Introduction into physics of chiral magnetic skyrmions: rigorous solutions and experimental observations

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Dynamical and static stabilization mechanisms for skyrmions

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Topology, thermal fluctuations and quantum effects in nanomagnetism

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Stabilization of walls position in ferromagnetic nanowires

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Reduced models for domain walls in soft ferromagnetic films

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We study the Landau-Lifshitz energy of domain walls in soft ferromagnetic films. At the cross-over from symmetric N\\'eel to asymmetric N\\'eel and Bloch wall, we derive a reduced model that confirms an optimal splitting of the minimal energy into a numerically accessible contribution from a stray-field free wall-core, and an explicit contribution from the logarithmic tails of a symmetric N\\'eel wall that complete the rotation (joint work with R. Ignat and F. Otto).

For periodic domain patterns, we also quantify the influence of the interaction of neighboring wall tails on the average hard-axis magnetization in the domains. The theoretical prediction agrees well with experimental data (joint work with C. Hengst, F. Otto and R. Schäfer).

Skyrmion vs domain wall based racetrack memories

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The racetrack memory[1] seems to be a promising candidate for the design of ultra-dense, low-cost and low-power storage technology in the light of the recent advances in term of materials, devices and performances, such as velocity[2] [3]. Information can be coded in a magnetic region between two domain walls or, as predicted recently, in topological magnetic objects known as skyrmions. Here, we show the technological advantages and limitations of using Néel skyrmions manipulated by spin current generated via the spin-Hall effect as predicted by micromagnetic simulations by considering realistic experimental parameters[4][5]. Different scenarios will be discussed and a direct comparison between domain wall and skyrmion based racetrack memory will be presented in a context where the domain wall and skyrmion velocity are of the same order.

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Magnon-skyrmion interactions in chiral magnets

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We discuss the interaction of magnons with skyrmions textures in the chiral magnets which are characterized by the presence of a Dzyaloshinskii-Moriya interaction. The magnons experience an effective Lorentz force with an emergent magnetic field that is essentially determined by the topological charge density of the texture. This leads to skew scattering and a topological magnon Hall effect. An effective Thiele equation of motion for the skyrmion is derived with the help of the conserved energy-momentum tensor of the field theory. A finite magnon current leads to a momentum-transfer force on the skyrmion that possesses a transversal component due to the emergent magnetic scattering. Moreover, a thermal gas of magnons also results in a finite viscosity for the skyrmion.

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Stability of solitons for the Landau-Lifshitz equation with an easy-plane anisotropy

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We describe recent results concerning the orbital and asymptotic stability of dark solitons and multi-solitons for the Landau-Lifshitz equation with an easy-plane anisotropy. This is joint work with Andre de Laire (Université de Lille), and by Yakine Bahri (École polytechnique).

On singularity (non-)formation for Landau-Lifshitz equations

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Resonant Elastic X-ray Scattering on a Multidomain Skyrmion Lattice in Cu2OSeO3

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Cu2OSeO3 is a chiral ferrimagnetic insulator that carries a hexagonal array of spin whirls, known as a skyrmion lattice. We report the observation of a multidomain skyrmion state near the surface of a Cu2OSeO3 single crystal using soft resonant elastic x-ray scattering. This technique is an ideal tool to probe the magnetic order at the L3 edge of 3d metal compounds giving a depth sensitivity of ~50 nm. We show that for magnetic field directions deviating from the major cubic axes, the single-domain sixfold-symmetric skyrmion lattice breaks up into domains overcoming the propagation directions imposed by the cubic anisotropy. Our findings are discussed in the framework of competing anisotropies and magnetoelectric effects. In magnetoelectric crystals they open up a new way to manipulate the skyrmion lattice state.

Nearly parallel vortex filaments in the 3d Ginzburg-Landau equations

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Chaotic dynamics in nanocontact vortex oscillators

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Dynamics of antiferromagnetic solitons

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In this talk, we will discuss the dynamics of antiferromagnetic solitons with particular emphasis on its difference from the dynamics of ferromagnetic solitons. To that end, we start with the Lagrangian description of antiferromagnets on a bipartite lattice, which employs the unit vector in the direction of the staggered magentization as the order parameter. The sum of the Berry phases of two sublattices, which vanishes in the static state, forms the kinetic energy. The resultant Lagrangian for antiferromagnets is that of relativistic O(3) field theory, which differs from the nonrelativistic Lagrangian for ferromagnets with the Berry phase.

We will then discuss dynamics of antiferromagnetic solitons with two examples. Firstly, we study the Brownian dynamics of a 2D soliton subjected to a temperature gradient [1]. To this end, we derive the Langevin equation for the soliton's center of mass with the aid of the fluctuation-dissipation theorem. An antiferromagnetic soliton turns out to behave as a classical massive particle immersed in a viscous medium, which contrasts with a ferromagnetic soliton that behaves as a charged massless particle in a magnetic field due to the gyrotropic coupling between two spatial coordinates [2]. The result for the average drift velocity of a soliton (obtained from the Fokker-Planck equation) indicates that the Brownian motion of 2D antiferromagnetic solitons is different from that of 2D ferromagnetic solitons, which significantly slows down due to the gyrotropic force.

Secondly, we analyze the dynamics of a domain wall in 1D antiferromagnets driven by circularly polarized magnons [3]. In ferromagentic domain-wall cases, a magnon traversing a domain wall reverses its spin and deposits angular momentum on the domain wall. Addition of angular momentum to the domain wall translates directly into its shift toward the source of spin waves. The physics is different in an antiferromagnet in that translational motion of a wall is induced by transfer of linear momentum from magnons. We will explain the mechanism how linear momentum is transferred to the domain wall by exciting circularly-polarized magnons that has been known to pass through a static domain wall. \\
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Oppositely charged phases | Charge neutrality and screening

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We study the minimum energy conguration of a uniform distribution of negative
charge subject to Coulomb repulsive self-interaction and attractive interaction with a positively charged domain. After having established existence and uniqueness of a minimizing conguration, we prove charge neutrality and the complete screening of the Coulomb potential exerted by the positive charge, and we discuss the regularity properties of the solution. We also determine, in the variational sense of

Domain wall dynamics on curvilinear magnetic nanowires

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Curvature and torsion of magnetic nanowire drastically changes dynamical properties of magnetic domain wall.
It is shown that a local bend of a nanowire is a source of pinning potential for a transversal head-to-head (tail-to-tail) domain wall. Eigenfrequency of the domain wall free oscillations at the pinning potential and the effective friction are determined as functions of the curvature and domain wall width. The pinning potential originates from the effective curvature-induced Dzyaloshinsky-like term in the exchange energy. The theoretical results are verified by means of micromagnetic simulations for the case of parabolic shape of the wire bend.
The domain wall motion along a helix-shaped nanowire is studied for the case of spin-current driving via Zhang--Li mechanism. Two new effects are ascertained: (i) the curvature results in appearance of the Walker limit for a uniaxial wire, (ii) the torsion results in effective shift of the nonadiabatic spin torque parameter β. The latter effect changes considerably the domain wall velocity and can result in negative domain wall mobility. This effect can be also used for an experimental determination of the nonadiabatic parameter β and damping coefficient α.

Boundary and interior vortices in thin film micromagnetics

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Domain Wall Motion Driven by Spin Wave Pulses

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Spin waves (SW) and domain walls (DW) are key elements of various spintronic devices, such as racetrack memories [1] or magnon transistors [2]. The interaction between them has been studied for a continuous spin wave excitation on various geometries [3-6], and while an analytical study of the interaction is possible in an ideal case [3], the general picture is rather complicated, and a numerical analysis [4-6] is required to account for dipolar fields, internal DW modes or high order SW modes due to the finite stripe width.
In this work, we perform a numerical study of Bloch-type DW motion via spin waves in perpendicularly magnetized stripes. Both the continuous and the pulsed regimes of excitation are analyzed, and we find that spin wave pulses can
efficiently drive the domain wall away from the spin wave source. It is possible to distinguish two regimes of motion according to the duration of the pulses t (fig. 1a). For short pulses (t < 4 ns) the DW does not move during the
pulse, but rather acquires an initial speed after the pulse is switched off. In this regime, the DW velocity after the pulse is linear with the pulse duration. On the other hand, for long pulses (t > 10 ns), the DW motion starts during the pulse, and the DW retains its velocity after the pulse is switched off. In this second regime, DW velocity saturates and does no longer increase with the pulse duration. We also study the DW velocity dependence on frequency. We observe a smooth relationship with a well defined maximum for the velocity around 20 GHz, as can be seen in fig. 1b. For long pulses (t > 4 ns), an internal DW mode is excited at 23 GHz, leading to a reduced DW velocity. We also study the DW motion dependence on spin-wave intensity and the distance between the DW and the SW source. Altogether, our work explores the possibility of high-
speed coupling between magnon-based logic devices and DW-based memories.

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Traveling waves for Gross-Pitaevskii and related equations

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Collective excitations of magnetic vortices - from coupled pairs to magnonic vortex crystals

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Static and dynamic stability of chiral skyrmions

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The interaction of Neel walls in terms of their energy

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Micromagnetic analysis of skyrmion formation in constrained nano-pillar geometry with Co2FeAl ferromagnetic layer

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Magnetic skyrmions have gained popularity in recent years due to their possible use in magnetic data storage devices [1]. The topologically protected configuration allows the skyrmions to move freely even in presence crystal defects thereby relaxing the condition of having highly pure ferromagnetic films as in the case of memories based on vortex state or domain wall motion. Studies on formation of skyrmions in bilayer/trilayer systems has already been done by several groups where energy minimization in the presence of competing in-plane and out-of-plane anisotropies favors the skyrmion state [2]. For thin structures (< 4 nm), Dzyaloshinskii-Moriya Interaction (DMI) has been shown to stabilize such non-trivial magnetic states. A study on extended thin films with varying DMI strength was performed by You et al. [3] which showed the presence of a critical value of DMI strength to observe skyrmion structure. In this study, we analyze the effect of DMI in patterned nano-structures using micromagnetic simulations. A cylindrical nanopillar with 150 nm diameter and 4 nm thickness is discretized in 2 nm×2 nm×4 nm cells in x, y and z direction, respectively. Saturation magnetization is taken as 840 emu/cc whereas the gilbert damping constant is taken to be 0.01. Exchange interaction is set to 1.1×10-11J/m. The parameters used

are similar to that of Co2FeAl (CFA) Heusler alloy grown on MgO layer. The uniaxial out-of-plane anisotropy arising from the MgO-CFA interface was also taken into account. Energy of the system is minimized by solving the Landau-Lifshitz Gilbert equation for each individual cell using Bogacki-Shampine method. The ground state of the system is found by first applying a high field (1 Tesla) in the plane of the sample and then letting the magnetization relax under zero external field. It was seen that a threshold value of DMI exists corresponding to a fixed value of uniaxial anisotropy for skyrmion states to be energetically favorable, similar to the case of extended films. For higher anisotropy strength, DMI also needs to be higher to for formation of skyrmions. A simple single core hedgehog structure was obtained in our constrained geometry for values of DMI just above the threshold (fig 1). With the increase in DMI, complicated structures having several skyrmion cores were obtained. The value of topological charge was also calculated from the space dependent magnetic configuration of the relaxed states which, for skyrmion state, has an integral value of 1. Figure 2 shows the colormap where the phase boundary between skyrmion and non-skyrmion state is visible. The color in the figure represents the absolute value of dimensionless topological charge for a particular combination of anisotropy strength and DMI.

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Artificial Spin Ices: from real-space back to reciprocal space

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The creation of artificial frustrated arrays built lithographically out of custom tailored monodomain nanomagnets [1] has opened a rich play-ground for exploring unusual aspects of the physics of frustrated magnets.
From a theoretical point of view, it is surprising that systems with long-range dipolar interactions can realize the subtle balance of a frustrated magnet even in two dimensions. We briefly review the physics of frustrated `spin ice' phases in both the square and kagomé lattices models [2].
While the early appeal of these systems has been the ability to image individual magnetic islands, the continued miniaturization and accelerated dynamics of magnetic moments have rendered reciprocal space imaging techniques a more attractive means to observe these systems. One attractive target model is found in dipolar kagome ice, where such techniques can illuminate the nature of a cascade of transitions between two distinct spin-ice phases on the kagomé lattice, including two distinct spin-liquid phases and a low-temperature ordered phase, which arise from the crystallisation of monopoles and subsequent to ordering of higher multipole moments [3].
In particular, we review recent data extracted from soft x-ray scattering and discuss the theoretical foundations for the formation of pinch points in the evolution from local spin-ice phase (ice I) to the monopole charge ordered spin-ice phase (ice II) two-dimensional kagome ice systems [4]. In the spin ice I phase, the spin ice constraints do not allow a strict mapping to a lattice gauge theory, and the spin structure factor remains smooth. In the lower temperature ice II phase, owing to the monopole charge order the configurations can be formally mapped to a dimer model, and realizes a Coulomb phase with sharp pinch-points in the spin structure factor, as well as magnetic Bragg peaks indicating the magnetic charge order.

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Topological spin drag driven by skyrmion diffusion

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We study spin transport mediated stable skyrmion textures in magnetic thin films. Skyrmion charge can be pumped into the system by means of out-equilibrium torques. Due to its topological protection, the charge diffuses over the system, sustaining a spin current that only decays alge- braically with the distance between contacts. Gilbert damping favors the diffusion of skyrmion charge, otherwise the carriers (i.e. the motion of the center of mass of the texture) remain localized in cyclotron orbits. These ideas can be tested in films with interfacial Dzyaloshinskii-Moriya interaction.

Domain and wall patterns in thin-film ferromagnets

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Domain wall motion - asymptotics and collective coordinates

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Curvature-induced effects in ferromagnet nanosystems

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Curvature-driven modification of physical properties of magnetic systems with nontrivial geometry is the subject of intensive research. One can distinguish two groups of curvature-induced effects in nanomagnets: (i) magnetochiral effects unite the phenomena of curvature-induced chiral symmetry breaking and (ii) topologically induced magnetization patterning appears in curvilinear magnets, where orientation of the effective anisotropy axis is determined by the geometry.

We develop a general fully 3D approach to study dynamical and static properties of arbitrary curved ferromagnet nanoshells and nanowires. According to this approach two additional interaction terms appear in the exchange energy functional due to the curvature and torsion in wires (Gaussian and mean curvatures in the case of shells): an effective Dzyaloshinskii--Moriya interaction term and a geometrically induced anisotropy term. The magnetochiral effects are originated from the effective Dzyaloshinskii--Moriya interaction, while the magnetization patterning is related to the effective anisotropy. We illustrate our approach by several examples.

Charged domain walls in thin films

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Dynamics of ferromagnetic solitons via collective coordinates

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Stability and dynamics of antiferromagnetic skyrmions

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Manipulating small spin textures that can serve as bits of information by electric and spin currents is one of the main challenges in the field of spintronics. Ferromagnetic Skyrmions recently attracted a lot of attention because they are small in size and are better than domain walls at avoiding pinning sites while moved by electric current. Nevertheless, ferromagnetic Skyrmions also have certain disadvantages, such as the presence of stray fields and transverse dynamics, making them harder to employ in spintronic devices. To avoid these unwanted effects, we propose a novel topological object: the antiferromagnetic (AFM) Skyrmion [1] and explore its properties using analytical theory based on generalized Thiele equation and micromagnetic simulations. This topological texture has no stray fields and we show that its dynamics are faster compared to its ferromagnetic analogue. We obtain the range of stability and the dependence of AFM Skyrmion radius on the strength of Dzyaloshinskii-Moriya interaction coming from relativistic spin-orbit effects. Moreover, we study the temperature effects on the stability and mobility of AFM Skyrmions. We find that the thermal properties, e.g. such as the antiferromagnetic Skyrmion radius and diffusion constant, are rather different from those for ferromagnetic Skyrmions. More importantly, we show that due to unusual topology the AFM Skyrmions do not have a velocity component transverse to the current (no topological Hall effect) and thus may be interesting candidates for spintronic memory and logic applications.

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Nonlinear Domain Wall Resonances in garnet films with a stripe domain structure

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Nanoscale skyrmions - A new twist for spintronics

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Nanoscale magnetic knots, called skyrmions, are novel types of localized non-collinear spin textures which offer great potential for future magnetic memory and logic devices [1]. The twisting in the skyrmions' magnetization profile leads to a gain in energy with respect to a homogeneously magnetized, ferromagnetic state. As a result of this magnetization twisting, skyrmions have non-trivial topological properties, described by a topological charge, and are topologically protected against a transition into topologically trivial states. The energetics of skyrmionic states is explained by the Dzyaloshinskii-Moriya interaction [2] being relevant in material systems exhibiting large spin-orbit coupling and a lack of

inversion symmetry, in contrast to magnetic bubble domains which are stabilized by dipolar magnetic interactions.
Skyrmion lattices were initially observed in bulk non-centrosymmetric materials based on neutron diffraction experiments and Lorentz microscopy observations. However, recent experimental and theoretical work has focused on atomic- and nanolayers of magnetic materials with intrinsic or interface-induced chiral interactions, thereby achieving full compatibility with state-of-the-art technology which has been developed over the past decades in the field of GMR- and TMR-based devices. It has been shown both experimentally and theoretically that magnetic skyrmions in ultrathin film systems can be as small as one nanometer in diameter [3] and that their properties can largely be tuned by the choice of the substrate and overlayer materials [4].
Atomic-resolution spin-polarized scanning tunneling microscopy (SP-STM) and spectroscopy [5] has proven to be an invaluable tool for revealing the atomic-scale properties of ultimately small skyrmions [6-9]. By locally injecting spin-polarized electrons from an atomically sharp SP-STM tip, we are able to write and delete individual skyrmions one-by-one, making use of spin-transfer torque exerted by the injected high-energy spin-polarized electrons [4]. Switching rate and direction can be controlled by the parameters used for current injection. Alternatively, individual skyrmions can be created and deleted by local electric fields, which can be of great advantage in view of energy-saving skyrmionic device concepts. The subsequent detection of the written skyrmions can also be achieved by electrical means rather than by using a magnetic sensing element [10]. The demonstration of various methods for the creation and annihilation as well as the detection of individual nanoscale skyrmions highlight their great potential for future spintronic devices making use of individual topological charges as information carriers.

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