# Curvilinear Condensed Matter: Fundamentals and Applications

**717. WE-Heraeus-Seminar**

**24 - 26 June 2021**
**online via MeetAnyway**

WILHELM UND ELSE
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# Introduction

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## Aims and scope of the 717. WE-Heraeus-Seminar:

Extending two-dimensional structures into the three-dimensional (3D) space has become a general trend in multiple disciplines, including electronics, photonics, plasmonics and magnetics. This approach provides means to modify conventional or to launch novel functionalities by tailoring curvature and 3D shape. In the case of 3D curved magnetic thin films and nanowires the physics is driven by the interplay between exchange and magnetostatic interactions, which contain spatial derivatives in their energy functionals. This makes both interactions sensitive to the appearance of bends and twists in the physical space. Theoretical works predict the curvature-induced effective anisotropy and effective Dzyaloshinskii-Moriya interaction resulting in a multitude of novel effects including magnetochiral effects (chirality symmetry breaking) and topologically induced magnetization patterning. Those 3D magnetic architectures are already proven to be application relevant for life sciences, targeted delivery, realization of 3D spin-wave filters, and magneto-encephalography devices to name just a few. To this end, the initially fundamental topic of the magnetism in curved geometries strongly benefited from the input of the application-oriented community, which among others explores the shapeability aspect of the curved magnetic thin films. These activities resulted in the development of the family of shapeable magnetoelectronics which already includes flexible, printable, stretchable and even imperceptible magnetic field sensorics. The balance between the fundamental and applied inputs into the topic of magnetism in curved geometries is rather unique. This stimulates even further the development of new theoretical methods and novel fabrication/characterization techniques. The synergy will definitely enable us surpassing the exploratory research and will pave the way towards novel device concepts, where the geometry of a functional thin film will play a decisive role in determining the device performance.

## Scientific Organizers:


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|---|---|
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| Prof. Denis D. Sheka | Taras Shevchenko National University of Kyiv, Ukraine<br>E-mail: sheka@knu.ua |

# Introduction

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# Program (CET)

## Thursday, 24 June 2021

| | | |
|---|---|---|
| 08:30 – 08:35 | Scientific organizers | **Welcome words** |
| 08:35 – 08:50 | Stefan Jorda | **About the WE-Heraeus-Foundation** |
| 08:50 – 09:00 | Denys Makarov | **Introductory remarks** |
| 09:00 – 09:45 | Martin Kaltenbrunner | **Degradable materials with extreme mechanics for soft robots and electronics** |
| 09:45 – 10:15 | Carmine Ortix | **Topology and transport in nanostructures with curved geometries** |
| 10:15 – 10:45 | *COFFEE BREAK and Networking* | |
| 10:45 – 11:30 | Oleksandr Dobrovolskiy | **3D nanoarchitectures for superconductivity and nanomagnetism** |
| 11:30 – 12:00 | Paola Gentile | **Geometrically driven effects in curved superconducting nanostructures** |
| 12:00 – 12:30 | Volodymyr Kravchuk | **Dynamics of magnetic skyrmions in curvilinear films** |
| 12:30 – 13:30 | *LUNCH and Networking* | |

# Program (CET)

## Thursday, 24 June 2021

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|---|---|---|
| 13:30 – 14:15 | Amalio Fernandez-Pacheco | **A new platform for the experimental investigation of advanced three-dimensional geometrical effects in nanomagnetism** |
| 14:15 – 15:00 | Claire Donnelly | **Three-dimensional magnetic systems: from the bulk to patterned nanostructures** |
| 15:00 – 15:30 | Attila Kakay | **Spin-wave modes in curved 3D nanostructures** |
| 15:30 – 16:00 | *COFFEE BREAK and Networking* | |
| 16:00 – 16:45 | Olena Gomonay | **String model for antiferromagnetic domain wall: skyrmions and beyond** |
| 16:45 – 17:30 | Oleg Tretiakov | **Curvature effects on ferromagnetic materials and spin textures** |
| 17:30 – 18:00 | *COFFEE BREAK and Networking* | |
| 18:00 – 19:00 | Michael Dickey | **Liquid metals for soft and stretchable electronics** |

# Program (CET)

## Friday, 25 June 2021

| | | |
|---|---|---|
| 08:30 – 09:15 | Luisa Petti | **Flexible electronics and sensorics based on low-cost and high throughput processes** |
| 09:15 – 10:00 | Larysa Baraban | **Flexible nanoscale biosensor devices** |
| 10:00 – 10:30 | Yiwei Liu | **Flexible magnetic sensitive materials and sensors** |
| 10:30 – 11:00 | *COFFEE BREAK and Networking* | |
| 11:00 – 11:45 | Minjeong Ha | **Micro/nano-materials based interactive wearables for human augmented reality** |
| 11:45 – 12:15 | Yevhen Zabila | **Multifunctional flexible sensor platform for motion control in robotics** |
| 12:15 – 12:45 | Gaspare Varvaro | **SAF-based perpendicular magnetized GMR spin valves on large-area flexible substrates** |
| 12:45 – 13:30 | *LUNCH and Networking* | |

# Program (CET)

## Friday, 25 June 2021

| | | |
|---|---|---|
| 13:30 – 14:30 | **Poster talks** | |
| 14:30 – 15:30 | **Poster session** | |
| 15:30 – 16:00 | *COFFEE BREAK and Networking* | |
| 16:00 – 16:45 | Avadh Saxena | **Curvature effects in liquid crystal skyrmions** |
| 16:45 – 17:15 | Gaetano Napoli | **Nematic versus ferromagnetic shells: new insights in curvature-induced effects** |
| 17:15 – 17:30 | *COFFEE BREAK* | |
| 17:30 – 18:30 | Elena Vedmedenko | **Interlayer Dzyaloshinskii-Moriya Interactions** |

# Program (CET)

## Saturday, 26 June 2021

| | | |
|---|---|---|
| 08:30 – 09:00 | Anna Morozovska | **Flexo-sensitive vortex-like polarization structures in nanoscale ferroelectrics** |
| 09:00 – 09:30 | Alexander Edström | **Curved magnetism in $CrI_3$** |
| 09:30 – 10:00 | Justin Llandro | **Intricate magnetic configuration of self-assembled 3D gyroid nanostructures** |
| 10:00 – 10 :30 | Davide Peddis | **Hollow nanostructures: a new playground for curvilinear magnetism** |
| 10:30 – 11:00 | *COFFEE BREAK and Networking* | |
| 11:00 – 11:45 | Kostiantyn Yershov | **Soft and reconfigurable magnetic systems** |
| 11:45 – 12:15 | Fatih Zighem | **Links between strain fields and magnetic properties in thin films and nanostructures** |
| 12:15 – 12:45 | Vagson L. Carvalho-Santos | **Curvature-induced emergence of a second critical field for domain wall dynamics in bent nanostripes** |
| 12:45 – 13:15 | Anastasiia Korniienko | **The effect of curvature on eigenexcitations of magnetic skyrmion** |
| 13:15 | Scientific organizers | **Poster prize announcement**<br>**Closing remarks** |

# Posters

# Posters

| | | |
|---|---|---|
| **1** | Yelyzaveta Borysenko | **Ground states of the antiferromagnetic spin rings in strong magnetic fields** |
| **2** | Aicha Bouhlala | **Investigation of Structrural, Elastic and Thermodynamic Properties of $CeO_2$ : A DFT-based on simulation** |
| **3** | Claudia Fernández González | **Scale-up of nanowire synthesis for the application in composite bonded magnets** |
| **4** | Andrés Felipe Franco | **Trajectories of charged particles moving through magnetized tubes** |
| **5** | Nabil Hachem | **Surface critical behavior of semi-infinite ferrimagnetic mixed system** |
| **6** | Aurelio Hierro-Rodriguez | **Curvature-mediated spin textures in magnetic multi-layered nanotubes** |
| **7** | Jérôme Hurst | **Theoretical study of current induced domain wall motion in magnetic nanotubes with azimuthal magnetization** |
| **8** | El Mostafa Jalal | **Magnetic and thermodynamic properties of a hexagonal ferrimagnetic Ising nanowire with core/shell structure** |
| **9** | Vladimir Kolosov | **Novel type of bent-lattice nanostructure in crystallizing amorphous films: from transrotational microcrystals to amorphous models** |
| **10** | Lukas Körber | **Finite-element dynamic-matrix approach to calculate spin-wave dispersions in waveguides with arbitrary cross section** |

# Posters

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|---|---|---|
| **11** | Michaela Lammel | **Atomic layer deposition of Yttrium Iron Garnet (YIG) for 3D spintronics** |
| **12** | Naëmi Leo | **Small-angle neutron scattering on nanomagnetic gyroids structures** |
| **13** | Tanmoy Pati | **Space-time, relativity and quantum fields** |
| **14** | Oleksandr Pylypovskyi | **Effects of torsion and curvature in antiferromagnetic spin chains** |
| **15** | Gwendolyn Quasebarth | **Calculation of spin-wave eigenmodes in a hemisphere and Möbius strip** |
| **16** | Niurka R. Quintero | **The nonlinear Dirac equation with a spatially periodic potential** |
| **17** | Artem Tomilo | **Parallel computation of 3D magnetic structures** |
| **18** | Oleksii Volkov | **Experimental confirmation of curvature-induced effects in magnetic nanosystems** |
| **19** | Kai Wagner | **Nanoscale mechanics of antiferromagnetic domain walls in $Cr_2O_3$** |
| **20** | Qi Wang | **Long-range propagation of spin waves in transversely magnetized nano-scaled yttrium iron garnet conduits** |
| **21** | Ivan Yastremsky | **Enhanced longitudinal relaxation of solitons in ultrathin easy-axis ferromagnets** |
| **22** | Oleksandr Zaiets | **Circular stripe domains in magnetic heterostructures of cylindrical geometry** |

# Abstracts of Talks

(in alphabetical order)

# Flexible nanoscale biosensor devices

**L. Baraban**

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Synergy between, physics, material sciences and biotechnology during last decade has led to a tremendous scientific progress in the fields of biodetection and nanomedicine. This tight interaction led to the emergence of a new class of bioinspired systems that enables to bring the area of biosensorics e.g. for cell or molecular diagnostics and analytics to the new level. The advances are expected in terms of (i) possibility of early diagnostics of diseases due to the increased sensitivity of the detectors, (ii) real time and high throughput analysis offered by combination of integrated electronics and microfluidic approach, and (iii) establishing the new functional formats for the bioassays. One of the most promising candidates for the future diagnostics are the electronic nanobiosensors that have attracted great attention in the last decades since they provide rich quantitative information for medical and biotechnological assays without pre-treatment and specific optical labelling of the detected species.

At the same time, to bring state-of-the-art biomedical diagnostic devices to the hands of the people, it is important to reduce the price of the devices and allow for their high-volume delivery in a cost-efficient manner, e.g., container transportation. For the latter, a crucial aspect is to reduce the weight of the device. This can be achieved by replacing the conventional rigid substrates, like Si or glass by light weight and large area polymeric foils.

Here I will focus on two flexible diagnostic platforms for the analysis at the micro- and nanoscale, represented by (a) silicon nanowires based field effect transistors and (b) 2D materials based on molybdenum disulfide.

## References

[1] D. Karnaushenko, et al., Adv. Healthc. Mater. **4**(10), 1517 (2015).
[2] P. Zhang, et al., Small **15** (23), 1901265 (2019).
[3] L. Baraban, et al. Advanced Science **6** (15), 1900522 (2019).

# Curvature-induced emergence of a second critical field for domain wall dynamics in bent nanostripes


**G. H. R. Bittencourt[1], R. Moreno[2], R. Cacilhas[1],**

**S. Castillo-Sepúlveda[3], O. Chubykalo-Fesenko[4], D. Altbir[5],**

**and V. L. Carvalho-Santos[1]**

*[1] Departamento de Física, Universidade Federal de Viçosa*
*[2] Earth and Planetary Science, School of Geosciences, University of Edinburgh*
*[3] Facultad de Ingeniería, Universidad Autónoma de Chile*
*[4] Instituto de Ciencia de Materiales de Madrid*
*[5] Departamento de Física, CEDENNA, Universidad de Santiago de Chile*


Curved geometry strongly influences magnetic properties of nanostructured materials in the first place due to the influence of magnetostatic energy and by inducing effective anisotropies and Dzyloshinskii–Moriya interactions (DMIs) [1]. The particular case of curvature-induced magnetic phenomena in cylindrical nanowires (CNWs) and nanostripes (NSs) is especially interesting because these systems have been proposed as key components for different applications. Most of these applications demand precise control of the DW dynamics under the action of different external stimuli. The DW behavior in curved elements is modified as compared to straight ones. For example, in straight NSs, the oscillatory motion of a DW propagating under the Walker regime is dependent on the NS cross-section, being suppressed for CNWs [2]. Contrarily, in bent CNWs, the new degree of freedom introduced by curvature brings back the Walker breakdown [3]. In this talk, we present the obtained results on the dynamics of a transverse domain wall (DW) in a bent nanostripe under an external field and spin-polarized current [4]. Besides the standard Walker breakdown phenomenon, we show the emergence of a second Walker-like critical field, which depends on both the curvature of the nanostripe and its cross-section geometry. DW can change its phase in this field, i.e., it can be re-oriented along another direction with respect to the nanostripe face. Additionally, we show that the amplitude and frequency of the DW oscillations above the Walker breakdown field also depend on the nanostripe geometry and can be controlled by external stimuli. Our results evidence that the inclusion of local curvatures in nanostripes is an important component for applications that demand an adequate control of the DW phase by the proper choice of external stimuli.

## References


[1] Y. Gaididei *et al.*, Phys. Rev. Lett. **112**, 257203 (2014).
[2] D. Altbir *et al.*, Sci. Rep. **10**, 21911 (2020).
[3] R. Cacilhas *et al.*, Phys. Rev. B **101**, 184418 (2020).
[4] G. H. R. Bittencourt *et al.,* Appl. Phys. Lett. **118**, 142405 (2021).

# Liquid metals for soft and stretchable electronics

**Michael D. Dickey[1]**

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### Abstract

This talk will discuss efforts to pattern and shape-reconfigure liquid metals as conductive inks for stretchable, soft, and reconfigurable electronics[1]. Alloys of gallium have metallic conductivity, yet have low viscosity, low toxicity, and negligible volatility. Despite the large surface tension of the metal, it can be patterned into non-spherical 2D and 3D shapes due to the presence of an ultra-thin oxide skin that forms on its surface, as shown in the image.

Liquid metal is extremely soft and flows in response to stress to retain electrical continuity under extreme deformation. By embedding the metal into elastomeric or gel substrates, it is possible to form soft electrodes, stretchable antennas, and ultra-stretchable wires that maintain metallic conductivity up to ~800% strain. The resulting conductors are self-healing. The metals can also be filled into microchannels or hollow fibers for capacitive touch sensors, and mechanically tough fibers. It is also possible to 3D print the metal for source and drain contacts for transistors and as interconnects for energy harvesters. More recently, we demonstrated that liquid metal circuits can also be used for soft, tactile logic[2].

Perhaps one of the more unique aspects of liquid metals is the ability to manipulate their shape for reconfigurable electronics. Electrochemistry can deposit and remove the oxide layer to manipulate the interfacial tension—a dominante force at the microscale—over an enormous range. Reductive potentials remove the oxide layer and put the metal in a state of high tension. However, oxidative potentials deposit the oxide layer on the metal and put it in a state of low tension. Experiments suggest the tension could be near zero using less than one volt. Unlike electrowetting, which can require hundreds of volts, here, the changes result due to electrochemically deposited species on the metal surface.

### References

1. Dickey, M. D. Stretchable and Soft Electronics using Liquid Metals. *Adv. Mater.* **29**, 1606425 (2017).
2. Jin, Y. *et al.* Materials Tactile Logic via Innervated Soft Thermochromic Elastomers. *Nat. Commun.* **10**, 4187 (2019).

# 3D nanoarchitectures for superconductivity and nanomagnetism

**Oleksandr V. Dobrovolskiy[1,2]**

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[2]*Institute of Physics, Goethe University, Frankfurt am Main, Germany*

Patterned superconductors and nanomagnets are traditionally 2D planar structures, but recent work is expanding superconductivity and nanomagnetism into the third dimension. This expansion is triggered by advanced synthesis methods and the discovery of novel geometry- and topology-induced effects. In addition to self-assembled systems, a high level of maturity is now reached in direct-write nanofabrication by focused electron and focused ion beam induced deposition (FEBID and FIBID, respectively) [1], whose potential for various domains of nanomagnetism and superconductivity is outlined in this contribution.

1. 3D ferromagnetic elements allow for breaking the symmetry in the dynamics of superconducting vortices and studying vortex ratchet (rectification) effects. This opens new horizons for magnon fluxonics addressing the interplay between superconductivity and spin-wave physics [2].

2. In contradistinction to planar superconductor structures, the complex 3D geometry determines topologically nontrivial screening currents in superconductors that crucially affects the dynamics of vortices therein. Successful examples of the extension of fluxonic conduits into third dimension will be demonstrated [3,4].

3. Magnonic networks require efficient steering of spin waves which becomes challenging in curved waveguides. A solution is offered by a graded refractive index which smoothly alters the wave trajectory with minimal reflections and can be achieved via a gradual change of e.g. magnetization [5-7] in 3D structures.

4. Despite of exciting theoretical predictions and strong application potential of curvilinear magnetism, the development of fabrication techniques is a essential for this topical area. Fortunately, CAD-assisted direct-write nanofabrication demonstrates potential for bridging this gap, that is expected to open new horizons for curvilinear magnetism and chiral magnonics as will be commented in the talk.

## References

[1] A. Fernandez-Pacheco et al., Materials **13**, 3774 (2020)
[2] O. V. Dobrovolskiy et al., Nat. Phys. **15**, 477 (2019).
[3] O. V. Dobrovolskiy et al., Nat. Commun., **9**, 4927 (2018).
[4] F. Porrati et al., ACS Nano, **13**, 6287 (2019).
[5] O. V. Dobrovolskiy et al., ACS Appl. Mater. Interf. **11**, 17654 (2019).
[6] S. A. Bunyaev, et al., Appl. Phys. Lett. **118**, 022408 (2021).
[7] O. V. Dobrovolskiy et al., Appl. Phys. Lett. **118**, 132405 (2021).

# Three-dimensional magnetic systems: from the bulk to patterned nanostructures

**C. Donnelly**[1]

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Three dimensional magnetic systems promise significant opportunities for applications, for example providing higher density devices and new functionalities associated with complex topology and greater degrees of freedom [1,2]. With recent advances in both characterization and nanofabrication techniques, the experimental investigation of these complex systems is now possible, opening the door to the elucidation of new properties and rich physics.

For the characterization of 3D nanomagnetic systems, we have developed techniques to map both the three-dimensional magnetic structure [3,4,5], and its dynamical response to external excitations [4], revealing the configuration and behaviour of topological structures within the bulk of a system [3,4]. With recent advances in analytical techniques [6,7], it is now possible to locate and identify 3D magnetic solitons, leading to the first observation of nanoscale magnetic vortex rings [6].

Finally, recent advances in nanofabrication make possible the fabrication of complex 3D magnetic nanostructures [8], leading to the realisation of highly coupled curvilinear systems [9]. These new experimental capabilities for 3D magnetic systems open the door to complex three-dimensional magnetic structures, and their dynamic behaviour.

## References

[1] Fernández-Pacheco et al., Nature Communications **8**, 15756 (2017).
[2] C. Donnelly and V. Scagnoli, J. Phys. D: Cond. Matt. **32**, 213001 (2020).
[3] C. Donnelly et al., Nature **547**, 328 (2017).
[4] C. Donnelly et al., Nature Nanotechnology **15**, 356 (2020).
[5] K. Witte, et al., Nano Lett. **20**, 1305 (2020).
[6] C. Donnelly et al., Nat. Phys. **17**, 316 (2020)
[7] N. Cooper, PRL. **82**, 1554 (1999).
[8] L. Skoric et al., Nano Lett. **20**, 184 (2020).
[9] C. Donnelly et al., *In review*

# Curved Magnetism in $CrI_3$

**A. Edström[1,2], D. Amoroso[3], S. Picozzi[3], P. Barone[4] and M. Stengel[1,5]**

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Magnetic order in freestanding 2D materials was believed to be impossible until the recent discovery of ferromagnetism in monolayers of van der Waals materials, such as $CrI_3$ [see Fig. 1(a)] [1]. Inhomogeneous deformations in the form of curvature, which can be especially large in such systems, have further opened the way to a whole new range of exciting phenomena that originate from inversion-symmetry breaking, e.g. magnetochiral effects related to Dzyaloshinskii–Moriya interaction (DMI), or Rashba-Dresselhaus type spin-orbit coupling (SOC). Unfortunately, curvature also breaks translational symmetry, making it difficult to treat with standard theoretical methods of solid-state physics; hence, a quantitative understanding of these effects based on first-principles theory is currently missing.

Here, we use density-functional theory (DFT) calculations, including non-collinear magnetism and SOC, to investigate the interplay of curvature and magnetic order in monolayer $CrI_3$. In particular, we perform calculations on $CrI_3$ nanotubes [see Fig. 1(b)-(c)] of different radii to parametrize the energy of different magnetic configurations as function of curvature. We find a crossover from a radially oriented spin order at small curvatures, to a state magnetized perpendicular to the nanotube axis at larger curvatures. We explain this outcome in terms of curvature-induced Dzyaloshinskii-Moriya interactions and changes to the magnetic anisotropy. Remarkably, these effects are predominantly non-relativistic in nature, and therefore not limited by the weakness of SOC.

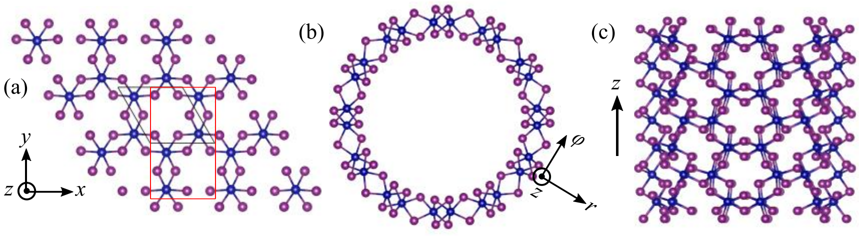


Fig. 1: (a) Monolayer CrI3 (b)-(c) A representative 11.1 Å radius nanotube seen from two directions.

We acknowledge financial support from the Swedish Research Council (VR - 2018-06807) and the ERC Consolidator Grant "MULTIFLEXO" (No. 724529).

## References

[1] B. Huang et al., Nature **546**, 270 (2017)

# A new platform for the experimental investigation of advanced three-dimensional geometrical effects in nanomagnetism

**A. Fernández-Pacheco[1,2]**, D. Sanz-Hernández[2], L. Skoric[2], F. Meng[2], C. Donnelly[2], K. Fallon[1], A. Hierro-Rodríguez[1]

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During the last few years, there have been a number of exciting theoretical predictions in three-dimensional (3D) systems, including the emergence of new types of domain walls, the ultra-fast motion of spin textures and associated spontaneous emission of spin waves, or unprecedented forms of anisotropy and magneto-chiral interactions induced by symmetry-breaking geometrical effects [1-4]. In order to fully explore these and other effects experimentally, new nanotechnology tools able to shape and probe complex 3D nanoscale geometries are required.

In this talk, I will present an overview of our recent work in this realm, where we are developing a new platform for advanced studies in 3D nanomagnetism. At the core of this platform, we find focused electron beam induced deposition (FEBID), an emerging lithography technique which can directly write magnetic materials with nanoscale resolution [5]. Thanks to the modelling of the growth processes during FEBID [6] and a new computational algorithm, we can now 3D print nanostructures with resolutions of a few tens of nm [7], which enables *e.g.* the imprinting of new chiral magnetic textures and defects via geometry [8]. The combination of 3D printing with standard thin film deposition methods can be also exploited for advanced domain wall transfer in 3D [9-10]. Complementing nanofabrication, I will present advanced characterization of 3D nanostructures using different methods, including a new magneto-optical method that exploits dark field effects [10].

I acknowledge strong collaboration with P. Fischer, S. Ferrer, R. Belkhou, J. Fowlkes, R. Lavrijsen, S. Holmes, J. M. De Teresa and D. Suess, as well as funding from EPSRC, the Winton Program for the Physics of Sustainability, the Royal Society and the CELINA EU COST project.

## References

[1] R. Streubel et al. J. Phys. D. Appl. Phys. **49**, 363001 (2016).
[2] A. Fernández-Pacheco, et al. Nat. Commun. **8**, 15756 (2017).
[3] D. Sheka et al. arXiv:1904.02641 (2019).
[4] P. Fischer et al. APL Materials **8**, 010701 (2020).
[5] A. Fernández-Pacheco et al. Sci Rep **3**, (2013).
[6] D. Sanz-Hernández, Beilstein J. Nanotechnol. **8**, 2151 (2017).
[7] L. Skoric, et al. Nano Lett. **20**, 184 (2020).
[8] D. Sanz-Hernández, arXiv:2001.07130 (2020)
[9] D. Sanz-Hernández et al, Nanomaterials **8**, 483 (2018).
[10] D. Sanz-Hernández, ACS Nano **11**, 11066 (2017).

# Geometrically driven effects in curved superconducting nanostructures

**Paola Gentile[1,2]**

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The most recent advances in nanotechnology have demonstrated the possibility to create flexible semiconductor nanomaterials which are bent into curved, deformable objects ranging from semiconductor nanotubes, to nanohelices, etc. The consequences of the nanowire bending on the electronic quantum properties have been demonstrated to become particular important in systems with structure inversion asymmetry, where the interplay between nanoscale deformations and Rashba spin-orbit coupling (RSOC) allows an all-geometrical and electrical control of electronic spin textures and spin transport properties [1,2,3], as well as curvature-assisted spin interferometry [4]. In the presence of superconducting pairing, inversion symmetry breaking makes neither spin nor parity good quantum numbers anymore. The ensuing mixing of even spin-singlet and odd spin-triplet channels leads to a series of novel features, from unconventional surface states to topological phases. Within this framework, we have explored the impact that nanoscale geometry has on superconducting properties of low-dimensional materials, showing that the interplay between RSOC and shape deformations can lead to novel paths for a geometric manipulation of the superconducting state, both for spin-singlet and spin-triplet quantum configurations [5], then significantly affecting the Josephson effect of weak links between Rashba coupled straight superconducting nanowires with geometric misalignment [6] as well as between nanowires of topological superconductors with non-trivial geometric curvature [7].

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## References

[1] P. Gentile., M. Cuoco, C. Ortix, SPIN, Vol. **3**, No. 2, 1340002 (2013).
[2] Z.-J. Ying, P. Gentile, C. Ortix, M. Cuoco, Phys. Rev. B **94**, 081406(R) (2016).
[3] G. Francica, P. Gentile, M. Cuoco, EPL **127**, 30001 (2019).
[4] Z.-J. Ying, P. Gentile, J. P. Baltanás, D. Frustaglia, C. Ortix, M. Cuoco, Phys. Rev. Research **2**, 023167 (2020).
[5] Z.-J. Ying, M. Cuoco, C. Ortix, P. Gentile, Phys. Rev. B **96**, 100506(R) (2017).
[6] Z.-J. Ying, M. Cuoco, P. Gentile, C. Ortix, 2017 16th International Superconductive Electronics Conference (ISEC), IEEE Xplore (2018).
[7] G. Francica, M. Cuoco, P. Gentile, Phys. Rev. B **101**, 094504 (2020).

# String model for antiferromagnetic domain wall: skyrmions and beyond

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Functionality of antiferromagnetic (AF) systems under the action of spin and/or electric current, we focus on the (spin) current-induced magnetic dynamics of AF domain walls and skyrmions [1]. First, we introduce the string model relevant for interpretation of slow dynamics of the AF domain wall. As illustration of the approach we consider two examples: i) optimal shape and ii) current-induced dynamics of the closed $180^0$ domain wall loop in AF with magnetoelastic interactions. Second, we discuss free and forced magnetic dynamics of an isolated AF skyrmion focusing mainly on the features which have no direct ferromagnetic counterpart. We start from the analysis of the localized eigen-modes which are mainly localized at the skyrmion boundary and compare results of the direct calculations with prediction of string model. We present classification of localised modes according to their spin, angular mometum and frequency, dependence of frequencies vs skyrmion radius, and modification of spectra in presence of the external magnetic field. We show that DC magnetic field which removes degeneracy of clock- and couterclock-wise modes is an additional tool for manipulation of AF skyrmion dynamics. We believe that our results open a way for manipulation, control and detection of the dynamical states of AF textures.

## References

[1] V. Kravchuk, O, Gomonay, D. Sheka et al., Phys. Rev. B, 99, 1 (2019)

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# Micro/Nano-Materials Based Interactive Wearables for Human Augmented Reality

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With the growing interest in human augmented reality (AR), there have been significant advances in wearable and interactive electronics. The concept of wearables drives electronics from pocket to the wrist, but it faces numerous challenges to provide better feelings of wearing and interactive experience of a real-world environment. To address such demands, wearable devices turn to an imperceptible design rather than accessory type. Also, the multiple sensory modalities of wearable devices allow the high accuracy and more realistic perception to user, which includes haptic, visual, and auditory. For this purpose, we developed highly compliant and interactive wearable devices based on micro/nano-materials. The novel architected micro/nano-materials offer unique characteristics in geometry design and synthesis, which does not appear in bulk materials. We profoundly navigate the new characteristics of such materials and various applications of flexible physical sensors and controllable soft actuators that hold great promise in establishing the interactive wearables.

For the tactile and motion perception, we designed bio-inspired interlocked and hierarchical ZnO nanowire arrays for static and dynamic pressure-sensitive electronic skins.[1] Inspired by skin structures and functions, we developed a hierarchical polymer architecture with gradient stiffness for motion-sensitive and triboelectric sensors.[2] To design more compliant motion sensors, we suggested printable giant magnetoresistive sensors that enable conformal attachment on the skin.[3] Second, we combined sensors and actuators in a single device and applied to self-regulating soft actuators that are composed of aligned magnetic particles in the thermo-responsive polymers.[4] Finally, we proposed the telehaptic interactivity that transmits touch over a network and play an equivalent texture to a receiver who is in a remote site. All of our strategies contribute to enhancing the future AR technologies and explore many applications from entertainment to medicine, education.

## References

[1] M. Ha, S. Lim, J. Park, D.-S. Um, Y. Lee, H. Ko, Adv. Funct. Mater. **25**, 2841 (2015)

[2] M. Ha, S. Lim, S. Cho, Y. Lee, S. Na, C. Baig, H. Ko, ACS Nano **12**, 3964 (2018)

[3] M. Ha, G. S. Cañón Bermúdez, T. Kosub, Y. Zabila, Y. Wang, J. Fassbender, D. Makarov, Adv. Mater. **33**, 2005521 (2021)

[4] M. Ha, G. S. Cañón Bermúdez, J. A.-C. Liu, E. S. Oliveros Mata, B. A. Evans, J. B. Tracy, D. Makarov, Adv. Mater. 2008751 (2021)

# Spin-wave modes in curved 3D nanostructures

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Spin waves in magnetic nanotubes have shown interesting non-reciprocal properties in their dispersion relation, group velocity, frequency linewidth and attenuation lengths [1,2,3]. The reported chiral effects are similar to those induced by the Dzyalonshiinsky-Moriya interaction [4,5], however in curved shells the dynamic fields originating from the dipole-dipole and isotropic-exchange interactions are responsible for the curvature-induced magnetochiral effects. We show, that the isotropic-exchange interaction can also induce non-reciprocal spin-wave transport; the so-called Berry phase [6] of spin waves. A disentanglement of the dipole-dipole and exchange contributions to the non-reciprocity will be discussed for the general helical equilibrium state and spin-wave transport in nanotubes. We have analytically described the full spin-wave dispersion in cylindrical nanotubes when its equilibrium state evolves from an axial to an azimuthal magnetization state. In the helical state, due to the combined action of the two magnetochiral effects every single sign combination of the azimuthal and axial wave vectors leads to different dispersion, allowing for a very sophisticated tuning of the spin-wave transport. We will discuss in compliance with the generalised curvilinear theory [7] the effect of the curvature on thin magnetic shells and it will be extended to thick nanotubes. Moreover, the change of topology, in this case the transition from a thin shell nanotube to a wire will be discussed.

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[1] J. Otálora et al., Phys. Rev. Lett. **117**, 227203 (2016).
[2] J. Otálora et al., Phys. Rev. B **95**, 184415 (2017).
[3] J. Otálora et al., Phys. Rev. B 98, 014403 (2018).
[4] I. Dzyaloshinsky, Journal of Physics and Chemistry of Solids **4**, 241 (1958).
[5] T. Moriya, Phys. Rev. Lett. **4**, 228 (1960).
[6] V.K. Dugaev et al., Phys. Rev. B **72**, 024456 (2005).
[7] D. Sheka et al., Communications Physics **3**, 128 (2020).

# Degradable Materials with Extreme Mechanics for Soft Robots and Electronics

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Nature inspires a wide class of bio-mimetic systems ranging from soft robotic actuators to perceptive electronic skins that enhance and support our life. The growing demand for assistive, medical and bioelectronic technologies, however, raises concerns on the ecological footprint of these emerging platforms, as they are often designed for a defined, limited operational lifetime. Introducing a key feature essential to nature - biodegradability - will enable soft electronic and robotic devices that reduce (electronic) waste and are paramount for a sustainable future.

We here introduce materials and methods such as tough yet biodegradable gels for soft systems that facilitate a broad range of applications, from transient wearable electronics to metabolizable soft robots. The biogels are highly stretchable (>300%), are able to heal and are resistant to dehydration. They are fully degradable in wastewater in 10 days and can survive in ambient conditions for more than one year, pass extended fatigue tests (330,000 cycles) without decay in mechanical performance and even operate for prolonged times when fully submerged in water. Built from such biogels with tunable, extreme mechanical properties, our forms of soft electronics and robots uniquely combine performance and durability with degradability. Electronic skins that measure pressure, strain, temperature, and humidity serve as human-friendly on-skin interfaces or equip robotic systems with sensory feedback. Such advances in the synthesis of biodegradable, mechanically tough and stable materials that do not compromise in performance when compared to their non-degradable counterparts may bring bionic soft systems a step closer to nature and enable human-friendly technologies with reduced ecological footprint.

# The effect of curvature on eigenexcitations of magnetic skyrmion


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Skyrmions are promising candidates as information carriers for future high-density information-storage and logic devices [1, 2]. Skyrmions are non-collinear stable spin configurations with particle-like properties, which are stabilized due to chiral interactions, such as the Dzyaloshinskii–Moriya interaction (DMI). Theory predicts that surface curvature can induce a DMI like interaction [3] and thus stabilize chiral magnetic objects.

We consider a thin ferromagnetic film, a surface of rotation in form of a Gaussian profile, with intrinsic DMI and easy-axis anisotropy pointing along the surface normal. The intrinsic DMI with the curvature induced DMI can stabilize the Néel-type skyrmions at the top of the Gaussian bump [4] (for a certain range of parameters).

Here, we studied the linear spin excitations over the skyrmion pinned on the bump using analytical methods and finite element numerical (FEM) simulations. Due to the bump induced translational symmetry breaking the skyrmion translational mode (azimuthal quantum number μ=1) gains the nonzero frequency forming the gyromode. Using the collective variable approach we estimate the gyromode frequency in the limit case when the curvature radius much exceeds the radius of skyrmion. It is proportional to the second derivative of the mean curvature at the bump center. The frequency of the CCW mode with the azimuthal number μ= -1 decreases with increasing curvature. With increasing the bump amplitude the higher order skyrmion modes with μ= ±2 and μ= 3 are generated. The spectra obtained from full scale FEM micromagnetic simulations are in good agreement with solution of the corresponding eigenvalue problem and with the collective variables approach (for the gyromode).

## References


[1] Zhang, X., Ezawa, M., & Zhou, Y. Sci. Rep., 5(1), (2015).
[2] Fert, A., Cros, V., & Sampaio, J. Nat. Nanotechnol., 8(3), 152–156, (2013).
[3] Yu. Gaididei, V. P. Kravchuk, D. D. Sheka, Phys.Rev. Lett.112, 257203,(2014).
[4] V. P. Kravchuk et al., Phys. Rev. Lett. 120, 067201 (2018)

# Dynamics of magnetic skyrmions in curvilinear films

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Curvature drastically changes the dynamical properties of magnetic skyrmions. In a curvilinear film, skyrmions experience effective driving force originating from the curvature gradients. This effect mainly relies on the curvature-induced emergence of the effective Dzyaloshinskii-Moriya interaction (DMI) [1]. The same physical mechanism leads to the drift of a domain wall in quasi one-dimensional wires with curvature gradients [2]. The strength of the curvature-induced driving force essentially depends on the skyrmion type (Néel or Bloch), while the direction of motion is determined by the type of magnetic ordering (ferro- or antiferromagnetic). The effective curvature-induced potentials are linear and quadratic with respect to the principal curvatures for the Néel and Bloch skyrmions, respectively. This difference is due to the interfacial type nature of the curvature-induced DMI, which supports the stabilization of Néel skyrmions. For vanishing damping, the ferromagnetic skyrmions move perpendicularly while the small-radius antiferromagnetic skyrmions move along the mean curvature gradients. Both types of skyrmions experience the curvature-induced deformations of various types (radial-symmetrical, elliptical) during their motion along the surface. This leads to skyrmion energy corrections which are quadratic in the principal curvatures. As a result, the Bloch skyrmion dynamics is significantly influenced by the curvature-induced deformation of the skyrmion profile.

As an example, we consider a cylindrical surface with sinusoidal generatrix. For the case of positive DMI constant and negative topological charge of the skyrmions, we found that the Néel skyrmions are pinned on the convexities, while Bloch skyrmions are pinned both on the convexities and the concavities of the surface. Antiferromagnetic skyrmions demonstrate oscillations in the vicinity of the pinning positions. For Bloch skyrmions the oscillation frequency is linear in the deformation amplitude, while for Néel skyrmions it shows a square root dependence on the amplitude.

## References

[1] Yu. Gaididei, V.P. Kravchuk, D.D. Sheka, PRL, **112**, 257203 (2014).
[2] K.V. Yershov, V.P. Kravchuk, D.D. Sheka, et al., PRB, **98**, 060409(R) (2018).

# Flexible magnetic sensitive materials and sensors

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In recent years, with the rapid development of flexible electronics, flexible displays, flexible sensors, flexible storages and other flexible electronic devices have received more and more attention, which are triggering a revolution in electronic technology. In particular, flexible sensor technology is a very challenging direction, and has broad prospects in the fields of artificial intelligence, medical health and other fields [1]. By combining liquid metals, polymers and magnetic particles, we have developed a series of flexible functional devices, including high conductivity and high stability stretchable electrodes, stretchable heaters, flexible tactile sensors, and high precision stretchable strain sensors, and bio-inspired pain perception system [2]. In addition, by combining the polymers and amorphous magnetic wire, we have realized a flexible magnetic sensor with low detection limit and broad working range, a highly sensitive digital flexible tactile sensor [3], and a self-powered strain sensor, which lays a good foundation for the applications of multifunctional electronic skins.

## References

[1] Y. Liu, M. Pharr, G. A. Salvatore, ACS Nano. 11,9614 (2017).
[2] F. L. Li, Y. W. Liu, Run-Wei Li, et al, Adv. Sci. 2004208. (2021).
[3] Y. Z. Wu, Y. W. Liu, Run-Wei Li, et al, Sci. Robot. 3, eaat0429. (2018)

# Intricate Magnetic Configuration of Self-assembled 3D Gyroid Nanostructures

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Arrays of interacting 2D nanomagnets display unprecedented electromagnetic properties via collective effects, demonstrated in artificial spin ices and magnonic crystals. Progress towards 3D magnetic metamaterials is hampered by two challenges: fabricating 3D structures near intrinsic magnetic lengthscales (sub-100 nm) and visualizing their magnetic configurations. Here, we fabricate and measure nanoscale magnetic gyroids, periodic chiral networks comprised of nanowire-like struts forming 3-connected vertices. Via block co-polymer templating, we produce $Ni_{75}Fe_{25}$ single-gyroid and double-gyroid (an inversion pair of single-gyroids) nanostructures with a 42 nm unit cell and 11 nm diameter struts, comparable to the exchange length in Ni-Fe. We visualize their magnetization distributions via off-axis electron holography with sub-nm spatial resolution and interpret the patterns using finite-element micromagnetic simulations [1]. Our results suggest an intricate, frustrated remanent state which is ferromagnetic but without a unique equilibrium configuration, (**Figure 1**) opening new possibilities for collective phenomena in magnetism, including 3D magnonic crystals and unconventional computing.

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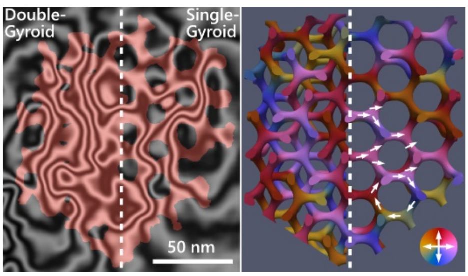


**Figure 1**: Magnetic induction contour map (left), micromagnetic simulation showing magnetization angle (center) and simulated induction map (right) of $Ni_{75}Fe_{25}$ nanoparticle with single-gyroid and double-gyroid regions.

**References:** [1] J. Llandro *et al.*, Nano Letters **20**, 3642 (2020).

**Flexo-Sensitive Vortex-like Polarization Structures in Nanoscale Ferroelectrics**

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Using the Landau-Ginzburg-Devonshire phenomenological approach along with electrostatic equations and elasticity theory, we perform finite element modeling of the electric polarization, electric field, and elastic stresses and strains in a ferroelectric nanoparticles and thin films. Finite element modelling performed for a spherical $BaTiO_3$ core-shell nanoparticles reveal that the distribution of the vortex-type polarization is highly sensitive to the values of flexoelectric coupling [1]. For a cylindrical nanoparticle we reveal the quadrupolar-type diffuse domain structure consisting of two oppositely oriented diffuse axial domains located near the cylinder ends, which are separated by a region with a zero-axial polarization; we have termed this "flexon" to underline the flexoelectric nature of its axial polarization [2]. In the azimuthal plane, the flexon displays the polarization state of a meron. We show that this new type of chiral polarization structure is stabilized by an anisotropic flexoelectric coupling. For thin films we reveal that an out-of-plane polarization component can be very sensitive to the flexoelectric coupling for periodic quasi-2D stripe domains and 3D vortex-antivortex structures [3]. The relatively wide temperature range (from 200 to 400 K) of the flexo-sensitive vortex-like polarization stability gives us the hope that the structures can be observed experimentally by scanning probe and nonlinear optical microscopy methods.

[1]. Eugene A. Eliseev, Anna N. Morozovska, Riccardo Hertel, Hanna V. Shevliakova, Yevhen M. Fomichov, Victor Yu. Reshetnyak, and Dean R. Evans. Flexo-Elastic Control Factors of Domain Morphology in Core-Shell Ferroelectric Nanoparticles: Soft and Rigid Shells. Acta Materialia, **212**, 116889 (2021) https://doi.org/10.1016/j.actamat.2021.116889

[2]. Anna N. Morozovska, Riccardo Hertel, Salia Cherifi-Hertel, Victor Yu. Reshetnyak, Eugene A. Eliseev, and Dean R. Evans. Introducing the Flexon - a New Chiral Polarization State in Ferroelectrics (http://arxiv.org/abs/2104.00598)

[3]. Anna N. Morozovska, Eugene A. Eliseev, Sergei V. Kalinin, and Riccardo Hertel. Flexo-Sensitive Polarization Vortices in Thin Ferroelectric Films (http://arxiv.org/abs/2105.06719)

# Nematic versus ferromagnetic shells: new insights in curvature-induced effects

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We draw a parallel between ferromagnetic materials and nematic liquid crystals confined on curved surfaces, which are both characterized by local interaction and anchoring potentials. We show that the extrinsic curvature of the shell combined with the out-of-plane component of the director field gives rise to chirality effects. This interplay produces an effective energy term reminiscent of the chiral term in cholesteric liquid crystals, with the curvature tensor acting as a sort of anisotropic helicity. We discuss also how the different nature of the order parameter, a vector in ferromagnets and a tensor in nematics, yields different textures on surfaces with the same topology as the sphere.

## References

[1] G. Napoli, O. V. Pylypovskyi, D. D. Sheka, and L. Vergori, e-prints arXiv:2102.1349 (2021)

[2] D. D. Sheka, O. V. Pylypovskyi, P. Landeros, Y. Gaididei, A. Kákay, and D. Makarov, Commun. Phys. **3**, 128 (2020).

# Topology and Transport in Nanostructures with Curved Geometries

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Recent advances in nanostructuring techniques have enabled the synthesis of compact three-dimensional nanoarchitectures: constructs of one- or two-dimensional nanostructures assembled in curved geometries, such as nanotubes and nanohelices. In this talk, I will discuss examples of unique geometry-driven topological and transport properties. These include the appearance of a non-linear Hall effect with time-reversal symmetry due to the Berry curvature dipole in corrugated bilayer graphene [1,2], the geometric control of spin transport properties in curved metallic nanochannels [3], the prediction of a strongly directional magnetotransport in carbon nanoscrolls [4], and the generation of topological insulating phases in shape-deformed semiconducting nanowires [5].

## References

[1] R. Battilomo, N. Scopigno, C. Ortix, Physical Review Letters **123**, 196403 (2019).
[2] S.-C. Ho, C.-H. Chang, Y.-C. Hsieh, S.-T. Lo, B. Huang, T.-H.-Yen Vu, C. Ortix, T.-M. Chen, Nature Electronics **4**, 116 (2021).
[3] K. S. Das, D. Makarov, P. Gentile, M. Cuoco, B. J. van Wees, C. Ortix, I. J. Vera-Marun, Nano Letters **19**, 6839 (2019).
[4] C.-H. Chang, C. Ortix, Nano Letters **17**, 3076 (2017).
[5] P. Gentile, M. Cuoco, C. Ortix, Physical Review Letters **115**, 256801 (2015).

# Hollow nanostructures: a new playground for curvilinear magnetism

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Magnetic nanoparticles with a spherical shape have been largely investigated in the last few decades owing to their unique magnetic properties being determined by finite size effects and mainly by surface effects arising from the large surface/volume (R=S/V). The possibility to synthesize spherical hollow magnetic nanoparticles allows R to be further enhanced with a consequent increase of topological disorder and magnetic frustration, thus opening new perspectives to explore the surface magnetism at the nanoscale. In addition, hollow spherical nanoparticles can be considered as a thin spherical shell, i.e., as one of the simplest 3D object for studying the effect of curvature at the nanoscale level. After a short review about the more exciting results about possibility to prepare different hollow nanostructures, this communication will present results the peculiar magnetic structure in hollow nanoparticles with R ≅1.5 (external diameter ~9.4 nm and shell thickness of ~1.4 nm). These hollow nanoparticles have been investigated by AC/DC magnetization measurements and using zero-field/in-field 57Fe Mössbauer spectrometry. The zero-field hyperfine structure suggests some topological disorder, whereas the in-field one shows the presence of a complex magnetic structure that can be fairly described as due to two opposite pseudo speromagnetic sublattices attributed to octahedral and tetrahedral iron sites. Such an unusual feature, observed for the first time in crystalline materials, is consistent with the presence of non-collinear spin structure originated from the increased surface role due to the hollow morphology. Monte Carlo simulations on a ferrimagnetic hollow nanoparticles unambiguously corroborate the critical role of the surface anisotropy on the non-collinearity of spin structure in our samples. [1], [2]

## References

[1] V. Bonanni, M. Basini, D. Peddis, A. Lascialfari, G. Rossi, and P. Torelli, "X-ray magnetic circular dichroism discloses surface spins correlation in maghemite hollow nanoparticles," *Appl. Phys. Lett.*, vol. 112 (2018), pp. 1–5.

[2] F. Sayed *et al.*, "Surface E ff ects in Ultrathin Iron Oxide Hollow Nanoparticles : Exploring Magnetic Disorder at the Nanoscale," *J. Phys. Chem. C*, vol. 122 (2018), pp. 7516–7524.

# Flexible electronics and sensorics based on low-cost and high throughput processes

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Thanks to the extraordinary advances recently experienced in the field of materials, manufacturing processes, device architectures, and system integration, it is now possible to realize electronic devices featuring not only standard electrical properties, but also more unique and novel mechanical and chemical capabilities. Electronic devices which can ubiquitously conform to any complex three-dimensionally shaped surface and/or dissolute or degrade in specific environments are extremely important to develop environmental sensors, on-body wearable, or even implantable devices, as well as environmentally friendly and biodegradable precision agriculture monitoring solutions. In the realization of all these systems, printing technologies play a key role offering advantages such as cost-effectiveness, large-area scalability, as well as availability of a wide range of sustainable and biocompatible/biodegradable substrates and materials. Very recently, direct lasing of flexible or paper substrates to laser graphitize carbon-rich substrates is gaining increasingly attention, due to its scalable and potentially cheaper alternative for the fabrication of electrically conductive electrodes or interconnections.

Here, our recent work in the field of cost-effective and high throughput processing of flexible electronic devices will be shown. Firstly, we will present a wide range of different electronic devices (e.g., diodes, capacitors, antennas, electrodes, sensors, and biosensors) realized using both printing and laser induced graphitization (LIG) on different types of substrates (e.g., polyimide, paper) will be presented. Next, characterization of mechanical (bending, stretching) and chemical (dissolubility) characteristics will be displayed. Finally, we will discuss applications of these innovative components in both wearable sports and healthcare applications, as well as in the field of precision agriculture and food quality and control monitoring.

# Curvature Effects in Liquid Crystal Skyrmions

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Both two and three dimensional topologically protected defects called skyrmions and skyrmion tubes have been observed in liquid crystals. Cholesteric liquid crystals confined between parallel substrates can stabilize skyrmions. We have previously studied alignment-induced patterning and assembly of such skyrmions [1]. In this talk we will model the effect of curved boundaries, confinement and tilting of external field on skyrmion interaction and movement within a Q-tensor model. These results will be contrasted with skyrmions in chiral magnets and other physical systems. We will also discuss a more complex topological cousin of the skyrmion, called a hopfion, and how its characteristics could be understood in terms of a certain mapping and linking of preimages [2]. The hopfion is a stable three-dimensional topological soliton in which any two field lines of the director field are linked exactly once. Our findings have potential applications for data storage and soft robotics.

## References

[1] A. Duzgun, A. Saxena and J. V. Selinger, Phys. Rev. Res., **3**, L012005 (2021).
[2] P. J. Ackerman and I. I. Smalyukh, Phys. Rev. X, **7**, 011006 (2017).

# Curvature Effects on Ferromagnetic Materials and Spin Textures

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Curvature effects in magnetism may have dramatic effects on ferromagnetic properties of thin films [1] as well as on topological spin textures, such as chiral domain walls [2]. First, I will talk about large curvature effects on micromagnetic energy of a thin ferromagnetic film in the presence of nonlocal dipolar interactions. I will show that the interplay of dipolar interaction and surface curvature by itself can produce perpendicular anisotropy. It can be controlled by engineering a special type of periodic surface shape structures. Similar effects can be achieved by a significant surface roughness in the film. We show by analytical methods of asymptotic homogenization that in general the anisotropy can point in an arbitrary direction depending on the surface curvature. This result is robust and does not require any additional spin-orbit interaction.

Second, I will present an analytic study of domain-wall statics and dynamics in ferromagnetic nanotubes with spin-orbit induced Dzyaloshinskii-Moriya interaction (DMI). Even at the level of statics, dramatic effects arise from the interplay of space curvature and DMI: the domains become chirally twisted, leading to more compact domain walls. The dynamics of these chiral structures exhibits several interesting features. Under weak applied currents, they propagate without distortion. The dynamical response is further enriched by the application of an external magnetic field: the domain-wall velocity becomes chirality dependent and can be significantly increased by varying the DMI. These characteristics allow for enhanced control of domain-wall motion in nanotubes with DMI, increasing their potential as information carriers in future logic and storage devices.

## References

[1] O. A. Tretiakov, et al., Phys. Rev. Lett. **119**, 077203 (2017).
[2] A. Goussev, et al., Phys. Rev. B 93, 054418 (2016).

# SAF-based perpendicular magnetized GMR spin valves on large-area flexible substrates

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Flexible spintronic devices have received a great deal of attention over the past few years thanks to the wide number of advantages (lightness, flexibility, shapeability, wearability and low cost) with respect to the conventional rigid counterpart [1]. While the progress and development of longitudinal magnetized devices on non-planar substrates has been remarkable over the last years, perpendicularly magnetized structures on flexible substrates are rather unexplored despite they allow for additional functionality and improved performance that make them of interest for many applications such as wearable electronics, soft robotics and biomedicine.
To fill this gap, flexible Co/Pd-based GMR spin-valve multi-stacks consisting of a $[Co/Pd]_N$ free-layer and a fully compensated $[Co/Pd]_N/Ru/[Co/Pd]_N$ synthetic antiferromagnet reference electrode separated by a Cu spacer, were prepared by direct deposition on polyethylene naphthalate (PEN) polymer tapes (Teonex®) [2] and by using a transfer-and-bonding approach exploiting the low adhesion of a gold underlayer to SiOx/Si(100) substrates [3]. Large-area flexible spin-valve thin film heterostructures with a perpendicular magnetic anisotropy (PMA) and a GMR ratio comparable to that of conventional rigid heterostructures deposited on SiOx/Si(100) substrates were obtained. Measurements under bending conditions also reveal the robustness of the flexible spin-valves, whose magneto-resistive properties are moderately affected even under a bending angle of 180°, thus paving the way for their integration on curved surfaces. To prove the high potential of such systems compared to the most investigated devices with in-plane magnetic anisotropy, PMA-GMR flexible films deposited on PEN tapes were integrated in on-skin interactive electronics to realize touchless human-machine interfaces, which are intuitive to use, energy efficient, and insensitive to external magnetic disturbances [2].

## References

[1] M Melzer et al. J. Phys. D: Appl. Phys. 53 083002 (2020)
[2] P. Makushko et al., , Adv. Funct. Mater. 2101089 (2021)
[3] M. Hassan et al., Nanoscale Advances 3 3076 (2021)

# Interlayer Dzyaloshinskii-Moriya Interactions

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The magnetic interfacial Dzyaloshinskii-Moriya interaction (DMI) in multi-layered thin films can lead to exotic chiral spin states, of paramount importance for future spintronic technologies [1]. Interfacial DMI is normally manifested as an intralayer interaction defining a rotational sense for the magnetization within two-dimensional films. Recently, we have shown theoretically that in addition to the interfacial DMI, magnetic layers can interact by means of a so-far neglected interlayer DM coupling across a spacer [2]. In contrast to the interfacial DMI, this interaction leads to the formation of three-dimensional spin spirals with unique rotational sense within as well as between the interfaces and, hence, combines intra- and inter-plane chiralities. Direct evidence of the interlayer-DMI at room temperature has recently been observed in synthetic magnetic heterostructures resulting in chiral exchange-biased hysteretic loops [3]. Schematics of the interlayer-DMI in synthetic magnetic heterostructures is shown in Fig.1. The realization of systems integrating interlayer magnetic chiral interactions paves the way for the creation of unprecedented magnetic effects in the emerging field of three-dimensional nanomagnetism and spintronics.

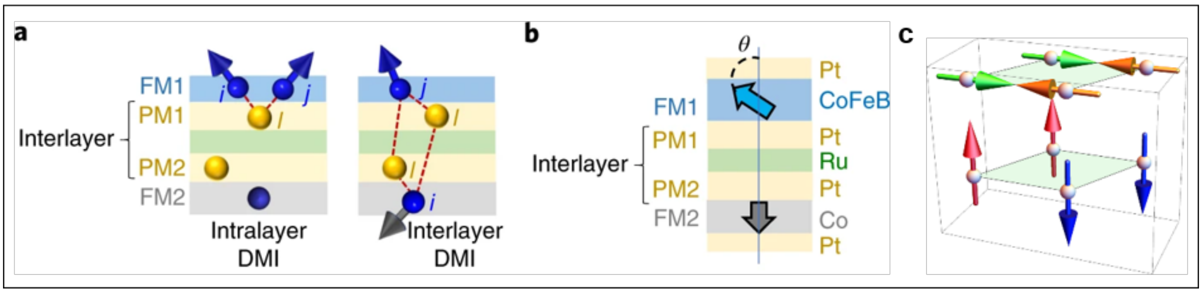


Fig.1 *(a) The presence of standard intralayer DMI (left) in ultra-thin ferromagnetic ferromagnetic layers results in interactiion between spins within the same ferromagnetic layer via a paramagnetic layer leading to chiral coupling and noncollinear spin configurations within the layer. Analogously, an interlayer DMI effect (right) results in a chiral coupling between spins of two neighbouring layers separated by a spacer. (b) Schematics of the magnetic state in strongly ferromagnetic multilayers with interlayer DMI. (c) Unit cell of a low-energy three-dimensional spin structure due to the interlayer DMI between two very weakly ferromagnetic layers. This magnetic state shows clockwise chirality across the layers in two different directions.*

[1] J. Hagemeister, N. Romming, K. von Bergmann, E. Y. Vedmedenko, R. Wiesendanger, *Stability of single skyrmionic bits*, Nature Commun. **6**, 8455 (2015)

[2] E. Y. Vedmedenko, P. Arregi, J. Anders, A. Berger, *Interlayer Dzyaloshinskii-Moriya Interactions*, Phys. Rev. Lett. **122**, 257202 (2019)

[3] A. Fernandez-Pacheco, E. Y. Vedmedenko, F. Ummelen, R. Mansell, D. Petit, R. P. Cowburn, *Symmetry-Breaking Interlayer Dzyaloshinskii-Moriya Interactions in Synthetic Antiferromagnets*, Nature Mater. **18**, 679 (2019)

# Soft and Reconfigurable Magnetic Systems

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Soft condensed matter systems such as membranes and wires are of great importance both in biological context and in industrial applications. Soft magnetic materials opens new possibilities in the construction and fabrication of shapeable magnetoelectronics [1], interactive human-machine interfaces [2,3], and programmable magnetic materials [4,5]. Remote control of the shape and three-dimensional (3D) navigation of the soft magnet by means of the external magnetic field stimulate intensive investigations in the area of milli- [3–6] and microrobotics [7,8] for flexible electronics and biomedical applications.

Basic models for description of nanoscaled magnetoelastic system include two subsystems: the precession Landau-Lifshitz dynamics of magnetic subsystem is coupled with the Newtonian dynamics of elastic substrate. The development of this approach for a Heisenberg magnet on elastic membranes and wires resulted in novel effects, including magnetization induced deformation of ferromagnetic ring [9], periodic shrinking of the membrane due to soliton-soliton interaction [10], the curvature-induced geometrical frustration in magnetic systems [11,12], and deformations of ferromagnetic ribbons induced by Dzialoshinskii-Moria interaction [13].

## References

[1] D. Makarov et al., Appl. Phys. Rev. **3**, 011101 (2016)
[2] J. Wang et al., Mater. Today **21**, 508 (2018)
[3] W. Hu et al., Nature (London) **554**, 81 (2018)
[4] G. Z. Lum et al., Proc. Natl. Acad. Sci. USA **113**, E6007 (2016)
[5] Y. Kim et al., Nature (London) **558**, 274 (2018)
[6] H. Lu et al., Nat. Commun. **9**, 3944 (2018)
[7] M. Medina-Sánchez et al., Adv. Funct. Mater. **28**, 1707228 (2018)
[8] H. Ceylan et al., ACS Nano **13**, 3353 (2019)
[9] Yu. Gaididei et al., Phys. Rev. B **99**, 014404 (2019)
[10] R. Dandoloff et al., Phys. Rev. Lett. **74**, 813 (1995).
[11] A. Saxena et al., Phys. Rev. B **55**, 11049 (1997).
[12] A. Saxena et al., Physica A **261**, 13 (1998).
[13] K. Yershov et al., Phys. Rev. B **100**, 140407(R) (2019).

# Multifunctional flexible sensor platform for motion control in robotics

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Our work is focused on the development of flexible sensors for applications in robotics. We consider new concepts for the construction of multifunctional sensors based on the properties of the studied functional materials. The object of our work is thin layers of material with selected electrophysical properties. We examine the response and nature of changes in their properties under complex conditions to split the contribution of each individual factor. As an example, we will demonstrate a functional element made of pure bismuth. It will show how the same device can serve both as a strain and magnetic field sensor. The implementation of the abovementioned concept allows designing robots with a sense of touch feeling.

# Links between strain fields and magnetic properties in thin films and nanostructures

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Since about two decades, the need to understand the links between magneto-electronic properties of nanoscale systems and their strains has been of increasing interest. The reasons for this renewed interest in fundamental or applied physics studies on magnetoelastic effects are numerous. They are linked to the recent appearance of new thematic fields of nanomagnetism such as i) curvilinear magnetism that deals with the effects of curvatures (without taking account of the possible strain effect) of nanometric objects on the magnetic configuration, ii) flexible or stretchable systems which are the subject of applied studies on the performance of magnetic nanostructures on flexible substrates or more generally iii) straintronics that aims at developing magnetoelectric systems whose performance is controlled by elastic strains. In all cases, the understanding of magnetoelastic effects at small scales is important because they condition the properties of the objects studied. The presentation focuses on the links between mechanical state and magnetic properties. For that purpose, we have developed *in situ* experimental tools by combining mechanical tests and magnetic probes (MOKE, FMR). These tests have been realized on magnetic films, nanowires and antidots deposited on Kapton®. Concerning the control of magnetization at low strains, a specific attention has been made on the links between strain field and the magnetic mode localizations. Thus, we have made simulations to estimate the strain field and micromagnetic configuration and we will show that magnetic modes undergo differently the applied strains. For higher applied strains, the effect of cracks and buckles on thin films and nanowires have been studied by combining AFM and FMR. We show that the evolution of magnetic anisotropy in films is related to the stresses generated during damaging, while it is not affected by breaking of translational invariance. Moreover, we have put into evidence a delay of damaging onset in nanowires as compared to films. As for films, the nanowire magnetic behavior is mainly impacted by the stresses generated during cracks, due to magnetoelastic coupling. Consequently, we show that the damping properties of permalloy are weakly affected by the numerous cracks, even at strain equal to 20%.

## References

[1] N. Challab et al., ACS Appl. Mater. Inter. in press (2021)
[2] S. Merabtine et al. Nano Lett. **18**, 5, 3199 (2018)
[3] S. Merabtine et al. Sci Rep **8**, 13695 (2018)

# Abstracts of Posters

(in alphabetical order)

# Ground states of the antiferromagnetic spin rings in strong magnetic fields

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Antiferromagnetic (AFM) materials have distinct advances compared to ferromagnets, that allow to use them in variety of spintronic applications [1,2]. Antiferromagnetically coupled curvilinear spin chains are of fundamental interest as simplest systems possessing interplay between the geometry and magnetic subsystem [3].

In this work, we analyze the ground states of AFM ring-shaped spin chain with the nearest-neighbour Heisenberg exchange and single-ion anisotropy in presence of external magnetic field. The direction of magnetic field coincides with the symmetry axis of the ring. Collinear two-sublattice 1D curved AFM chain with even number of spins is considered, and the hard axis of anisotropy is oriented tangentially to the chain.

Within the classical continuum approach its magnetic state is described by two order parameters, the Néel and ferromagnetism vector fields. In the ground state, the Néel vector is oriented perpendicularly to the ring plane.

The magnetic field applied along the ring normal allows to observe spin-flop and spin-flip orientational phase transitions. We determine the dependency of spin-flop and spin-flip transition fields on the ring curvature and the critical curvature which separates two topologically different ground states above spin-flop transition. The first one with the Néel order parameter within the normal plane is mainly determined by the anisotropy at small curvatures. The second ground state at large curvatures is represented by onion ordering of the Néel vector. With the applied fields larger than critical spin-flip transition field Néel order parameter vanishes, which leads to ferromagnetic ground state. The phase diagram of AFM as a function of applied field intensity and the ring curvature is developed.

**References**

[1] V. Baltz, A. Manchon, M. Tsoi, T. Moriyama, T. Ono, Y. Tserkovnyak, Reviews of Modern Physics **90**(1), 015005 (2018).

[2] O. Gomonay, T. Jungwirth, J. Sinova, RRL **11**(4), 1700022 (2017).

[3] O. V. Pylypovskyi, D. Y. Kononenko, K. V. Yershov, U. K. Rößler, A. V. Tomilo, J. Fassbender, J. van den Brink, D. Makarov, D. D. Sheka, Nano Letters **20**(11), 8157–8162 (2020).

# Investigation of Structrural, Elastic and Thermodynamic Properties of $CeO_2$ : A DFT-Based on Simulation

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Comprehension of materials physics requires fundamental knowledge of its properties. Simulation plays an important role in determining these properties. The latter minimizes the costs of expensive and dangerous requirements of an experiment or various models about specific phenomenon that is difficult to achieve experimentally. Among these simulation methods, the particular method is used (FP-LAPW) which based on the DFT, and the calculation was carried out using the wien2k code to determine the structural, elastic and thermodynamic properties of the $CeO_2$ compound such as the Cerium oxide is mainly used in the automotive industry and as a fuel cell electrolyte.

The optimization of structure was carried out in ferromagnetic and non-magnetic states. The compound was found to be stable in the non-magnetic state. In our contribution, we have also calculated the elastic constants, the Young's modulus and Poisson's ratio of this compound that are found in good agreement with the results published in the literature. Thermal effects on some macroscopic properties (thermal expansion coefficient and heat capacity) of $CeO_2$ oxide are investigated by employing the quasi-harmonic Debye model in a temperature range from 0 K to 600 K and in the pressure range from 0 GPa to 20 GPa.

**Keywords:** CeO2, FP-LAPW, Wien2k, Approximations, Properties.

## Reference

[1] P.Blaha,K.Schwarz,P.Sorantin,S.K.Trickey,Comput.Phys.Commun.59(1990) 339.

[2] Murnaghan, F.D., Proc. Natl. Acad. Sci., 30 (1944) 244.

[3]S. Tariq, S. Saad, M.I. Jamil, S.M. SohailGilani, S. Mahmood Ramay, A. Mahmood Ab initio study on half-metallic, electronic and thermodynamic attributes of LaFeO3 Eur. Phys. J. Plus, 133,p.87 (2018).

[4] P.Blochl,O.Jepsen,O.K.Andersen,Phys.Rev.B49(1994)16223.

[5] Michael Nolan, Sonja Grigoleit, Dean C. Sayle , Stephen C. Parker, Graeme W. Watson, Surface Science, 576 (2005) 217– 229.

# Scale-up of nanowire synthesis for the application in composite bonded magnets

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In the last years, nanowires appear to be materials to play a key role in the development of new nanodevices in many fields of applications like recording schemes, neuroscience, water splitting... The quantity of nanowires produced in a laboratory is enough to supply material for these applications. However, applications related to nanomedicine or the production of composites materials require the fabrication of big quantities of nanowires to go from the laboratory or research papers to real industry production.

In this work, we carried out the scaling-up of the production of magnetic nanowires for applications in which large amounts are needed. There were two mean issues to focus on: to increase the number of produced nanowires and to reduce the cost of the synthesis process to make these nanostructures competitive at industrial applications. Template electrodeposition was chosen to grow the nanowires because it is a versatile and non-expensive technique that allows us the synthesis of a wide range of metallic and oxide materials. Changing high purity starting materials for other ones with less quality and modifying the anodization and growth conditions we have managed to reduce the price, the synthesis time and to increase the production of nanowires in our laboratory and we have stablished the conditions to implement this process in industry. Also, we show an application where FeCo nanowires, growth using this scaled-up procedure, combined with strontium ferrite powder were used to synthesize a prototype of composite based permanent magnet [1] whose properties were improved with respect to the strontium ferrite magnets to fill the gap between ferrites and rare-earth magnets.

## References

[1] Guzmán-Mínguez, J. C., et al. ACS Applied Nano Materials **3.10**, 9842-9851 (2020).

## Trajectories of charged particles moving through magnetized tubes

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The propagation of charged particles under the effect of a magnetostatic field has been of interest for researchers due to applications such as cyclotrons, microscopy, and optical laser pulses. At the nanometer scale, the trajectories of these particles still are affected by the magnetostatic field generated by thin magnetic films and nanostructures. Moreover, these kinds of systems showcase novel and interesting phenomena at the nanoscale. One of such phenomena is the chiral symmetry breaking in curved magnetic materials [1-3], which can induce chirality-dependant domain wall dynamics, skyrmions, non-symmetric propagation of spin waves, and curvature dependant equilibrium states. Furthermore, curved magnetic structures also show interesting potential applications in flexible magneto-electronics and flexible magnetic sensors [4].

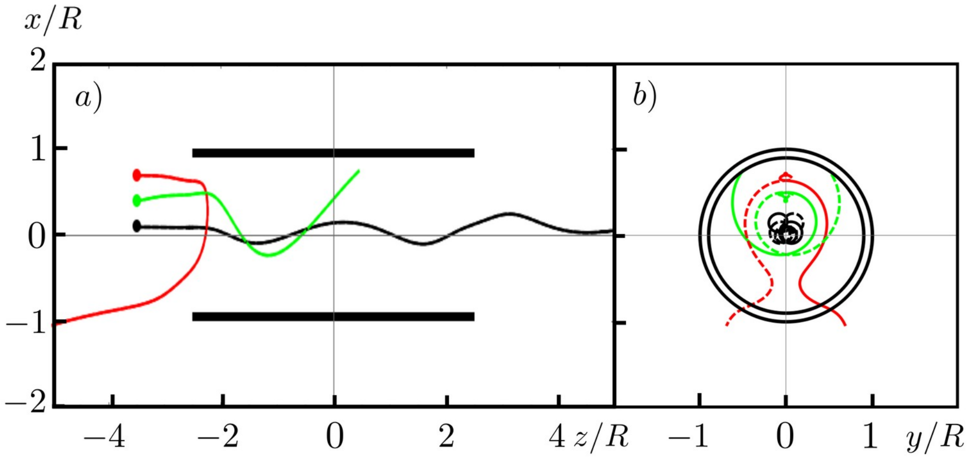


Figure 1. 2D representation in the a) *zx* and b) *yx* plane of typical trajectories of charged particles traversing a longitudinally magnetized tube.

In this talk we will show the trajectories of charged particles moving under a magnetostatic field induced by an open nano-cylinder. We study theoretically the trajectories induced by the magnetostatic field of nanotubes with radial and longitudinal magnetization, and perform a systematic study as function of several initial conditions of the particle and different physical parameters of the tube. Three distinct types of trajectories were obtained, those that traversed the tube, those that were deflected, and those that collision with the tube, as shown in figure 1 for the longitudinally magnetized tube. Finally, we identify how the various initial conditions would induce each of the three kinds of trajectories and how would they affect the ending point of the particles.

[1] P. Landeros and A. S. Nuñez, J. Appl. Phys. **108**, 033917 (2010).
[2] V. P. Kravchuk et al., Phys. Rev. Lett. **120**, 067201 (2018).
[3] D. D. Sheka et al., Commun. Phys. 3, **128**, (2020).
[4] R. Streubel et al., J. Phys. D: Appl. Phys. **49**, 363001 (2016).

# Surface Critical Behavior of Semi-Infinite Ferrimagnetic Mixed System

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Using the mean-field approximation and Monte Carlo simulation, we have investigated the three-dimensional semi-infinite mixed spin-1/2 and spin-3/2 ferrimagnetic Ising system with crystal field. According to the ratio *R* of bulk and surface exchange interactions and the ratio *Y* of bulk and surface crystal fields, we have classified four qualitative types of phase diagrams characterized by the presence or absence of ordinary, extraordinary, surface and special phase transitions. The critical behavior of the surface and bulk magnetizations has also been highlighted in the vicinity of these different transitions. At low temperatures, two critical end-points appear in the bulk and on the surface in the ordered region limiting two successive first-order phase transitions.

## References

[1] S. Zouhair, M. Monkade, A. El Antari, M. El Bouziani, N. Hachem, M. Madani, Surface Review and Letters **28**, 2150025 (2021)

[2] A. Bakchich, M. El Bouziani, Journal of Physics: Condensed Matter **11**, 6147 (1999)

# Curvature-mediated spin textures in magnetic multi-layered nanotubes

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Expanding nanomagnetism research into controlling and understanding of artificially synthesized three-dimensional magnetic nanostructures opens a path to exciting novel physical phenomena with potential impact for technological applications [1]. In this framework, one of the emerging scientific areas is curvilinear nanomagnetism, which showcases interesting curvature-induced effects in the magnetic properties of materials [2].

Here, we report on an experimental study of magnetic curved nano-objects, which consist of magnetic multi-layered nanotubes (MMNTs) that were fabricated by depositing a magnetic heterostructure on the curved surface of non-magnetic nanowires. The system studied is a Pt/Co/Ni multilayer system with Dzyaloshinskii–Moriya interaction (DMI). We have characterized the nanoscale spin texture in the MMNTs by means of full-field magnetic transmission soft X-ray microscopy at the MISTRAL beamline of the ALBA Synchrotron (Spain). Specifically, element-specific magnetic tomography was performed. Interestingly, we have found vortex states of the magnetization with a distinct helicity that reverses its sign along the length of the nanowire creating a titled domain wall (DW). This unusual DW configuration arises as direct effect of the MMNT curvature in combination with the intrinsic DMI of the heterostructure leading to a curvature-mediated DMI effect [3].

## References

[1] A. Fernandez-Pacheco et al., Nature Comm. **8** 15756 (2017)
[2] E.Y. Vedmedenko et al., J.Phys.D: Appl.Phys. **53** 453001 (2020)
[3] E. Josten et al., arXiv:2103.13310 (2021)

# Theoretical study of current induced domain wall motion in magnetic nanotubes with azimuthal magnetization [1]

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While magnetic nanowires and nanotubes have been synthesized and investigated for three decades, it is only recently that their properties are being monitored at the scale of single objects, such as for instance domain wall motion. Recently very peculiar class of domains were observed in 30 µm CoNiB nanotubes – domains with azimuthal (flux-closure) magnetization [2]. This peculiar magnetization orientation in long tubes have been attributed to possible two sources of magnetic anisotropy: intergranular interface anisotropy and magneto-elastic coupling (inverse magnetostriction). Interestingly, it opens the possibility of moving those structures with only electric currents, via the Oersted field, at very high speed. To this end, we perform a theoretical and numerical study on the current induced domain wall dynamics in magnetic tubes with azimuthal domains focusing particularly on the effect of the Oersted field and spin-torque-induced effects (STT). We establish a phase diagram where stable azimuthal domains are predicted as a function of the anisotropy strength $K_s$ and the tube geometry, see Fig. 1. In addition, stable Néel and Bloch wall structures are predicted resulting of a competition between the curvature induced exchange energy, the demagnetization energy and the anisotropy energy. We show the existence of STT and/or Oersted dominated regime for both domain wall structure and we report large domain wall speeds reaching potentially 800 m/s and the presence of a so-called Walker breakdown. We show how the domain wall speed and the walker field depend on the anisotropy and the geometrical parameter of the magnetic tubes. Our study may guide the experimental realization of magnetic tubes for finding the optimal parameters to get the desire properties.

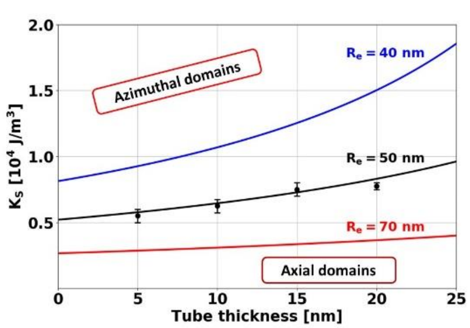


Fig. 1 : Threshold values of the anisotropy strength separating axial monodomain (below the curve) from azimuthal monodomain (above the curve) as a function of the tube thickness for three different external tube radius. The markers indicate an estimation of the threshold anisotropy value obtained with feeLLGood simulations [http://feellgood.neel.cnrs.fr].

## References

[1] J.Hurst, A.De Riz, M.Staňo, J.-C. Toussaint,O. Fruchart and D.Gusakov, Theoretical study of current induced domain wall motion in magnetic nanotubes with azimuthal domains, Phys. Rev. B **103**, 024434 (**2021**).
[2] M.Staňo, O. Fruchart, Magnetic Nanowires and Nanotubes, Handbook of Magnetic Materials, Elsevier, v. 27, pp.155-267 (**2018**).

# Magnetic and thermodynamic properties of a hexagonal ferrimagnetic Ising nanowire with core/shell structure

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The magnetic properties of the hexagonal Ising nanowire, consisting of a ferromagnetic core of spin-3/2 atoms surrounded by a ferromagnetic shell of spin-1/2 atoms, have been studied by Monte Carlo simulations (MCS) and Mean-Field Approximation (MFA). It has been shown that the existence of spin-3/2 at the nanowire core plays an important role in magnetic properties of the system. In addition, The dependence of the phase diagrams on the effects of crystal field and exchange interactions were also discussed in detail. Depending on different values of the magnetic parameters, we have found various types of magnetization curves. In particular, the compensation behavior has been discovered for certain parameters.

**Keywords**: hexagonal, Monte Carlo, Mean-Field Approximation ,Magnetization.

**References:**

[1] B. Boughazi, M. Boughrara, M. Kerouad. Physica A: Statistical Mechanics

[2] E. Kantar. J Supercond Nov Magn. 28, 2865–2873 (2015).

[3] N.Hachem , I.A. Badrour, A. El Antari, A.Lafhal, M. Madani, M.El Bouziani. Chinese Journal of Physics. S057790732030174X (2020).

# Novel Type of Bent-Lattice Nanostructure in Crystallizing Amorphous Films: from Transrotational Microcrystals to Amorphous Models

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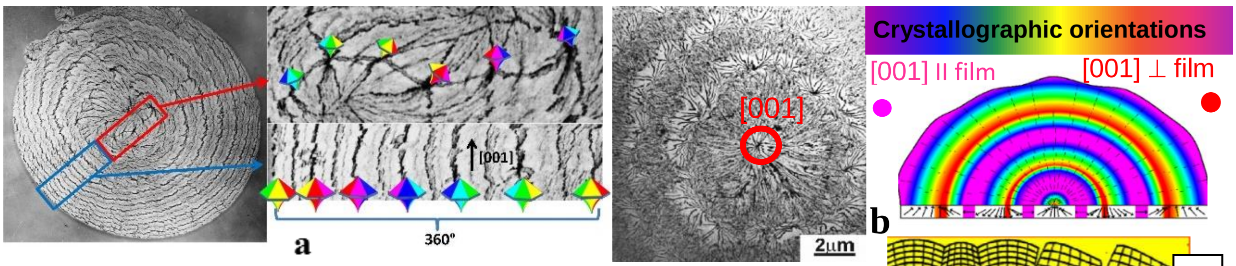
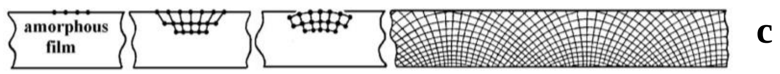
Exotic thin crystals with unexpected **transrotational** micro-, nanostructures [1] have been discovered by transmission electron microscopy (TEM) for crystal growth in thin (10-100 nm) amorphous films of different chemical nature (oxides, chalcogenides, metals and alloys including magnetic materials) prepared by various methods. The unusual phenomenon can be traced ***in situ*** in TEM column, Fig.1a-b: dislocation independent regular internal bending of crystal lattice planes in a growing crystal. Such **transrotation** (unit cell **trans**lation is complicated by small **rotation** realized round an axis lying in the film plane) can result in strong regular lattice orientation gradients (up to 300 degrees per 1μm) of different geometries: cylindrical, ellipsoidal, toroidal, saddle, etc. Perfect transrotational microcrystal initially resembles ideal single crystal enclosed in a curved space. Complex skyrmion-like lattice orientation texture is observed in some spherulite crystals, Fig.1b. The transrotation phenomenon is the basis for novel lattice-orientation/rotation nanoengineering of functional, smart thin-film materials. Transrotational micro crystals have been eventually recognized by other authors in some vital thin film materials, i.e. PCMs for memory [2-3]. Atomic model and possible mechanism of the phenomenon, Fig.1c, are discussed. Transrotational microcrystals show us the unusual ways of atom packing in low-dimensional areas with curved "crystal" planes. We propose new concept for models of amorphous state: fine-grained structures with crystal lattice curvature, Fig.1d (with "dilatons"/"contractons" pulsating/circulating in dynamics).



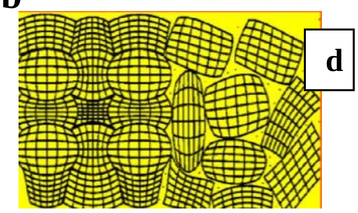




Fig. 1. Transrotational microcrystals: TEM for Se (**a**) and $Fe_2O_3$ (**b**) with schemes of lattice orientations shown in colors; proposed mechanism of **transrotational** crystal growth based on surface nucleation (**c**); new concept for amorphous models (**d**) - 2 simple schematic variants (left - right), in statics (pulsating or/and circulating, etc., when considered in dynamics).

## References

[1] V.Yu. Kolosov and A.R.Tholen, Acta Mater., **48**, 1829 (2000).

[2] B. J. Kooi and J. T. M. De Hosson, J. App. Phys. **95**, 4714 (2004).

[3] E. Rimini et al, J. App. Phys. **105**, 123502 (2009).

# Finite-element dynamic-matrix approach to calculate spin-wave dispersions in waveguides with arbitrary cross section

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One of the key objectives in curvilinear magnetism is the determination of the spin-wave dispersion and mode profiles in magnetic waveguides with surface curvature. Due to the geometrical complexity, dynamic micromagnetic simulations are often used to obtain quantitive predictions where only approximate analytical approaches are available. However, especially in geometries which require an accurate modeling of the sample surface, these dynamic micromagnetic simulations become computionally exhausting. To address this challenge, we present a finite-element dynamic-matrix approach to efficiently calculate the dispersion and spatial mode profiles of spin waves propagating in waveguides with arbitrary cross section where the equilibrium magnetization is invariant along the propagation direction. This is achieved by solving a linearized version of the equation of motion of the magnetization numerically only in a single cross section of the waveguide at hand. To take account of the dipolar interaction we present an extension of the well-known Fredkin-Koehler method to plane waves. As an application of our method, we present the first results on the spin-wave dispersion in nanotubes with thick shell which exhibits higher-order standing modes along the radial direction as well as an extremely strong dispersion asymmetry compared to thin-shell nanotubes.

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# Atomic Layer Deposition of Yttrium Iron Garnet (YIG) for 3D Spintronics

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In the last decades, the field of spintronics was mostly confined to planar sample geometries. Recently, however, developing and using three-dimensional (3D) magnetic structures has gained increasing interests, as it became clear that going beyond the planar film paradigm might enable a variety of new phenomena in magnetic structures. Currently, the materials used to assemble such 3D spintronic structures are predominantly metallic. This makes it difficult to study the magnetic response of a given 3D structure separately from its electronic one. Establishing viable fabrication protocols for the realization of 3D magnetic insulators thus is an important endeavor.

We show here that it is possible to deposit yttrium iron garnet ($Y_3Fe_5O_{12}$, YIG) thin films via atomic layer deposition (ALD). YIG is the prototype ferrimagnet widely used in spintronics owing to its low coercivity. Moreover, the magnetization damping in YIG is very low, making it the ideal test material for magnon transport and other magnonic experiments. What concerns ALD of YIG, we utilize a supercycle approach based on the combination of sub-nanometer thin layers of the binary systems $Fe_2O_3$ and $Y_2O_3$ with correct atomic ratios. We deposit $Fe_2O_3$/$Y_2O_3$ multilayer stacks on $Y_3Al_5O_{12}$ substrates and use a subsequent annealing step to obtain crystalline YIG films. Our process is robust against typical growth-related deviations, ensuring a good reproducibility. Detailed structural and magnetic characterization shows that our ALD-YIG thin films are of good crystalline quality, with magnetic properties comparable to the ones realized via other deposition techniques. Since atomic layer deposition enables a conformal coating of arbitrarily-shaped substrates, the ALD of YIG opens the door to fabricate novel 3D magnetic nanostructures.

# Small-angle neutron scattering of nanomagnetic gyroid structures

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Gyroids are minimal-surface structures that can be formed by self-assembly of block co-polymers. Such soft matter structures, which also occur naturally in butterfly wings, have attracted recent research interest due to their interesting topological features and nanoscale local curvature, which can e.g. be interesting for photonic applications. In combination with a magnetic material their unique connectivity structure – with three legs meeting in each vertex – also makes gyroids also a three-dimensional artificial spin system with a high degree of geometrical frustration, which potentially could exhibit a classical spin-liquid phase.

Here, I will present small angle neutron scattering (SANS) measurements from a structurally-single-domain magnetic nickel network electroplated into a self-assembled block co-polymer gyroid template. Scattering from the three-dimensional structure with cubic lattice symmetry (space group $I4_132$) reveals a periodicity of ~62 nm. We used a polarised neutron beam (i.e. half-polarised SANS) to measure the scattering signal at applied fields of 1 T, 100 mT and 20 mT, and observed changes in the magnetic SANS signal, which becomes more diffusive at low fields. This indicates a higher degree of magnetic disorder and frustration.

To elucidate the relationship between the complex structure and emergent magnetism, we performed micromagnetic simulations and calculated the respective scattering intensities. We aim to compare the simulations to the observed SANS data to obtain an average nanomagnetic model at each applied magnetic field.

# Space-Time , Relativity and Quantum Fields


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***Presented by <u>Tanmoy Pati</u>***



This abstract will present the Evolution of Space-Time, Special and General Relativity and Quantum fields(QED and QCD).The fundamental Question is how to develop a standard theory which can describe the entire physical properties for macro and micro scale of the universe.Formulation of the standard model of particle physics have unified some invisible,probabilistic quantum phenomena brilliantly, and Unified the 3 fundamen--tal forces are apparently very dispersed versions of the same and more fundamental force but surprisingly Gravity is excluded from there. But complete theory of Gravity GR by Einstein is very accurate and experimentally well verified in it's own way. In Another hand the 'Strong-Electroweak' theory is also very mathematical rich and experimentally verified in 2012 with finding of Higgs boson.So It is clear that a more fundamental theory is needed to describe the complete behaviour of elementary particle and of fundamental forces. Of course there has a lot of try to unify this by assumption from vibration of string and change in their mode of vibration using multidimensional calabi yau manifold or to quantize the entire spacetime grid by small energy-momentum packet.But here that's not the central discussion.Here we will essentially discuss the Relativistic mechanics and formulation of Quantum version of electrodynamics by Feynman,Schwinger and Tomonaga Followed with the Chromodynamics for complete description of the behaviour of the elementary particle interaction by SU(3)*SU(2)*U(1) symmetry group by Gell-Mann. In that time Classical field theory was formulated.In 1948 the quantization of fields was finished with Feynman. In 1954 Yang Mills theory also was developed.Yang−Mills theory is a gauge theory based on a special unitary group SU(N), or more generally any compact, reductive Lie algebra and can describe the field in general accurately. In brief The standard model of particle physics has hadrons(can interact with strong force) and Leptons. These are Fermions which obeys FD stat. And Bosons obeys BE stat. Lagrangian for standard model need to be well described here.



REFERENCES: QED: The Strange Theory of Light and Matter by Feynman. Dynamics of the Standard Model by J. F. Donoghue
Quantum Field Theory and the Standard Model by Schwortz.

# Effects of torsion and curvature in antiferromagnetic spin chains

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Antiferromagnets represent a wide class of technologically promising materials for spintronic and spinorbirtonic devices with multiple magnetic sublattices [1]. An efficient manipulation of antiferromagnetic textures requires the presence of the Dzyaloshinskii-Moriya interaction (DMI), which is present in crystals of special symmetry, and thus limits the number of available materials. In contrast to antiferromagnets, it is already established that in ferromagnetic thin films and nanowires chiral responses can be tailored relying on curvilinear geometries [2].

Here, we explore curvature effects in curvilinear antiferromagnets which are stemming from exchange interaction [3]. It is shown that intrinsically achiral curvilinear antiferromagnetic spin chains behave as a biaxial chiral helimagnet with a curvature-tunable anisotropy and DMI. In contrast to ferromagnetic spin chains, the dipolar interaction leads to the hard-axis anisotropy. This allows to observe the effects of geometry even in chains with small curvature and torsion because of absence of other competing easy axis anisotropies except the geometry-induced one. The latter determines the homogeneous antiferromagnetic state at low curvatures and the gap for spin waves. The geometry-driven DMI determines the helimagnetic phase transition and leads to the appearance of the region with the negative group velocity at the dispersion curve. We note, that the anisotropy in curvilinear antiferromagnetic spin chains is an additional source of geometry-driven effects on magnetic textures [4].

## References

[1] V. Baltz, A. Manchon et al., Rev. Mod. Phys. **90**, 015005 (2018)
[2] R. Streubel, P. Fischer, et al., J. Phys. D.: Appl. Phys. **49**, 363001 (2016)
[3] O. Pylypovskyi, D. Kononenko et al., Nano Lett. **20**, 8157 (2020)
[4] O. Pylypovskyi, Y. Borysenko et al, Appl. Phys. Lett., **118**, 182405(2021)

# Calculation of spin-wave eigenmodes in a hemisphere and Möbius strip

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We study the effect of curvature on the eigenmodes of hemispheres and Möbius rings using a dynamic-matrix approach[1] implemented into our finite-element micromagnetic simulator[2,3]. By default, this method delivers the mode profiles as well as their frequencies without the need for an a priori knowledge of the expected spin-wave modes. It was found, contrary to the expectations, that the equilibrium vortex core polarization (up or down) in the studied hemisphere has no impact on the spin-wave frequencies. The calculated mode profiles were categorized based on their radial and azimuthal mode indices and compared with those obtained for a flat reference vortex disks. It was found that the curvature induces mostly tiny differences in mode profiles and their dynamics. As a second case study the spin-wave eigenmodes and the dispersion of a Möbius strip was calculated and compared with a flat wire of the same cross section as well as with modes of a flat ring. Categorizing the modes according to their radial and azimuthal indices, we find that modes with half integer azimuthal indices are present. Moreover, the dispersion is asymmetric regarding the sign of the azimuthal mode index. The lifting of the degeneracy is originating from the exchange interaction, attributed to the torsion present in the Möebius ring similar to the torsion induced asymmetric dispersion in nanowires reported by Y. Gaididei et al. in Ref [4].

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[1] M. d’Aquino, “Computation of Magnetization Normal Oscillation Modes in Complex Micromagnetic Systems,” IFAC Proceedings Volumes **45**, 504–509 (2012).
[2] A. Kákay, E. Westphal, R. Hertel, *IEEE Transactions on Magnetics*, **46**, 2303 (2010).
[3] G. Quasebarth, Bachelor thesis: https://zenodo.org/record/4506399.
[4] Y. Gaididei et al., *J. Phys. A: Math. Theor*. **50,** 385401 (2017).

# The nonlinear Dirac equation with a spatially periodic potential


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Soliton dynamics in the nonlinear Dirac equation, in 1+1 dimension with scalar-scalar self-interaction will be discussed by adding a potential with spatial period λ . The time-dependent response of the solitary waves of width L to this perturbation is explained by mapping the original problem into the Newtonian-like equation for the center of mass of the soliton. In this representation the particle is under an effective potential with the same period λ. However, the value of λ also affects the amplitude of this potential in such away that for small values of λ (λ<<L) it reaches the value zero and the soliton moves uniformly as a free particle. Alternatively, when λ is greater than L or comparable to the soliton width the dynamics of the soliton is richer. In particular in the non-relativistic limit the center of mass is governed by the equation of a simple pendulum. There is a critical initial velocity for which the soliton oscillates within a long period and travels a large distance. Below this critical velocity the soliton also oscillates with a small amplitude about its initial position, while above this critical velocity the soliton moves unidirectionally. These analytical predictions perfectly agree with the simulations of the nonlinear Dirac equation.

There are instabilities observed in [1,2] for the parametrically driven nonlinear Dirac equation with spatially periodic force due to the length scale competition related to the width of the soliton L and to the period of the force λ. Here these instabilities are detected only for large values of the amplitude of the spatial potential.


## References


[1] N. R. Quintero, B. Sánchez-Rey, F. Cooper, and Franz G Mertens. *Length-scale competition in the parametrically driven nonlinear Dirac equation with a spatially periodic force.* J. Phys. A: Math. Theor. **52,** 285201 (2019).

[2] *F. Cooper, A. Khare, N. R. Quintero, B. Sánchez-Rey, Franz G Mertens, and A. Saxena. Parametrically driven nonlinear Dirac equation with arbitrary nonlinearity equation with arbitrary nonlinearity*. J. Phys. A: Math. Theor. **53**, 075203 (2020).

# Parallel computation of 3D magnetic structures

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Intensive experimental and theoretical research for novel materials introduces new architectures for magnetic devices, where shape and topology plays a crucial role [1]. A powerful way to study them as well as confirm analytical predictions is to compute the corresponding equations of motion numerically. Here, we present a spin-lattice simulation suite SLaSi, which can address flexible magnetic one- and two- dimensional spin lattices. They can represent soft wires and ribbons, where the coupling between magnetic and mechanical subsystem results into spontaneous deformations and symmetry breaks [2]. The SLaSi is a C-written program, where exchange, single-ion anisotropy, Zeeman energy, dipolar interaction, and Dzyaloshinskii-Moriya interaction are taken into account for the description cubic, square, and triangular lattices. Dynamics of the mechanical sub-system is modelled by the overdamped Newton equations, while magnetic sub-system is modelled by LLG. Speedup of the computations is achieved by parallelization using MPI and CUDA frameworks.

[1] Streubel et al, J. Phys. D: Appl. Phys., 49, 363001 (2016), Fernandez-Pacheco et al, Nat. Comm. 8, 15756 (2017).
[2] Gaididei et al, Phys. Rev. B., 99, 014404 (2019), Yershov et al, Phys. Rev. B, 100, 140407 (2019)

# Experimental confirmation of curvature-induced effects in magnetic nanosystems

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Curvilinear magnetism is the emerging field in micromagnetism which studies influences of external geometry and its topology on magnetic vector fields [1]. Much attention was paid to fundamental theoretical investigations of curvature-induced effects for local [2,3] and non-local magnetic interactions [4], which results in the prediction of various magnetochiral effects [2,5], topologically-induced magnetic patterns [5,6], stabilization of individual skyrmions [7,8] and skyrmion lattices [9] on curvilinear defects. Recently, we provided the very first experimental confirmation and quantitative assessment of the existence of the curvature-induced chiral interaction of exchange origin in a conventional soft ferromagnetic material [10]. In its turn, the interplay between the intrinsic and exchange-induced Dzyaloshinskii-Moriya interaction (DMI) paves the way to a mesoscale DMI [3], whose symmetry and strength depends both on the geometrical and material parameters of the magnetic system. Extending this concept we proposed a novel approach towards artificial magnetoelectric materials with helimagnetic nanohelices embedded in a piezoelectric matrix [11], where electric field could control magnetic states through the utilization of curvature-induced effects.

## References

[1] R. Streubel et. al., J. Phys. D: Appl. Phys. 49,363001 (2016).
[2] Y. Gaididei et al., Phys. Rev. Lett. 112, 257203 (2014).
[3] O. Volkov et al., Sci. Rep. 8, 866 (2018).
[4] D. D. Sheka et al., Commun. Phys. 3, 128 (2020).
[5] V. P. Kravchuk et al., Phys. Rev. B 85, 144433 (2012).
[6] O. V. Pylypovskyi et al., Phys. Rev. Lett. 114, 197204 (2015).
[7] V. P. Kravchuk et al., Phys. Rev. B 94, 144402 (2016).
[8] O. V. Pylypovskyi et al., Physical Review Applied 10, 064057 (2018).
[9] V. P. Kravchuk et al., Phys. Rev. Lett. 120, 067201 (2018).
[10] O. M. Volkov et al., Phys. Rev. Lett. 123, 077201 (2019).
[11] O. M. Volkov et al., J. Phys. D: Appl. Phys. 52, 345001 (2019).

# Nanoscale mechanics of antiferromagnetic domain walls in Cr2O3

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Magneto-electric antiferromagnets hold promise for future spintronic devices, as they offer magnetic field hardness, high switching speeds combined with electric and magnetic control of their order parameters, owing to the magneto-electric coupling [1]. As information and functionality is encoded in the antiferromagnetic order parameter, its manipulation, read-out and nanoscale texture are paramount for device operation, as well as interesting from a fundamental point of view. E.g. spin-textures in such materials are theorized to carry an intrinsic magnetization [2]. Here we study a single crystal 'textbook' magneto-electric antiferromagnet, Cr2O3, by nanoscale imaging of its surface magnetization via magnetic stray field imaging by scanning nitrogen vacancy magnetometry [3]. This surface magnetization is directly linked to the bulk Neel vector of Cr2O3 and thereby allows for nanoscale imaging of antiferromagnet spin textures. After confirming magneto-electric poling [4], local electrodes are utilized to nucleate single domain walls, which we then study on the nanometer scale. Manipulation of the domain wall is demonstrated both by local laser heating [5], as well as the creation of an energy landscape for the domain wall via topographic structuring [3]. We analyze the interaction of the domain wall with topographic islands both experimentally and in simulations. This analysis yields information about the domain wall boundary conditions at topographic edges and an estimate of the full 3D-profile of the texture based on minimizing the domain walls surface energy. A Snell like refraction of the domain wall path is found, that can be represented in an analytical approximation as a 'refractive index' for a given island dimension as demonstrated for a range of incidence angles.

We then observe bistable domain wall paths configurations and switching between them is demonstrated and imaged experimentally. This pinning and control of the domain wall position constitutes the main ingredients for logic devices based on domain walls in magneto-electric antiferromagnets and their fundamental study.

[1] T. Jungwirth et al., Nature Physics **14**, 200 (2018)
[2] Erlend G. Tveten et al.,PRB **93**, 104408 (2016)
[3] Hedrich, N., Wagner, K., et al. Nat. Phys. **17**, 574–577 (2021)
[4] B. B. Krichevtsov et al, Sov. Phys. JETP **67**, 378 (1988)
[5] S. Selzer et al., Phys. Rev. Lett. **117**, 107201 (2016)

# Long-range propagation of spin waves in transversely magnetized nano-scaled yttrium iron garnet conduits

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Spin-wave based data transport and information processing aims to complement computation technology by exploiting superior wave logic, with the benefits of potentially reducing the feature size, as well as allowing for data multiplexing and more energy efficient operations [1]. Recent studies provide advanced theoretical models for nano-scaled spin-wave conduits and revealed a reasonably long propagation distance for longitudinally magnetized conduits, thus proving the fundamental feasibility of this approach [2]. In contrast, due to a lack of analytical models and the experimental difficulties accompanied with fabricating and investigating nano-sized magnetic structures, little focus has been put on transversely magnetized nano-conduits. However, these systems are of great interest offering a large group velocity and a potentially protected transport of energy and information caused by the intrinsic chirality of the spin-wave modes [3] and thus promising a significantly enhanced spin-wave decay length. Here, we present a study of propagating spin-wave packets in a transversely magnetized nanoscopic yttrium iron garnet conduit of 50 nm width. Space and time-resolved micro-focused Brillouin-light-scattering spectroscopy is employed to measure the spin-wave group velocity and decay length. A long-range spin-wave propagation is observed with a decay length of up to 8 µm, which is several times larger than reported values for the corresponding longitudinal magnetized state [2]. In addition, a large spin-wave lifetime of up to 44.7 ns is found. The results are supported with micro-magnetic simulations, revealing a frequency non-reciprocity for counter-propagating spin waves, caused by the trapezoidal cross-section of the studied structure and the associated curved internal field distribution which introduces a special symmetry break. The presence of this non-reciprocity is experimentally verified and is particularly interesting for an application in spin-wave logic gates since it allows for a novel device architecture.

[1] A. A. Serga, A. V. Chumak, and B. Hillebrands, “YIG magnonics,” Journal of Physics D: Applied Physics43, 264002 (2010).

[2] B. Heinz, T. Brächer, M. Schneider, Q. Wang, B. Lägel, A. M. Friedel, D. Breitbach, S. Steinert, T. Meyer, M. Kewenig, C. Dubs, P. Pirro, and A. V. Chumak, “Propagation of spin-wave packets in individual nano-sized yttrium iron garnet magnonic conduits,” Nano Letters 20, 4220–4227(2020).

[3] M. Mohseni, R. Verba, T. Brächer, Q. Wang, D. A. Bozhko, B. Hillebrands, and P. Pirro, “Backscattering immunity of dipole-exchange magnetostatic surface spin waves,” Phys. Rev. Lett.122, 197201 (2019).

## Enhanced longitudinal relaxation of solitons in ultrathin easy-axis ferromagnets

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The relaxation fundamentally determines the operation speed and energy efficiency of spintronic and spinorbitronic devices. The nature of the longitudinal relaxation mechanism for solitons in ferromagnets is in the transient change, i.e. drop and subsequent recovery of the modulus of the magnetization within the region of the ferromagnet where the domain wall passes. For bulk ferromagnets this contribution for the most technologically relevant cases turned out to be negligible. We develop a theory of the longitudinal relaxation of solitons in ultrathin magnetic films and predict the effect of increase of the longitudinal relaxation mechanism with the decrease of the film thickness. We apply this formalism for a technologically relevant case of ultrathin asymmetrically sandwiched Co films with Dzyaloshinskii-Moria interaction and demonstrate that the contribution of the longitudinal relaxation to the damping of domain walls is comparable or even stronger than any other mechanism discussed before including spin pumping. The discussed here enhancement is generic and is valid for other magnetic solitons, including skyrmions. The obtained result is of great importance for designing and optimization of spintronic and spinorbitronic devices, including those for data storage and manipulation.

# Circular stripe domains in magnetic heterostructures of cylindrical geometry

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Ferromagnetic films with perpendicular anisotropy are well-known to create stripe domains formations under the influence of in-plain external magnetic field [1]. The nonlocal magnetostatics interaction plays the key role in formation of the stripe domains. A perpendicularly magnetized layer in a vertically stacked magnetic heterostructures can also demonstrate stripe domains under the influence of the interlayer exchange coupling with thick layer which has in-plane magnetization [2].

Here we consider a vertically stacked magnetic heterostructures Py/Pd/Co of cylindrical geometry, where we predict formation of circular stripe domains in the Co nanodisk under the influence of the interlayer exchange coupling with the thick vortex-state Py nanodisk. Using OOMMF micromagnetic simulations [3] we model this heterostructure and built the phase diagram of equilibrium magnetisation states in the Co disk. Basing on this diagram, one can conclude that consecutive phase transitions between the vortex in the cone phase, the circular stipe domain and the vortex state take place with changing the interlayer exchange coupling parameter and Co disk thickness. Analytical analysis gives us boundaries for phases which are in a good agreement with data from simulations.
The existence of circular stripe domains corresponds to experimentally detected donut state [2].

## References

[1] A. Hubert and R. Schäfer, *Magnetic domains: the analysis of magnetic microstructures*, Springer (2009)
[2] R. Streubel et al, Scientific Reports **5**, 8787 (2015)
[3] Object Oriented MicroMagnetic computing Framework (OOMMF)