systems.

Here, we report on the fabrication and characterization of very high-quality tunnel ferromagnetic JJs with aluminum electrodes, demonstrating the hysteretic behavior of the magnetic field pattern and preserving typical transport properties of tunnel Al junctions [10,11]. These MJJs, characterized by a very low damping, present values of the Josephson coupling energy suitable for the actual integration into the ferro-transmon architecture. This is a first fundamental step towards the actual integration of MJJs as active elements in quantum circuits. Moreover, quantum circuits and qubits relying on tunnel ferromagnetic Josephson junctions will introduce novel forms of global order and thus warrant thorough investigation to gain a complete understanding and control of all phenomena occurring at S/F interfaces, encompassing dissipation modes and fluctuations.

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# POSTER SESSION 2/H
# THEORETICAL AND COMPUTATIONAL MODELS IN MAGNETISM

# Swift magnet: fast and high precision computation of magnetic field produced by permanent magnet of various topology with analytical models

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Swift magnet is a tool designed and developed by Spin to efficiently, precisely and quickly calculate the magnetic field produced by permanent magnets of various geometries. In Swift magnet, the magnetic field is calculated exactly at every point in three-dimensional space with algorithms based on the analytical expression of the field produced by magnets of various geometries. Calculating the field using the analytical expression involves a lower computational cost and greater accuracy compared to calculations performed using finite element FEM models. Swift magnet is designed to save time without losing accuracy, reducing the computational cost for calculating the field. The field calculation has so far been implemented for cylindrical magnets with axial and diametrical magnetization, ring magnets with axial and radial magnetization, parallelepipeds with magnetization perpendicular to the various faces, arc magnets with various magnetization directions, and thanks to the superposition principle of the effects it is also possible to analytically calculate the Halbach configuration field. Permanent magnets are used in various applications for example magnets are widely used in electric motors, actuators, loudspeakers, position sensors, magnetic separators, magnetic bearing devices, alternators. The field generated by these types of permanent magnets is calculated on the basis of the Amperian current model or the Coulombian model, depending on the specific case. According to the Coulombian model, fictitious magnetic charges can be placed on the surface of the magnet and inside it, while the Amperian current model involves the determination of the vector potential generated by fictitious currents flowing around and inside the magnet. Thus, the challenge is determining which model is the most accurate for calculating the various components of the magnetic field. The analytical expression of the field produced by magnets with these geometries, especially in the case of cylindrical, ring or arc-shaped permanent magnets, makes it possible to use complete and incomplete elliptic integrals of the first, second and third types, depending on the magnetization of the magnet and on the analytical model type. To calculate generalized complete elliptic integrals, it is used an algorithm created by R. Bulirsch, which allows the complete elliptic integrals of the first, second and third types and linear combinations of them to be calculated quickly and precisely.

# AMaRaNTA: An AiiDA-based Workflow To Automate Calculations Of Exchange Parameters In 2D Magnets

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2D magnetic materials have sourced great attention in the last few years [1]. Intrinsic theoretical interest arises from the very existence of magnetism below the 3D limit, which has been proven only recently after decades of debate, as well as from the observed richness in magnetic phases, encompassing conventional ferromagnetic and antiferromagnetic as well as more exotic textures. Besides, these materials are known to offer practical applications in fields such as spintronics.

The popularity gained by such research field has motivated the adaptation of first-principles approaches, combined with model Hamiltonians, to evaluate exchange parameters, needed for the prediction of magnetic textures [2]. However, the methodology is not uniquely established as of today, which results in a lack of systematicity in the data produced; as a consequence, contrasting predictions may at times arise, preventing a full comprehension of the nature of exchange interaction in some cases [3].

To tackle such issue, we have developed the computational package **AMaRaNTA (Automating MAgnetic paRAmeters iN a Tensorial Approach)**, offering an unprecedented, systematic way of automating Density Functional Theory simulations of exchange parameters for 2D magnets. The output of AMaRaNTA consists of i) the full exchange tensor for 1st nearest neighbours ii) the scalar, isotropic exchange constant for 2nd and 3rd nearest neighbours: both aspects allow us to push the research beyond the state of the art, since previous efforts in this respect were limited to 1st nearest neighbours and non-fully-tensorial approaches only [4].

AMaRaNTA comes in the form of an AiiDA workchain [5], based on the Vienna Ab-initio Simulation Package (VASP) for DFT calculations [6]; actual evaluation of the exchange parameters is done by post-processing DFT total energies via the so-called four-states method [2]. Ease of use is guaranteed in that the user is only required to provide a structure file; AMaRaNTA takes care of building the necessary simulation cells and, through AiiDA, to set up all calculations, retrieve the results and extract the exchange parameters.

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- Crespi, M. (organizing committee)
- Crupi, V. (oral session 3)

- Cuccurullo, S. (oral session 1)
- Cucini, R. (oral session 7, poster session 2C)
- Cucinotta, G. (poster session 1D, poster session 2B)
- Cugini, F. (poster session 1A, poster session 2D)

# D

- Dagur, D. (oral session 3, poster session 2F)
- Dalal, B. (poster session 2A)
- Dall'Olio, S. (poster session 1A)
- Das, T. K. (oral session 4)
- Dediu, V. A. (program committee, oral session 5, poster session 2D)
- De Julián Fernández, C. (program committee, chair keynote lecture 2, oral session 2, oral session 6, poster session 1E, poster session 1E, poster session 2D)
- Del Bianco, L. (advisory board, chair oral session 1, oral session 8, poster session 1C)
- Del Conte, C. (oral session 5)
- Del Giacco, A. (oral session 8, poster session 2C)
- Della Penna, S. (oral session 1)
- Della Ventura, B. (oral session 1, poster session 1C)
- Delodovici, F. (poster session 2F)
- Del Puerto Morales, M. (poster session 1E)
- De Luca, M. (oral session 1, poster session 1C)
- De Renzi, R. (oral session 4, oral session 7, poster session 2A, poster session 2G, poster session 2G)
- De Toro, J. A. (oral session 8)
- De Trizio, L. (poster session 1E)
- De Vita, A. (oral session 7)
- Diaz-Ufano, C. (poster session 1E)

- Dickson, M. (poster session 2A)

- Dimoulas, A. (oral session 3)

- Di Palma, L. (poster session 2G)

- Di Pietro, A. (poster session 2B, poster session 2F)

- Di Stefano, O. (oral session 5)

- Dolabella, S. (poster session 2F)

- Dreyer, R. (poster session 2C)

- Dri, C. (oral session 7)

- Droghetti, A. (poster session 2D)

- Durin, G. (poster session 2B)

# E

- Eckvahl, J (oral session 7)

# F

- Fabbrici, S. (oral session 6, poster session 1A)

- Facoetti, A. (poster session 1E)

- Fagiani, F. (oral session 6, poster session 2F, poster session 2F)

- Falqui, A. (poster session 1E)

- Fanciulli, M. (oral session 3)

- Fanciullini, L. (poster session 1A)

- Fantuzzi, S. (poster session 1D)

- Fasolato, C. (poster session 2F)

- Ferraiuolo, R. (poster session 2G)

- Ferrara, E. (poster session 1A)

- Ferretti, A. (oral session 3)

- Ferretti, A. M. (organizing committee, poster session 1E, poster session 2E)

- Ferretti, M. (poster session 1A, poster session 1A)

- Fiebig, M. (poster session 2F)

- Figini, S. (poster session 1C)
- Filibian, M. (poster session 1E)
- Filippi, A. R. (poster session 1C)
- Finardi, A. M. (oral session 7, poster session 2F)
- Finocchio, G. (advisory board, oral session 3, poster session 1B)
- Fiorani, D. (advisory board)
- Fiore Mosca, D. (oral session 7)
- Fiori, S. (oral session 3)
- Florio, P. (poster session 2C)
- Fittipaldi, M. (program committee, poster session 1A, poster session 1D, poster session 1D, poster session 1D)
- Fix, M. (oral session 6)
- Fiorino, P. C.. (oral session 7)
- Fournée, V. (oral session 6)
- Franchini, C. (oral session 7, oral session 7, poster session 2H)
- Frassinetti, J. (poster session 2A, poster session 2G)
- Fratesi, G. (oral session 3, oral session 5, poster session 2B, poster session 2B, poster session 2B)
- Fujii, J. (oral session 7, poster session 2F)
- Fulgione, A. (poster session 1C)
- Furlani F. (oral session 1)

# G

- Gabbani, A. (oral session 2, poster session 1C, poster session 1E)
- Galland, C. (poster session 1B)
- Galli, G. (poster session 1C)
- Gallino, I. (poster session 1A)
- Gallo, L. (poster session 1A)
- Gallo, S. (poster session 1E)

- Gallo-Cordova, A. (poster session 1E)
- Gandini, G. (poster session 2F, poster session 2F)
- Garcia, E. (oral session 7, poster session 2G)
- Garlatti, E. (keynote lecture 3, oral session 4)
- Garulli, G. (poster session 1A)
- Gatti, C. (advisory board, chair oral session 7)
- Gatto, M. L. (poster session 1C)
- Gerace, A. (poster session 1E, poster session 2E)
- Gerina, M. (poster session 1E)
- Ghavimi, A. (poster session 1A)
- Ghibaudo, N. (poster session 1A)
- Ghirri, A. (oral session 4, oral session 5)
- Giaconi, N. (oral session 4, oral session 4, poster session 2B)
- Giampietri, A. (oral session 3, poster session 2B)
- Gibertini, M. (poster session 2H)
- Giordano, A. (poster session 1B)
- Girardi, D. (poster session 2C, poster session 2C)
- Giroletti, E. (poster session 1D)
- Giugni, A. (poster session 2F)
- Gnoli, L. (oral session 5)
- Graf, M. J. (poster session 2A)
- Granados Miralles, C. (poster session 2E)
- Granata, C. (poster session 2G)
- Grau, L. (poster session 2E)
- Graziosi, P. (poster session 2D)
- Greco, G. (oral session 8, poster session 1C)
- Grimaldi, A. (oral session 3, poster session 1B)
- Grochala, W. (poster session 2G)
- Grochot, K. (oral session 3)
- Groppi, F. (poster session 1E)

- Guarino, V. (poster session 1E)
- Gubbiotti, G. (advisory board, oral session 5, poster session 2C)
- Gutfleisch, O. (plenary lecture 1)

# H

- Hafshejani, A. F. (poster session 2F)
- Hajducek, J. (poster session 2B)
- Halder, A. (poster session 2D)
- Hänke, T. (oral session 1)
- Harris, D. (poster session 2A)
- Hassan, M. (oral session 6)
- Heyderman, L. (oral session 5)
- Heinz, B. (oral session 5, oral session 8)
- Hilschenz, I. (oral session 1)
- Hrabovsky, D. (oral session 2)
- Hueso, L. E. (keynote lecture 4)

# I

- Iannotti, V. (advisory board, oral session 1, poster session 1C, poster session 1E)
- Ibarra, A. (poster session 1C)
- Ibarra, M. R. (oral session 2)
- Imperatori, P. (poster session 1F)
- Innocenti, C. (oral session 2, poster session 1C, poster session 1E, poster session 1E)

# J

- Jana, A. (poster session 2F)
- Jönsson, P. E. (oral session 8)

# K

- Kabanov, V. (poster session 2D)
- Kaciulis, S. (oral session 6)
- Kazunari, Y. (poster session 2A)
- Kalaboukhov, A. (oral session 1)
- Khanjani, M. V. (oral session 3)
- Kobe, S. (poster session 2E)
- Kohl, F. (oral session 8)
- Koplak, O. (oral session 8)
- Koteras, K. (poster session 2G)
- Kozenkova, E. (poster session 1C)
- Krzyaniak, M. D. (oral session 7)
- Kuepferling, M. (oral session 3, poster session 2F)
- Kumar, A. (oral session 4)
- Kumar Rakshit, R. (poster session 2D)

# L

- Lahoubi, M. (poster session 2E, poster session 2G)
- Lake, S. (poster session 2C)
- Lamperti, A. (poster session 2F)
- Lanotte, L. (poster session 1E)
- Lantieri, M. (poster session 1A)
- Lascialfari A. (conference chair, poster session 1C, poster session 1D, poster session 1D, poster session 1D, poster session 1E, poster session 1E)
- Langer, J. (oral session 3)
- Latino, G. (poster session 1D, poster session 1D)
- Laurenzana, A. (poster session 1C, poster session 1E)

- Laureti, S. (oral session 6, poster session 1F)
- Lavacchi, A. (poster session 1C)
- Łazarski, S. (oral session 3)
- Lenardi, C. (poster session 1E)
- Levati, V. (poster session 2C)
- Li Bassi, A. (poster session 2C)
- Lintzeris, A. (oral session 3)
- Locarno, S. (poster session 1E)
- Locatelli, L. (oral session 3, poster session 2F, poster session 2F)
- Lombardi, F. (oral session 1)
- Long, J. R. (poster session 2A)
- Longo, D. (poster session 2B)
- Longo, E. (oral session 3, oral session 3, poster session 2F, poster session 2F)
- Longo, M. (poster session 2F)
- López-Ortega, A. (poster session 1E, poster session 1E)
- Lorenzana, J. (poster session 2G)
- Losero, E. (poster session 1B)
- Lottini, E. (poster session 1E, poster session 1E)
- Lupi, N. (oral session 4)

# M

- Macaluso, E. (oral session 7)
- Maccaferri, N. (keynote lecture 2)
- Madami, M. (oral session 5, oral session 5, poster session 2C, poster session 2C)
- Maggioni, D. (poster session 1E)
- Magni, A. (oral session 3, poster session 2B, poster session 2B, poster session 2F)

- Maikudi Isah, M. (poster session 1D, poster session 2A, poster session 2A)
- Makarov, D. (plenary lecture 2)
- Maksutoglu, M. (oral session 5)
- Maltoni, P. (oral session 8, poster session 1A)
- Manari, E. (poster session 2H)
- Manca, N. (oral session 1)
- Manna, N. (poster session 1E)
- Manenti, S. (poster session 1E)
- Manftinetti, P. (poster session 1E)
- Mannini, M. (program committee, oral session 4, oral session 4, poster session 1D, poster session 1D, poster session 2B)
- Mantovan, R. (oral session 3, poster session 2F, poster session 2F)
- Marchi, L. (poster session 1D)
- Margaris, G. (poster session 1E)
- Mariani, M. (organizing committee, poster session 1C, poster session 1D, poster session 1D, poster session 1D, poster session 1E, poster session 1E)
- Marino, M. (oral session 3, poster session 2B, poster session 2B)
- Marquina, C. (oral session 2)
- Marra, D. (oral session 1, poster session 1C)
- Marrazzo, A. (poster session 2H)
- Marré, D. (oral session 1)
- Martin Nuñez, J. (oral session 2)
- Martino, L. (poster session 1A)
- Maruccio, G. (program committee, poster session 1A)
- Marzola, P. (keynote lecture 1)
- Maspero, F. (oral session 1, oral session 5, oral session 8, poster session 2C)
- Massarotti, P. (poster session 2G)
- Massetti, C. (poster session 2F)

- Materassi, E. (oral session 6)
- Mathieu, R. (oral session 8)
- Mazej, Z. (poster session 2G)
- Mazza, L. (oral session 3)
- Mazzani, M. (poster session 2G)
- Mazzoni, R. (poster session 1D)
- Meneghini, C. (oral session 2)
- Menichetti, S. (oral session 4)
- Mercurio, A. (oral session 5)
- Meroni, D. (poster session 1E)
- Messana, G. (poster session 1C)
- Messori, A. (poster session 1D)
- Mezzi, A. (oral session 6)
- Milanesi, P. (poster session 2F)
- Mitrović, V. F. (oral session 7, poster session 2A, poster session 2G)
- Mohan, A. (oral session 2)
- Molle, A. (poster session 2F)
- Molteni, E. (oral session 3, oral session 5, poster session 2B, poster session 2B)
- Monteduro, A. G. (poster session 1A)
- Montemurro, D. (poster session 2G)
- Motta, A. (poster session 1C)
- Motti, F. (oral session 3, oral session 5)
- Mozzzati, M. C. (poster session 1A)
- Müller, A. M. (oral session 5)
- Mungpara, D. (oral session 1)
- Muzzi, B. (oral session 2, poster session 1C, poster session 1E, poster session 1E, poster session 2E)

# N

- Naaman, N. (oral session 1)
- Nessi, L. (poster session 2F)
- Nitschke, J. E. (poster session 2B)

# O

- Ocker, B. (oral session 3)
- Olivetti, E. S. (poster session 1A, poster session 2B)
- Omelyanchik, A. (poster session 1C, poster session 1E, poster session 1E)
- Onida, G. (poster session 2B)
- Onuorah, I. J. (poster session 2A)
- Orlando, F. (poster session 2H)
- Orsini, F. (organizing committee, poster session 1E, poster session 1E, poster session 1E)
- Ortiz, B. R. (poster session 2G)
- Otero, E. (poster session 1D, poster session 2B)
- Otero Martinez, C. (poster session 1E)

# P

- Panaccione, G. (program committee, oral session 3, oral session 7, poster session 2C, poster session 2F)
- Panseri, S. (oral session 1)
- Panzeri, M. (poster session 2C)
- Paolasini, L. (keynote lecture 5)
- Park, J. G. (poster session 2A)
- Parlato, L. (poster session 2G)
- Pavarini, E. (advisory board)

- Peddis, D. (program committee, oral session 2, chair oral session 8, oral session 8, poster session 1A, poster session 1A, poster session 1E, poster session 1E, poster session 1E, poster session 1E, poster session 1F)
- Pellegrino, L. (oral session 1)
- Pellizzi, N. (oral session 6)
- Pepe, G. P. (poster session 2G)
- Pérez-Pardo, M. T. (poster session 1A)
- Perfetti, M. (poster session 1D, poster session 1D)
- Petrecca, M. (oral session 2, poster session 1C)
- Petrov, A. (poster session 2F)
- Petrucci, G. (poster session 1C)
- Petti, D. (oral session 6, poster session 2C, poster session 2C)
- Piamonteze, C. (oral session 5)
- Piazzoni, M. (poster session 1E)
- Picone, A. (oral session 3, poster session 2B, poster session 2B, poster session 2B)
- Picozzi, S. (program committee, plenary lecture 3, poster session 2B, poster session 2F, poster session 2H)
- Pierantozzi, G. M. (oral session 7)
- Piligkos, S. (oral session 4)
- Pincelli, T. (oral session 7)
- Pineider, F. (program committee, oral session 2, poster session 1C, poster session 1E)
- Pinto, A. (poster session 1C)
- Pirro, P. (oral session 5, oral session 8)
- Pisani, F. (poster session 1C)
- Plaza, A. E. (oral session 1, oral session 8)
- Plumb, K. W. (poster session 2A)
- Poggini, L. (poster session 1D, poster session 2B)
- Poggini, N. (oral session 4, oral session 4)

- Polewczyk, V. (poster session 2F)
- Poneti, G. (poster session 1D)
- Ponti, A. (conference chair, poster session 2E)
- Porru, M. (organizing committee, poster session 1E, poster session 1E)
- Postuma, I. (poster session 1C)
- Pradham, G. (poster session 2B, poster session 2B)
- Prando, G. (organizing committee, poster session 2A, poster session 2A)
- Preda, L. (poster session 1C)
- Provino, A. (poster session 1E)
- Pugno, N. M. (oral session 8, poster session 1C)
- Puliafito, V. (program committee, oral session 3)

# Q

- Quaresmini, L. (poster session 2C)
- Quesada, A. (poster session 2E)

# R

- Ragucci, E. (oral session 1)
- Raimondo, E. (oral session 3, poster session 1B)
- Rakshit, R. K. (oral session 5)
- Ranieri, D. (poster session 2B)
- Rau, J. G. (poster session 2A)
- Rawat, R. (poster session 2F)
- Recordati, C. (poster session 1E)
- Riddiford, L. (oral session 5)
- Rigamonti, A. (advisory board, chair oral session 6)
- Rigamonti, L. (poster session 1D)
- Riminucci, A. (oral session 5, poster session 2D)

- Rinaldi, C. (program committee, oral session 6, poster session 2F, poster session 2F)
- Rizzato, S. (poster session 1A)
- Rizzi, P. (poster session 2B, poster session 2B)
- Robustelli Test, A. (organizing committee, poster session 1C)
- Rodionova, V. (poster session 1C)
- Rodrigues, D. (oral session 3)
- Rodriguez, M. (poster session 1A)
- Rodriguez-Rivera, J. A. (poster session 2A)
- Rodriguez-Suárez, P. (poster session 2E)
- Rohit, K. (poster session 2F)
- Rossi, G. (advisory board, oral session 7, poster session 2C, poster session 2F)
- Rossi, L. (poster session 1E)
- Rubano, A. (poster session 2F)
- Rusnati, Federico A. (poster session 1D)
- Russo, V. (poster session 2C)
- Rutkowski, B. (oral session 8)

# S

- Sahoo, S. (oral session 5)
- Sainctavit, P. (oral session 4)
- Sakač, N. (oral session 1)
- Salman, Z. (poster session 1D)
- Salvadori, E. (poster session 1D)
- Sangregorio, C. (advisory board, chair oral session 2, oral session 2, oral session 2, poster session 1C, poster session 1E, poster session 1E, poster session 1E, poster session 1E, poster session 2E)

- Sanna, S. (program committee, oral session 5, chair oral session 6, oral session 6, oral session 7, poster session 1D, poster session 2A, poster session 2A, poster session 2G)
- Sanna Angotzic, M. (poster session 1E, poster session 1F)
- Santangelo, S. (poster session 2E)
- Santanni, F. (poster session 1D, poster session 2B)
- Santini, P. (oral session 4)
- Sanvito, S. (advisory board, poster session 2D)
- Šarkanj, B. (oral session 1)
- Sarkar, T. (poster session 1A)
- Satariano, R. (poster session 2G)
- Savasta, S. (oral session 5)
- Scagnoli, V. (oral session 5, poster session 2A)
- Scavone, F. (poster session 1C, poster session 1E)
- Schmidt, G. (poster session 2C)
- Schneider, C. (oral session 5)
- Schwarz, A. (oral session 1)
- Sergo, R. (oral session 7)
- Serrano, G. (oral session 4, poster session 1D, poster session 2B)
- Sessoli, R. (advisory board, chair plenary lecture 3, chair keynote lecture 5, oral session 4, oral session 4, oral session 7, poster session 1D, poster session 1D, poster session 2B)
- Shafiei, A. (poster session 2F)
- Sharangi, P. (poster session 1A)
- Shumilin, A. (poster session 2D)
- Sidane, I. (poster session 1A)
- Silvani, R. (oral session 5, poster session 2C)
- Singh, G. (poster session 1E)
- Singh, M. (oral session 5, poster session 2D)
- Singh, S. (poster session 2A)

- Sirotti, F. (oral session 7)
- Skowroński, W. (oral session 3)
- Slimani, S. (poster session 1A)
- Soave, R. (organizing committee)
- Sola, A. (oral session 3, poster session 1A, poster session 2F)
- Solzi, M. (program committee, poster session 1A, poster session 2D)
- Sorace, L. (program committee, chair keynote lecture 3, chair keynote lecture 4, poster session 1D, poster session 1D, poster session 1D, poster session 1D)
- Sordan, R. (poster session 2F)
- Sorrentino, A. L. (oral session 4, oral session 4, poster session 2B)
- Spadaro, M. C. (oral session 8)
- Spadone, S. (oral session 1)
- Spizzo, F. (oral session 8, poster session 1C)
- Stampe Leiszner, S. (poster session 1D)
- Stavrić, S. (poster session 2H)
- Stella, G. M. (poster session 1C)
- Syrowatka, F. (poster session 2C)

# T

- Tacchi, S. (oral session 5, poster session 2C, poster session 2C)
- Tacconi, L. (poster session 1D)
- Tafuri, F. (poster session 2G)
- Takhsha Ghahfarokhi, M. (oral session 1, oral session 6, poster session 2B)
- Tassetti, A. (oral session 7)
- Tavcar, G. (poster session 2G)
- Tcyruylnikov, N. A.. (oral session 7)
- Telang, P. (poster session 2A)

- Tiberto, P. (program committee, chair keynote lecture 1, oral session 1, poster session 1A, poster session 1C, poster session 2B, poster session 2B)
- Tincani, L. (oral session 6)
- Tomasello, R. (poster session 1B)
- Torelli, P. (poster session 2F)
- Trevisi, G. (oral session 6)
- Triolo, C. (poster session 2E)
- Trioni, M. I. (organizing committee)
- Trohidou, K. N. (poster session 1E)
- Tsipas, P. (oral session 3)
- Tullo, P. (oral session 3)

# U

- Ud Din Babar, Z. (poster session 1E)
- Uhlíř, V. (oral session 1, poster session 2B)
- Ullrich, A. (oral session 6)

# V

- Vaclavkova, D. (oral session 5)
- Varvaro, G. (program committee, chair plenary lecture 2, oral session 6, oral session 8, poster session 1F)
- Vasilakaki, M. (poster session 1E)
- Varrassi, L. (poster session 2H)
- Velotta, R. (oral session 1, poster session 1C)
- Veneri, A. (poster session 1D)
- Venstra, W. (oral session 1)
- Veronese, I. (organizing committee, poster session 1E)
- Vettoliere, A. (poster session 2G)

- Viglianisi, C. (organizing committee)
- Villa, S. (poster session 1E)
- Vinai, G. (oral session 3, poster session 2F, poster session 2F)
- Vinattieri, A. (poster session 1E)
- Vitali, M. (poster session 2C)
- Vobornik, I. (poster session 2F)
- Vockenhuber, C. (oral session 5)

# W

- Wako, A. E. (poster session 2E)
- Wahlberg, E. (oral session 1)
- Wang, H. (oral session 5)
- Wasielewski, M. R. (oral session 7)
- Wiemer, C. (poster session 2F)
- Wilson, S. D. (poster session 2A, poster session 2G)
- Woodward, P. (oral session 7)

# X

- Xun, K. (poster session 2A)

# Y

- Yaacoub, N. (oral session 8, poster session 1E, poster session 1E, poster session 1F)
- Yang, B. (poster session 2B)
- Yang, Y. (poster session 1C)
- Young, R. M. (oral session 7)
- Yu, H. (oral session 5)

# Z

- Zacchini, S. (poster session 1D)
- Zadeh, A. B. (oral session 5)
- Zákutná, D. (poster session 1E)
- Zamborlini, G. (poster session 2B)
- Zhukov, A. (poster session 2E)
- Zhukova, V. (poster session 2E)
- Zucchetti, C. (poster session 2F)