# SYMPOSIUM EP02

Materials for Manipulating and Controlling Magnetic Skyrmions
November 28 - November 30, 2018

Symposium Organizers
Karin Everschor-Sitte, Johannes Gutenberg-Universität Mainz
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Symposium Support
Spin Phenomena Interdisciplinary Center (SPICE)
The UK Skyrmion Project

* Invited Paper

SESSION EP02.01: Opening Session
Session Chairs: Song Jin and Christopher Marrows
Wednesday Afternoon, November 28, 2018
Hynes, Level 2, Room 204

**1:30 PM *EP02.01.01**
**Skyrmion Dynamics—From Thermal Diffusion to Ultra-Fast Motion** Mathias Klaeui[1, 2]; [1]Univ Mainz, Mainz, Germany; [2]Materials Science in Mainz, Johannes Gutenberg University Mainz, Mainz, Germany.

The three key requirements for spintronics devices are: (i) stable spin structures for long term data retention; (ii) efficient spin manipulation for low power devices and (iii) ideally no susceptibility to stray fields as realized for antiferromagnets.
We explore different materials classes to tackle these challenges and explore the science necessary for a disruptive new technology.
To obtain ultimate stability, topological spin structures that emerge due to the Dzyaloshinskii-Moriya interaction (DMI), such as chiral domain walls and skyrmions are used. These possess a high stability and are of key importance for magnetic memories and logic devices [1,2]. We have investigated in detail the dynamics of topological spin structures, such as chiral domain walls that we can move synchronously with field pulses [3]. We determine in tailored multilayers the DMI, which leads to perfectly chiral spin structures.
For ultimately efficient spin manipulation, spin torques are maximized by using highly spin-polarized ferromagnetic materials [2] and using spin-orbit torques, we can efficiently manipulate magnetization [4-6].
We then combine materials with strong spin-orbit torques and strong DMI where novel topologically stabilized skyrmion spin structure emerge [5]. Using spin-orbit torques we demonstrate in optimized low pinning materials for the first time that we can move a train of skyrmions in a “racetrack”-type device reliably [5,6]. We find that skyrmions exhibit a skyrmion Hall effect leading to a component of the displacement perpendicular to the current flow [6]. We study the field - induced dynamics of skyrmions [7] and find that the trajectory of the skyrmion’s position is accurately described by our quasi particle equation of motion.
While thus highly reproducible driven skyrmion motion is possible, we have recently developed new ultra-low pinning multilayer stacks, which exhibit thermally activated dynamics of skyrmions [8]. Here the energy landscape is sufficiently flat so that we observe pure diffusive motion of skyrmion quasiparticles at room temperature [8]. Furthermore, in contrast to the analytical calculations, we find a strong temperature dependence of the diffusion and explain these observations based on thermally activated excitations. Finally we can employ skyrmion diffusion in a skyrmion reshuffler device enabling novel stochastic computing approaches [8].

References:
[1] O. Boulle et al., Mater. Sci. Eng. R 72, 159 (2011).
[2] M. Jourdan et al, Nat. Comm. 5, 3974 (2014).
[3] J.-S. Kim et al., Nat. Comm. 5, 3429 (2014).
[4] J. Cramer et al., Nano Lett. 18, 1064 (2018). T. Seifert et al., Nat. Comm. (in press 2018), arxiv:1709.00768.
[5] S. Woo et al., Nat. Mat. 15, 501 (2016); S. Jaiswal et al., APL 111, 022409 (2017).
[6] K. Litzius et al., Nat. Phys. 13, 170 (2017). K. Litzius et al., (in preparation)
[7] F. Büttner et al., Nat. Phys. 11, 225 (2015).
[8] C. Schütte et al., PRB 90, 174434 (2014); J. Zazvorka, M. Kläui et al., arxiv:1805.05924

**2:00 PM *EP02.01.02**
**Real-Space Observation of Topological Spin Textures and Their Dynamics in Thin Chiral-Lattice Magnets** Xiuzhen Yu; RIKEN CEMS, Saitama, Japan.

The topological spin textures have recently attracted enormous attention owing to their topological nature and emergent electromagnetic properties[1)]. Here, I will present real-space observations of nanometer-scale topological spin textures and their lattice forms, such as meron-antimeron square lattice (sq.-ML), hexagonal skyrmion lattice (hex-SkL) and their structural transition from the sq.-ML into hex-SkL with finely tuning the magnetic field which is applied normally to a thin chiral-lattice magnet, $Co_8Zn_9Mn_3$. The topological phase transition between a hex-SkL phase and non-topological spin textures, helical or conical structure, have been demonstrated by means of the *in-situ* Lorentz transformation electron microscopy observations with current excitation[2)] or quenching the thermal equilibrium SkL in thin helimagnets[3)]. In addition, the skyrmion dynamics, such as the Brownian motion of skyrmion in a chiral-lattice insulator, the collective transformation of sparsely-populated skyrmions to microcrystals of skyrmions, and the current-driven skyrmion motion will be shown.

These works were done in collaborations with Profs. Yoshinori Tokura, Naoto Nagaosa, Masashi Kawasaki, Taka-hisa Arima, Maximam Mostovoy, Yusuke Tokunaga, Fumitaka Kagawa and Masahiko Mochizuki and Drs. Tasujiro Taguchi, Wataru Koshibae, Shinichro Seki, Naoya Kanazawa, Tomoyuki Yokouchi, Daisuke Morikawa, Masao Nakamura, Kiyou Shibata, and Yoshio Kaneko.

**References:**

1) Nagaosa, N. & Tokura, Y. *Nat. Nanotechnol*. 8, 899 (2013).
2) X. Z. Yu, et al. *Adv. Mater.* 29, 1606178 (2017).
3) X. Z. Yu, D. Morikawa, T. Yokouchi, K. Shibata, N. Kanazawa, F. Kagawa, T.-H.Arima and Y. Tokura, *Nature Physics*, DOI:10.1038/s41567-018-0155-3 (2018).

**2:30 PM BREAK**

SESSION EP02.02: New Materials for Magnetic Skyrmions
Session Chairs: Christopher Marrows and Yuriy Mokrousov
Wednesday Afternoon, November 28, 2018
Hynes, Level 2, Room 204

**3:30 PM *EP02.02.01**

**Topology, Non-Collinear Spin Structures and Skyrmions in Heusler Compounds** Claudia Felser[1], Stuart Parkin[2], Chandra Shekhar[1] and Ajaya K. Nayak[2, 3]; [1]Max Planck Institute Chemical Physics of Solids, Dresden, Germany; [2]Max Planck Institute of Microstructure Physics, Halle, Germany; [3]School of Physical Sciences, National Institute of Science Education and Research (NISER), Bhubaneswar, India.

Topological insulators (TIs), Weyl and Dirac semimetals are new quantum states of matter, which have attracted considerable interest from the condensed matter community. Heusler compounds are a remarkable class of materials which exhibit a wide range of extraordinary multi-functionalities including tunable topological insulators, half metallic ferromagnets and non collinear topological spin structures [1]. The required band inversion has already been unambiguously identified by angle-resolved photoemission (ARPES) and transport [2]. Weyl and Dirac semimetals open up new research directions and applications that result from the large Berry phases that they exhibit: these lead to giant anomalous Hall effect (AHE), spin Hall effects (SHE) and topological spin structures. In the C1b Heusler compounds such as GdPtBi, the inclusion of rare earth atoms allows the use of magnetic exchange fields to induce Weyl points in magnetic fields, which break time-reversal symmetry [3-5]. However, even antiferromagnetic Manganese-rich Heusler compounds can be designed with frustrated spins, large Berry curvature as a consequence of Weyl points close to the Fermi energy [6]: this has recently been proven via a giant AHE for single crystals of $Mn_3Sn$ and $Mn_3Ge$ [7,8]. In general Mn-rich Heusler compounds with heavy transition metals such as $Mn_2RnSn$ show a large Dzyaloshinskii-Moriya interaction (DMI) and therefore non-collinear spin structures [9,10]. Skyrmions, topologically stable spin textures, are of great interest for new generations of spintronic devices. Depending on the crystal symmetries, two distinct types of swirling of the skyrmions, named Bloch and Neel types, have been observed experimentally. In a family of acentric tetragonal Heusler compounds with $D_{2d}$ crystal symmetry Skyrmions with a special type of spin-swirling, called antiskyrmions, can even realized. The interplay between the anisotropic exchange and DMI modifies a helical magnetic phase that propagates in the tetragonal basal plane into antiskyrmions arranged on a hexagonal lattice. The flexibility of their manipulation in the present system is demonstrated by the achievement of antiskyrmions up to 400 K and their zero field metastable state at low temperatures [11]. The family of tetragonal Heusler materials including non-collinear spin structures and Skyrmions opens a new spintronics direction including the realization of skyrmionics.

[1] Graf, et al., Progress in Solid State Chemistry 39 1 (2011)
[2] Liu, et al., Nature Communication **7,** 12924 (2016)
[3] Hirschberger et al. Nature Mat. **15**, 1161 (2016)
[4] Shekhar, et al. arXiv: 1604.01641

**4:00 PM EP02.02.02**

**Terbium, Europium and Thulium Iron Garnets as a Platform for Insulator Spintronics** Ethan Rosenberg, Jackson A. Bauer, Lukas Beran, Can Onur Avci, Bingqian Song, Geoffrey Beach and Caroline A. Ross; Massachusetts Institute of Technology, Cambridge, Massachusetts, United States.

Rare earth (RE) garnets with formula RE_3Fe_5O_12 provide a rich class of ferrimagnetic insulators in which anisotropy, saturation magnetization and compensation temperature can be tuned by choice of rare earth, ratio of rare earth to iron, and oxygen off-stoichiometry. Here we describe the growth, magnetic and spintronic properties of epitaxial terbium iron garnet (TbIG) and europium iron garnet (EuIG) thin films with perpendicular magnetic anisotropy (PMA), in comparison to the better-studied thulium iron garnet (TmIG). Reciprocal space mapping shows that all the films are lattice matched to gadolinium gallium garnet (GGG) or substituted GGG (SGGG) substrates without strain relaxation, even for films up to 56 nm thick. The PMA is governed by magnetoelastic anisotropy, and bopth EuIG and TbIG are under in-plane compression on GGG. EuIG exhibits PMA for both (111) and (100) GGG orientations whereas TbIG exhibits PMA for (111) but not (100) GGG, as expected from the sign of the magnetostriction coefficients. In contrast, TbIG on SGGG (111) is in tension and has an in-plane easy axis. Films grown at higher oxygen pressures have excess rare earth which is believed to replace $Fe^{3+}$ on the octahedral sites, altering the sublattice magnetization. TbIG films have a compensation temperature of around 330K. The EuIG films have damping parameter of 0.025, whereas damping in TmIG is 0.016 and increases when a Pt overlayer is added. Polycrystalline EuIG was grown on a range of substrates and showed PMA when the thermal expansion mismatch led to in plane compression. Anomalous Hall effect (AHE) measurements of Pt/EuIG/GGG Hall crosses show that the spin mixing conductance of Pt/EuIG is orientation-dependent, with values for (111) EuIG being an order of magnitude larger than those of (001) EuIG. AHE measurements of Pt/TbIG/GGG Hall crosses reveal a sign change in the AHE amplitude at the compensation point, analogous to all-metallic Pt/ferrimagnet systems, and indicating that the spin Hall magnetoresistance-induced AHE is dominated by the Fe sublattice rather than the net magnetization. Pt/TmIG/GGG showed a Dzyaloshinskii-Moriya interaction (DMI) field of ~50 Oe, sufficient to stabilize homochiral Neel-type domain walls in 5 nm thick TmIG. Moreover, magnetic imaging showed domain sizes of 10 – 20 nm. These results show that RE garnet/Pt heterostructures are excellent candidates for obtaining skyrmions and other chiral textures at room temperature.

**4:15 PM EP02.02.03**

**Current-Driven Dynamics of Chiral Domain Walls in Thulium Iron Garnet/Platinum Bilayers** Can Onur Avci, Ethan Rosenberg, Lucas M. Caretta, Lukas Beran, Felix Buettner, Caroline A. Ross and Geoffrey Beach; Massachusetts Institute of Technology, Cambridge, Massachusetts, United States.

Magnetic insulators (MIs), especially iron-based garnets, possess remarkable properties such as ultralow damping, long magnon decay lengths and high structural quality which can provide significant advantages for practical applications with respect to their metallic magnetic counterparts. Recently, robust perpendicular magnetic anisotropy is obtained in ferrimagnetic thin films of thulium, europium, and terbium iron garnet (TmIG, EuIG, and TbIG) grown on Gadolinium Gallium Garnet substrates down to a thickness of 5.1 nm with saturation magnetization close to the bulk value [1,2]. By using the spin Hall effect in Pt we have demonstrated efficient spin current injection through the TmIG/Pt interface, which we quantified by the spin Hall magnetoresistance and harmonic Hall effect measurements [1-3]. This spin current is strong enough to realize deterministic spin-orbit torque-driven magnetization switching of TmIG(~10 nm)/Pt bilayer both with quasi-dc (5 ms) as well as pulsed currents down to 2 ns width[1,4]. The switching current density through Pt is found to be of the order of ~10^7 (~10^8) A/cm2 using dc (pulsed) current, comparable to the reported values, e.g., for Pt/Co[5]. We then investigated the structure and current-driven dynamics of domain walls in TmIG/Pt bilayer. We found that, solely using electrical currents, domain walls can be efficiently moved indicating the presence of Neel-type domain wall texture in this system. Detailed analysis revealed that homochiral domain walls are stabilized by the Dzyaloshinkii-Moriya interaction occurring at the TmIG/Pt interface which produces an effective field of ~50 Oe. By using nanosecond-long pulses we determined the current-driven domain wall intrinsic velocities of the order of ~800 m/s per current densities as low as $1.2\times10^{12}$ A/m$^2$, one of the highest reported in any ferromagnetic system thus far. In this presentation, along with the above findings, we will discuss the scanning transmission x-ray microscopy imaging of chiral textures in TmIG/Pt and the possibility of obtaining skyrmions in rare earth-based garnets at room temperature.
[1] Avci et al., Nat. Mater. 16, 309 (2017); [2]Quindeau et al., Adv. Elec. Mater. 3, 1600376 (2017); [3]Avci et al., PRB 95, 115428 (2017); [4]Avci et al., APL 111, 072406 (2017); [5]Miron et al., Nature 476, 189 (2011).

**4:30 PM EP02.02.04**
**Rare Earth-Transition Metal Alloys as Promising Materials for Small Skyrmions and Ultrafast Chiral Spin Texture Dynamics** Lucas M. Caretta[1], Maxwell Mann[1], Felix Buettner[1], Kohei Ueda[1], Bastian Pfau[2], Cristian Guenther[2], Piet Hessing[2], Alexandra Churikova[1], Christpher Klose[2], M Schneider[2], D Engel[2], Colin Marcus[1], David Bono[1], Kai Bagschik[3], Stefan Eisebitt[2] and Geoffrey Beach[1]; [1]Massachusetts Institute of Technology, Cambridge, Massachusetts, United States; [2]Max-Born Institute, Berlin, Germany; [3]DESY, Hamburg, Germany.

Spintronics is a research field geared towards understanding and controlling spins on the nanoscale, enabling next-generation data storage and manipulation. Ultimately, the technological and scientific challenge is to create ultrasmall solid-state magnetic bits (<10 nm) and to control their motion efficiently with ultrahigh velocities (>1 km/s). Inspired by materials used for hard disk drives, research so far has focused on ferromagnetic materials. However, these materials show fundamental limits for speed and size making applications unlikely. Ferromagnetic materials have large stray fields, causing ferromagnetic spin textures to repel each other over long distances. Stray field interactions also lead to a preferred demagnetization of the material, i.e., skyrmions are large (>100 nm) if they are not assisted by external fields or strong pinning. In addition, the velocity of magnetic solitons is fundamentally limited by the precessional dynamics underlying any coherent spin texture displacements, ultimately making motion inefficient. For skyrmions, the velocity is also limited by stripe-out instabilities and by topological damping. In both cases, the observed skyrmion velocities in ferromagnetic materials have always been lower than ~100 m/s. Moreover, ferromagnetic skyrmions suffer from a large skyrmion Hall angle and from topological damping. These fundamental limitations of ferromagnets call for new materials systems.
Here, we demonstrate that compensated rare earth - transition metal ferrimagnets (FiM) are not affected by these limits. FiM, comprised of two antiferromagnetically coupled sublattices, have two compensation temperatures: the magnetization compensation temperature $T_M$, defined by $M_s(T_M)=0$, and the angular momentum compensation temperature $T_A$ with vanishing spin density $S(T_A)=0$. Near $T_A$, the spins align with the magnetic field without any precession and a driving force immediately leads to acceleration in the direction of force. Near $T_M$, stray fields become negligible and spin textures are stabilized by the competition of local exchange, anisotropy, and Dzyaloshinskii-Moriya interaction (DMI). Thus, zero field skyrmions with less than 10 nm in diameter can be realized at room temperature and interactions skyrmions is completely suppressed. In other words, very efficient dynamics are expected to occur near $T_A$, and very small spin textures can be realized at $T_M$. Using these concepts in ferrimagnetic Pt/GdCo/Ta films, we realize a record-fast current-driven domain wall velocity of 1.3 km/s and record small room-temperature stable ~10 nm diameter skyrmions near $T_A$ and $T_M$, respectively. Moreover, $T_A$ and $T_M$ are engineered to be near each other and near room temperature for both fast dynamics and small textures. Compensated FiM are a promising spintronics candidate, as a range of easily accessible knobs, such as interfaces, annealing, sample temperature, and composition can control their properties.

**4:45 PM EP02.02.05**
**Electrical-Field-Control of Ferromagnetism and Magnetic Skyrmions in 2D CrI3 Monolayers** Pinghui Mo[1], Mengchao Shi[1], Jiwu Lu[1] and Jie Liu[1, 2]; [1]College of Electrical and Information Engineering, Hunan University, Changsha, China; [2]Department of Electrical Engineering, University of Washington, Seattle, Washington, United States.

We report our recent research findings about the electrical-field-controllability of ferromagnetism and magnetic Skyrmions in two-dimensional chromium tri-iodide monolayers [1][2]. By combining the fully first-principles non-collinear self-consistent field density functional theory (DFT) with relativistic spin-orbital coupling effects and the Monte Carlo calculations, we show that, an externally-applied out-of-plane electrical field can significantly alter the spin configuration of a free-standing two-dimensional chromium tri-iodide (CrI3) ferromagnetic monolayer.

The electrical-field-dependent Dzyaloshinskii-Moriya interaction, magnetocrystalline anisotropy, and magnetic exchange effects are quantitatively analyzed. It is shown that, by taking advantage of the counterbalancing effects of anisotropic symmetric exchange energy and antisymmetric exchange energy, the intrinsic ferromagnetism can be manipulated by externally applied out-of-plane electric fields. It is revealed that the out-of-plane electrical field could induce topologically-protected Neel-type Skyrmion ground state due to the breaking of inversion symmetry. By taking advantage of the above-mentioned properties, it is shown that 4-level data can be stored in a single monolayer-based spintronic device, which is of practical interests to realize the next-generation energy-efficient quaternary logic devices and multilevel memory devices.

Reference:
[1] Jie Liu, Mengchao Shi, Pinghui Mo, Jiwu Lu, "Electrical-field-induced magnetic Skyrmion ground state in a two-dimensional chromium tri-iodide ferromagnetic monolayer". AIP Advances, 8, 055316 (2018). DOI: 10.1063/1.5030441
[2] Jie Liu, Mengchao Shi, Jiwu Lu, M. P. Anantram, "Analysis of electrical-field-dependent Dzyaloshinskii-Moriya interaction and magnetocrystalline anisotropy in a two-dimensional ferromagnetic monolayer", Physical Review B 97, 054416 (2018). DOI: 10.1103/PhysRevB.97.054416

SESSION EP02.03: Nucleation and Stabilization of Magnetic Skyrmions
Session Chairs: Karin Everschor-Sitte and Song Jin

Thursday Morning, November 29, 2018
Hynes, Level 2, Room 204

**8:00 AM *EP02.03.01**
**Electrical Writing, Processing and Deleting of Room-Temperature Ferrimagnetic Skyrmions** Seonghoon Woo; Korea Institute of Science and Technology, Seoul, Korea (the Republic of).

In spintronics, magnetic skyrmions are one of the most promising candidate for the next-generation memory-type application due to their nanometer-size, topological stability and efficient current-driven motion. [1] Recent efforts have realized the room-temperature stabilization of magnetic skyrmions and their current pulse-induced dynamic behaviours on nanotracks in magnetic heterostructures. [2, 3] However, there still exist many practical limitations for the realization of fully functional skyrmionic devices. In this presentation, we show our recent experimental demonstrations of the electrical writing, processing, and deleting of ferrimagnetic skyrmions observed by static and dynamic soft X-ray transmission microscopy.
We first demonstrate a new type of skyrmion, called *ferrimagnetic skyrmion*. Ferromagnetic skyrmions show undesirable topological effect, the skyrmion Hall effect, which leads to their current-driven motion towards device edges, where skyrmions could easily be annihilated by topographic defects. In this work, we present the stabilization of antiferromagnetically exchange-coupled skyrmions – ferrimagnetic skyrmions - and their current-driven dynamics in GdFeCo films. We demonstrate that ferrimagnetic skyrmions can move at a velocity of ~50 m $s^{-1}$ with significantly reduced skyrmion Hall angle, $\theta_{SkHE} <$ 20°, which highlights the possibility to build more reliable skyrmionic devices using ferrimagnetic and antiferromagnetic materials. [4]
Using the same material, we then demonstrate the electrical writing and subsequent deleting of a single magnetic skyrmion at room temperature, which are essential prerequisites for device application but have remained elusive so far. We also present that the number of written and destroyed skyrmions can be controlled by modulating the strength of spin orbit torques. The stroboscopic pump-probe X-ray measurement serves as a key technique to reveal the deterministic and completely reproducible nature of the observation. Micromagnetic simulations reveal the microscopic origin behind the observed topological fluctuation with great qualitative and quantitative agreement. Our findings show that the deterministic field-free writing and deleting of magnetic skyrmions can be readily achieved using electrical methods, which leap over a crucial hurdle toward building a practical skyrmionic device. [5]

**References.**
1. A. Fert *et al., Nat. Nanotechnol.* 8, 152–156 (2013).
2. S. Woo *et al.*, *Nat. Mater.* 15, 501–506 (2016).
3. S. Woo *et al.*, *Nat. Commun.* 8, 15573 (2017).
4. S. Woo *et al.*, *Nat. Commun.* 9, 959 (2018).
5. S. Woo *et al.*, *Nat. Electron.* 1, 288-296 (2018).

**8:30 AM EP02.03.02**
**Isolated Magnetic Skyrmions—From a Fundamental Understanding to the Observation of Ultrasmall Skyrmions at Room Temperature** Felix Buettner[1], Ivan Lemesh[1], Lucas M. Caretta[1], Maxwell Mann[1], Kohei Ueda[1], Bastian Pfau[2], Christian Günther[3], Piet Hessing[2], Alexandra Churikova[1], M Schneider[2], D Engel[2], Christpher Klose[2], Kai Bagschik[4], Stefan Eisebitt[2, 3] and Geoffrey Beach[1]; [1]Massachusetts Institute of Technology, Cambridge, United Kingdom; [2]Max Born Institut, Berlin, Germany; [3]Technische Universität Berlin, Berlin, Germany; [4]DESY, Hamburg, Germany.

Skyrmions are the smallest non-trivial entities in magnetism with great potential for data storage applications. They were recently observed at room temperature in magnetic multilayer systems [1-4], most of them in materials with sizable Dyzaloshinskii-Moriya interaction (DMI). Despite this experimental breakthrough, our understanding of skyrmions is still limited because existing theories cannot analytically predict how the skyrmion energy changes as a function of its size. In particular, for many decades, the 6-fold integral of the stray field energies was considered unsolvable and the contributions of DMI and stray fields to stabilizing skyrmions could not be distinguished.

This problem has now been solved. In this talk, I will present a unified theory that analytically approximates the energy, including stray fields, of isolated skyrmions of all sizes with 1% precision [5]. I will show that there are indeed two types of skyrmions, 'stray field skyrmions' and 'DMI skyrmions', but in contrast to common belief it is not the domain wall angle (Neel or Bloch type) that distinguishes these two types. Surprisingly, the type of skyrmion is also not a material property: DMI and stray field skyrmions can even co-exist in the same material at the same field. This form of bi-stability opens a whole new area of potential skyrmion applications.

There is a strong desire to make room-temperature skyrmions small and to move them fast. However, all room temperature skyrmions observed so far are stray field skyrmions, and I will show that this fundamentally limits their stable size to much larger than 10 nm at room temperature. By contrast, DMI skyrmions can be smaller than 10 nm even at room temperature and zero applied field. All presently available data indicates that such skyrmions cannot exist in ferromagnetic materials. Instead, ferrimagnets and antiferromagnets are the most promising materials for finding room-temperature DMI skyrmions. This theoretical prediction is confirmed by our first observation of sub-15 nm skyrmions in a ferrimagnetic material with strong DMI, where we also confirm that these skyrmions remain stable and retain their size at zero applied field.

[1] Büttner et al., Nat Phys. 11, 225 (2015).
[2] Woo et al., Nat Mater. 15, 501 (2016).
[3] Moreau-Luchaire et al., Nat Nano. 11, 444 (2016).
[4] Boulle et al., Nat Nano. 11, 449 (2016).
[5] Büttner et al., Sci. Rep. 8, 4464 (2018).

**8:45 AM *EP02.03.03**
**Stability and Manipulation of Magnetic Skyrmions** Giovanni Finocchio; University of Messina, Messina, Italy.

Magnetic skyrmions are topological protected solitons with a chirality that can be stabilized by the Dzyaloshinskii-Moriya interaction (DMI). Understanding the physical properties of magnetic skyrmions is important for fundamental research with the aim to develop new spintronic device paradigms where both logic and memory can be integrated at the same level or for unconventional computing. We have recently studied different mechanism of stabilization of skyrmions in confined devices, one of them needs a large DMI to introduce in the energy landscape an energetic minimum associated with a metastable skyrmion state and one that gives a skyrmion state which size depends on a trade off among magnetostatic, exchange and DMI energies. In this invited talk, we will show a universal model based on the micromagnetic formalism combining a proper ansatz and scaling relationships and a specific Q-d phase space (quality factor Q vs. reduced DMI d) that can be used to study skyrmion stability as a function of magnetic field and temperature[1]. We consider ultrathin, circular ferromagnetic magnetic dots. Those results show that magnetic skyrmions with a small radius—compared to the dot radius—are always metastable, while large radius skyrmions form a stable ground state. The change of energy profile determines the weak (strong) size dependence of the metastable (stable) skyrmion as a function of temperature and/or field. We also show as this fundamental results can be used for specific application in a racetrack memory device where the skyrmions in the track are metastable and therefore small—giving a high storage density while are detected under a magnetic tunnel junction having a polarized layer with a magnetization pointing along the out-of-plane direction which generates a dipolar field parallel to the skyrmion core magnetization [1]. This field can modify the stability properties of the skyrmion in the region below the contact, moving it through the Q-d phase space. By shifting the skyrmions across the line of stability, their radius will expand significantly making it much easier to detect from the tunnel magnetoresistance signal. After leaving the detection regions, the skyrmions will return to their small size in the metastable region. Finally, I will discuss the SHE-driven dynamics of a skyrmion in presence of an anisotropy gradient showing a scenario where the skyrmion is accelerated[2].

[1] R. Tomasello, et al Phys. Rev B 97, 060402(R) (2018)
[2]R. Tomasello, et al arXiv:1706.07569v2 (https://arxiv.org/abs/1706.07569).

**9:15 AM *EP02.03.04**

**Skyrmions Stabilized in Magnetic Heterostructures** Suzanne G. Te Velthuis; Materials Science Division, Argonne National Laboratory, Argonne, Illinois, United States.

Magnetic skyrmions are topologically stable spin textures exhibiting quasi-particle like behavior and consequently can be directed with low electric currents. The controlled manipulation of magnetic skyrmions at room temperature in thin films is envisioned to enable skyrmion-based low-power information technologies, and consequently has engaged the interest of the scientific community in recent years [1]. Using trilayered heterostructures we have demonstrate how diverging electric charge currents combined with the spin Hall effect in a heavy metal layer can be used to generate and manipulate magnetic Néel skyrmions in an adjacent ferromagnetic layer [2,3]. Under application of homogeneous currents, the motion of magnetic skyrmions is experimentally shown to exhibit transverse motion relative to the current direction, i.e., the skyrmion Hall effect [4]. This effect arises due to the non-trivial topological charge of the skyrmions and is the analogue of the ordinary Hall effect for electrical charges in the presence of a magnetic field. With increasing current density, the skyrmion Hall angle first increases monotonically, which can be linked to the influence of pinning by defects, and then saturates, indicating the flow regime for motion has been reached. From an applications perspective, minimizing the skyrmion size is equally important to controlling the creation and motion of skyrmions. To this end, we have investigated inversion asymmetric $[Pt/FM/X]_N$multilayers, where FM is a ferro- or ferrimagnet and X a transition or rare earth metal, which allows for various competing interactions to be tuned. Using magneto-optic Kerr imaging and Lorentz transmission electron microscopy, we show how the skyrmion size varies depending on the choice of metal X, the trilayer repetition number N, and the magnetic field.

Work at Argonne was supported by the Department of Energy, Office of Science, Basic Energy Science, Materials Sciences and Engineering Division.

[1] W. Jiang, *et al.*, Physics Reports **704**, 1 (2017).
[2] W. Jiang, *et al.,* Science **349**, 283 (2015).
[3] O. Heinonen, *et al.,* Phys. Rev. B **93**, 094407 (2016).
[4] W. Jiang, *et al.*, Nature Phys. **13**, 162 (2017).

**9:45 AM BREAK**

**10:15 AM *EP02.03.05**

**The Skyrmion-Bubble Transition in a Ferromagnetic Thin Film** Anne Bernand-Mantel, Lorenzo Camosi, Alexis Wartelle, Nicolas Rougemaille, Michael Darques and Laurent Ranno; Institut Néel-CNRS, Grenoble, France.

Magnetic skyrmions and bubbles, observed in ferromagnetic thin films with perpendicular magnetic anisotropy, are topological solitons which differ by their characteristic size and the balance in the energies at the origin of their stabilisation. However, these two spin textures have the same topology and a continuous transformation between them is allowed. In the present work, we derive an analytical model to explore the skyrmion-bubble transition. We evidence a region in the parameter space where both topological soliton solutions coexist and close to which transformations between skyrmion and bubbles are observed as a function of the magnetic field.

The nanoscale size and non-trivial topology of skyrmions make them particularly attractive for information technologies. The recent observations of skyrmions at room temperature and their fast displacement with low electrical currents [1], has triggered a revival of the quest for a memory based on topological solitons, taking the form of a skyrmion racetrack memory [2]. Magnetic bubbles and skyrmions are close relatives as they can share the same topology. However, their characteristic size differs and while classical bubbles present a long lifetime at RT, much shorter lifetimes were found for skyrmions of a few nanometers in recent experimental and theoretical. The case of intermediate-size solitons is more favorable, as stable room-temperature topological solitons with sizes of a few hundred to a few tens of nanometers have been reported in multilayers and even in a single ferromagnetic layer. These topological solitons are sometimes called skyrmion bubbles when the demagnetising energy plays a role in their stabilization. In this context, the necessity to clarify whether a fundamental difference exist between skyrmions and bubbles appears. In previous works, the difference between magnetic bubbles with a large number of collinear spins in their center and skyrmions with a compact core has been described [3]. In the present work [3], we have developed an analytical topological soliton model containing expressions of the long range demagnetising and exchange curvature energies, two key ingredients to stabilize bubbles and skyrmions in ferromagnetic thin films. This allowed us to construct a skyrmion and bubbles phase diagram and explore quantitatively the possible transitions between them. The observed skyrmion-bubble transition present similarities with the liquid-gaz transition, in particular a critical point is present above which the transformation between both spin textures becomes continuous. While distinct characteristics of skyrmions and bubbles remain, their common nature as topological solitons is emphasised.

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**10:45 AM EP02.03.06**

**Skyrmion Lifetimes in Ultrathin Films** Stephan von Malottki[1], Pavel Bessarab[4], Soumyajyoti Haldar[1], Anna Delin[2, 3] and Stefan Heinze[1]; [1]Institute of Theoretical Physics and Astrophysics, University of Kiel, Kiel, Germany; [2]Department of Applied Physics, School of Engineering Sciences, KTH Royal Institute of Technology, Kista, Sweden; [3]Department of Physics and Astronomy, Materials Theory Division, Uppsala University, Uppsala, Sweden; [4]School of Engineering and Natural Sciences, Science Institute, University of Iceland, Reykjavik, Iceland.

The thermal stability of magnetic skyrmions is a key issue for potential applications in spintronic devices. An Arrhenius law can be used to describe the skyrmion lifetime as a function of temperature, which requires knowledge of the energy barrier and the pre-exponential factor. While the energy barrier has already been addressed by several studies (e.g. [1]), the pre-exponential factor for the skyrmion collapse remains largely unexplored [2, 3]. Here, we obtain skyrmion lifetimes by calculating not only the energy barriers but also the pre-exponential factors for ultrathin films such as Pd/Fe bilayers on Ir(111) – a system which has been extensively studied from experiment [4]. We use an atomistic spin model based on parameters from first-principles via density functional theory [1]. In our approach, the minimum energy paths and thereby the energy barriers are calculated using the geodesic nudged elastic band method, while the pre-exponential factors are obtained using harmonic transition state theory [3]. We demonstrate that depending on the system the pre-exponential factor can change by orders of magnitude with magnetic field and thereby becomes crucial for skyrmion lifetimes. With our first-principles based approach we make predictions for the stability of skyrmions in other ultrathin film systems.

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**11:00 AM *EP02.03.07**
**Skyrmions Under the X-Rays** Thorsten Hesjedal[1], Shilei Zhang[1] and G. van der Laan[2]; [1]University of Oxford, Oxford, United Kingdom; [2]Diamond Light Source, Didcot, United Kingdom.

Magnetic skyrmions in noncentrosymmetric chiral magnets form ordered lattices with a periodicity ranging from 3-100 nm. This lengthscale lends itself to soft x-ray scattering experiments owing to the large resonant scattering cross-section for 3*d* elements, the excellent reciprocal space resolution, as well as the tunable surface sensitivity. We will present an overview of the capabilities of resonant elastic x-ray scattering (REXS) for the study of magnetic skyrmions [1], highlighting the following effects:

1) Topology [2]: Using circularly polarized light, REXS is capable to accurately determine the topological winding number of a skyrmion. This topology determination principle is a general experimental strategy, applicable to a wide range of topologically ordered magnetic materials.

2) Microscopic skyrmion properties [3]: By exploiting the polarization dependence of REXS, the exact surface helicity angles of twisted skyrmions for both left- and right-handed chiral bulk $Cu_2OSeO_3$ was determined.

3) Full 3D spin structure of skyrmions [4]: Using polarization-dependent REXS we found a continuous transformation of the skyrmion tubes from pure Néel-twisting at the surface to pure Bloch-twisting in the bulk over a distance of several hundred nanometers.

4) Rotating lattices [5]: In a magnetic field gradient, skyrmions undergo rotation with well-defined dynamics. This provides an effective way of controlling skyrmions in racetrack memory schemes.

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**11:30 AM *EP02.03.08**
**Stabilizing Spin Spirals and Isolated Skyrmions at Low Magnetic Field Exploiting Vanishing Magnetic Anisotropy** Marie Hervé[1], Bertrand Dupé[2], Rafael Lopes[3], Marie Böttcher[2], Maximiliano Martins[3], Timofey Balashov[1], Lukas Gerhard[4], Jairo Sinova[2] and Wulf Wulfhekel[1, 4]; [1]Physikalisches Institut, Karlsruhe Institute of Technology (KIT), Karlsruhe, Germany; [2]Institut für Physik, Johannes Gutenberg Universität Mainz, Mainz, Germany; [3]Serviço de Nanotecnologia Laboratório de Nanoscopia, Centro de Desenvolvimento da Tecnologia Nuclear, Belo Horizonte, Brazil; [4]Institute of Nanotechnology, Karlsruhe Institute of Technology, Karlsuhe, Germany.

Skyrmions are topologically protected non-collinear magnetic structures. The non-collinear Dzyaloshinskii-Moriya interaction originating from spin-orbit coupling drives their formation. The Dzyaloshinskii-Moriya interaction is enhanced at surfaces and interfaces via the hybridization of the magnetic atoms with 5d elements. It competes with Heisenberg exchange and magnetic anisotropy favoring collinear states. Isolated skyrmions in ultra-thin films so far required magnetic fields as high as several Tesla [1]. Here, we show that isolated skyrmions in a monolayer of Co/Ru(0001) can be stabilized down to vanishing fields [2]. Even with the weak spin-orbit coupling of the 4d element Ru, homochiral spin spirals and isolated skyrmions were detected with spin-sensitive scanning tunneling microscopy. Density functional theory calculations explain the stability of the chiral magnetic features by the absence of magnetic anisotropy energy.

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SESSION EP02.04: Transport Properties of Magnetic Skyrmions
Session Chairs: Suzanne Te Velthuis and Jiadong Zang
Thursday Afternoon, November 29, 2018
Hynes, Level 2, Room 204

**1:30 PM *EP02.04.01**
**Tailored Skyrmions in Magnetic Multilayers** Christos Panagopoulos; Nanyang Technological University, Singapore, Singapore.

Multilayers of Ir/Fe(*x*)/Co(*y*)/Pt enable us tailor the magnetic interactions governing skyrmion (Sk) properties, thereby tuning their thermodynamic stability parameter by an order of magnitude. In particular, Sk's exhibit a crossover between isolated (metastable) and disordered lattice configurations across samples, while their size and density can be tuned by factors of 2 and 10, respectively. To study magnetization dynamics, we determined the damping parameter characterizing the magnetization response, and identified a gyrotropic Sk excitation that persists over a wide range of temperatures and across varying sample compositions. To explore the interaction of skyrmions with electrical current we carried a detailed microscopic investigation, which allowed us identify magnetic structures forming via Sk-Sk interaction and their role in designing and interpreting electrical signatures in materials and devices hosting Sk's.

**2:00 PM EP02.04.02**

**Magnetic Imaging and Magnetotransport Measurements of Skyrmion Hosting Cubic B20 $Fe_{1-x}Co_xSi$ and $Fe_{1-x}Co_xGe$ Nanostructures** Nitish Mathur[1], Matthew J. Stolt[1], Sebastian G. Schneider[2], Kodai Niitsu[3], Xiuzhen Yu[3], Bernd F. Rellinghaus[2], Yoshinori Tokura[3] and Song Jin[1]; [1]University of Wisconsin-Madison, Madison, Wisconsin, United States; [2]IFW, Dresden, Germany; [3]RIKEN Center for Emergent Matter Science (CEMS), Wako, Japan.

Magnetic skyrmions are topological spin textures that have shown promise due to their potential application in high density and energy efficient memory nanodevices. Stable skyrmion phase can exist in chiral helimagnets with the non-centrosymmetric cubic B20 crystal structure, such as $Fe_{1-x}Co_xSi$ and FeGe, that have antisymmetric spin exchange interaction known as the Dzyaloshinskii-Moriya interaction (DMI). Nanostructuring further enhance the stability regime of skyrmion phase in these materials to larger range of temperature and applied magnetic field. We have developed "bottom-up" chemical vapor deposition (CVD) synthetic techniques to synthesize single-crystal FeGe nanowires (NWs), and cobalt alloyed $Fe_{1-x}Co_xSi$ (x<0.5) NWs and $Fe_{1-x}Co_xGe$ (x<0.1) nanoplates (NPLs). We have imaged the spin structures in these nanostructures with Lorentz transmission electron microscopy (LTEM) for $Fe_{1-x}Co_xGe$ NPLs and more intensive TEM-based magnetic imaging technique known as off-axis electron holography (EH) for $Fe_{1-x}Co_xSi$ NWs. Further, the evolution of different spin structures under varying applied magnetic field below $T_c$ could be electrically detected by the field-dependent magnetoresistance (MR) measurements which enable us to determine the critical fields for magnetic state transitions at different temperatures. For the $Fe_{1-x}Co_xGe$ NPLs, Hall measurements further revealed the topological Hall effect (THE) characteristics of skyrmion phases. The imaging and transport measurements were used in conjunction with one another to construct representative magnetic phase diagrams for the $Fe_{1-x}Co_xSi$ NWs and $Fe_{1-x}Co_xGe$ NPs respectively. These B20 materials can serve as nice model systems to study skyrmion physics and prototype devices by taking advantage of nanometer-sized magnetic skyrmion domains.

**2:15 PM *EP02.04.03**

**Emergent Transport Effect in Chiral Spin Textures** Yuriy Mokrousov[1, 2], Fabian Lux[1], Jan-Philipp Hanke[1, 2], Matthias Redies[1], Patrick Buhl[1], Frank Freimuth[1] and Stefan Bluegel[1]; [1]Forschungszentrum Juelich, Juelich, Germany; [2]University of Mainz, Institute of Physics, Mainz, Germany.

In the field of skyrmionics the progress in creation and manipulation of skyrmions with various size and charge has been truly remarkable. From the side of theory, in the past years various novel chiral particles such as chiral bobbers or hopfions have been predicted to exist under certain conditions. On the other hand, for experimental discovery and integration of these particles into future generation of devices their realiable detection by means of magnetotransport is imperative. Currently, this presents a significant problem, since our understanding of the transport properties of chiral spin textures is at a very preliminary level. In my talk I will review the recent progress in our understanding of the Hall effects and orbital magnetism exhibited by chiral particles of various nature. In particular, by starting from the adiabatic viewpoint that has been very successful in predicting various physical properties of chiral magnets such as topological Hall and topological spin Hall effects, we will arrive at and unravel the emergence of chiral and topological orbital magnetism in one- and two-dimensional spin systems. We will demonstrate that the emergent orbital magnetism has remarkable properties such as topological quantization, and its dynamics in skyrmionic systems can be used not only to detect the formation of skyrmions with different charge, but also to distinguish various types of dynamical "breathing" modes of skyrmion dynamics. Moreover, we will show that while beyond the adiabatic viewpoint the orbital magnetism of spin textures goes hand in hand with emergent Hall transport properties, remarkably, engineering the details of spin-orbit interaction and electronic structure in interfacial chiral systems allows for tuning the orbital and transport characteristics over orders of magnitude. We trace back such sensitivity of the emergent transport properties to the unique interplay of real-space and reciprocal-space topologies, and demonstrate that the Hall and orbital magnetization measurements can be used to categorize and uncover various topologically distinct phases of complex chiral magnets. This work was supported by Deutsche Forschungsgemeinschaft (projects MO 1731/5-1 and MO 1731/7-1) as well as by the DARPA TEE program through grant MIPR# HR0011831554 from DOI.

**2:45 PM BREAK**

**3:15 PM *EP02.04.04**

**Detection and Manipulation of Magnetic Skyrmions in Metal Silicide and Germanide Nanostructures** Song Jin; University of Wisconsin-Madison, Madison, Wisconsin, United States.

Skyrmions, novel topologically stable spin vortices, hold promise for next-generation magnetic storage due to their nanoscale domains to enable high information storage density and their low threshold for current-driven motion to enable ultralow energy consumption. One-dimensional (1D) nanowires are ideal hosts for skyrmions since they not only serve as a natural platform for magnetic racetrack memory devices but also can stabilize skyrmions. We have developed synthetic methods for nanowires (and nanoplates) of non-centrosymmetic cubic B20 monosilicides (MnSi, FeSi, CoSi) and monogermanides (FeGe) and their alloys (such as $Fe_xCo_{1-x}Si$), many of which display exotic helimagnetic and skyrmion magnetic phases with domain sizes from 10 to 230 nm. Collaborating with several groups, we have used Lorentz TEM, off-axis electron holography (EH), magnetotransport measurements, and dynamic magnetic cantilever measurements to confirm that magnetic skyrmion phases are stable over a larger magnetic field-temperature range in these nanostructures compared to bulk crystals and thin films. Magnetoresistance (MR) measurements revealed the critical magnetic fields for the transitions between different magnetic spin structures at different temperatures. Topological Hall effect (THE) measurements of MnSi nanowires and $Fe_{1-x}Co_xGe$ (x<0.1) nanoplates further confirmed the extended skyrmion stability. Particularly, FeGe nanowires and $Fe_{1-x}Co_xGe$ (x<0.1) nanoplates can host skyrmions with stability up to about 280 K. We have further demonstrated the current-driven motion of skyrmions in this extended skyrmion phase region in MnSi nanowires. These results open up the exploration of nanowires as an attractive platform for investigating skyrmion physics in 1D systems and exploiting skyrmions in magnetic storage concepts.

**3:45 PM *EP02.04.05**

**Various Topological Spin Textures and Emergent Phenomena in B20-Type Chiral Magnets** Naoya Kanazawa; Department of Applied Physics, University of Tokyo, Tokyo, Japan.

Topological properties of skyrmions, such as topological Hall effect and current-driven skyrmion motion, stimulate researches on design of new topological spin textures in pursuit of further novel functionalities. Examples of those spin structures include biskyrmions, Néel-type skyrmions, and chiral soliton lattice. One guiding principle for creating such winding spin textures is utilizing antisymmetric spin exchange interaction, namely Dzyaloshinskii-Moriya (DM) interaction, allowed in crystals without local/global space inversion symmetry.
We have realized various topological magnetic structures in a prototypical skyrmionic material, so-called B20-type compounds, by changing DM interaction, magnetic anisotropy and electronic structure, which are controlled by element substitution and device manufacturing. In this talk, we would like to show our recent results on formations of topological magnetic structures and consequent emergent phenomena in bulks and films of B20-type compounds [1-3].
This work is done in collaboration with K. Akiba, T. Arima, R. Arita, S. Awaji, C. D. Dewhurst, Y. Fujishiro, M. Ichikawa, K. Ishizaka, F. Kagawa, K. Kakurai, M. Kawasaki, A. Kikkawa, S. Kimura, T. Koretsune, Y. Kozuka, H. Mitamura, A. Miyake, D. Morikawa, T. Nakajima, A. Nakamura, K. Ohishi, H. M. Rønnow, K. Shibata, T. Shimojima, J. Shiogai, Y. Taguchi, M. Tokunaga, Y. Tokura, A. Tsukazaki, J. S. White, X. Z. Yu.
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**4:15 PM EP02.04.06**
**Magnetotransport Fingerprints of Bloch Points in Thin Films** Matthias Redies, Fabian Lux, Jan-Philipp Hanke, Patrick Buhl, Stefan Bluegel and Yuriy Mokrousov; Forschungszentrum Jülich, Jülich, Germany.

One of the most crucial aspects for the implementation of skyrmionic devices is the ability to distinguish the emergence of skyrmions by referring to electronic transport measurements [1]. Interestingly, it was recently argued theoretically and later confirmed experimentally [3], that in thin films of chiral magnets an intricate interplay of external fields and temperature with exchange, Dzyaloshinskii-Moriya interactions and magnetic anisotropy can result in the formation of novel chiral particles such as chiral bobbers [2]. This raises the question whether various topologically distinct chiral particles, such as skyrmions and bobbers can be reliably distinguished from each other in magnetotransport experiments [2]. Here, we use the tight-binding description of the electronic structure in combination with the Kubo linear response formalism to access the Hall transport properties and orbital magnetism of the chiral textures in thin films. Our theoretical analysis reveals that a phase transition from skyrmion tubes to chiral bobbers is accompanied by a drastic change in the Hall conductance and an overall enhancement of the orbital moment of the sample. We can trace this effect back to the presence of Bloch points, which can be characterized by a strongly non-collinear distribution of spins on the atomic scale occurring at the tip of the bobber. As a result, while the transport properties of the bobbers are qualitatively different from those exhibited by the skyrmion tubes, in contrast to the skyrmions whose Hall and orbital signal is robust with respect to their width and thickness of the sample, the Hall signatures of bobbers are strongly dependent on their shape and film thickness. We explain our finding based on the complex interplay of the electronic hybridization with the details of the non-collinear arrangement of spins around the Bloch points, and suggest that the remarkable diversity found in the Hall response of spin textures in thin films can provide a solid foundation for integration of skyrmions and bobbers into the future generation of memories and devices [3].

This work was supported by the DARPA TEE program through grant MIPR# HR0011831554 from DOI.

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**4:30 PM *EP02.04.07**
**Strong Topological Hall Effect and Zero-Field Skyrmion Formation in FeGe and Oxide Epitaxial Films** Fengyuan Yang; The Ohio State University, Columbus, Ohio, United States.

Abstract not available.

## SESSION EP02.05: Dynamics of Magnetic Skyrmions
Session Chairs: Anne Bernand-Mantel and Seonghoon Woo
Friday Morning, November 30, 2018
Hynes, Level 2, Room 204

**8:30 AM *EP02.05.01**
**Skyrmions in Magnetic Multilayers at Room Temperature—Manipulation, Electrical Detection and 3D Shaping** Vincent Cros[1], William Legrand[1], Davide Maccariello[1], Jean-Yves Chauleau[2, 1], Fernando Ajejas[1], Sophie Collin[1], Karim Bouzehouane[1], Nicolas Jaouen[2], Nicolas Reyren[1] and Albert Fert[1]; [1]Unité Mixte CNRS/Thales, Palaiseau, France; [2]Synchrotron soleil, Gif sur Yvette, France.

Up to recently, skyrmions were observed only at low temperature but an important effort of research has been recently devoted in several groups to stabilize small (< 100 nm) skyrmions above room temperature (RT) in magnetic multilayers through engineering of interfacial DMI [1].
In this presentation, I will present experimental imaging at RT on small skyrmions (30-80 nm) in several types of multilayers associating magnetic layers of Co and nonmagnetic layers of heavy metals (Pt, Ir, Ru etc…).
First, the talk will be devoted to illustrate the wealth of skyrmions and describe some of our key recent results. We will discuss: i) the **creation** of skyrmions by current pulses and its mechanism (spin transfer torque vs thermal effects) [2], ii) the **detection** of skyrmions (one by one) by Anomalous Hall Effect measurements [3], iii) the **current-induced motion** of skyrmions, the influence of defects on velocity and Skyrmion Hall Angle [2].
Then, we will present some experimental results together with modelling on **shaping skyrmions in 3D** [4] by a control of the relative values of DMI and dipole interactions for a given number of layers experimentally revealed by x-ray magnetic scattering (XRMS) [5] and its impact on spin torque induced dynamics. These advances made in technologically relevant materials opens the way for the development of several concepts of skyrmion based devices going from race-track memory type to MRAM, from still highly silicon-compatible memories, such as multi-level MRAM or skyrmion racetrack memories to disruptive “beyond CMOS” technologies such as neuro-inspired architectures.

Acknowl: EU grant MAGicSky No. FET-Open-665095, FLAG-ERA SoGraph (ANR-15-GRFL-0005), ANR grant TOPSky (ANR-17-CE24-0025) and DARPA MIPR# HR0011831554 for financial support.
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**9:00 AM EP02.05.02**
**Influence of Magnetic Field on Current Induced Skyrmion Motion in Multilayer Systems** Katharina Zeissler[1], Simone Finizio[2], Joerg Raabe[2], Thomas A. Moore[1], Gavin Burnell[1] and Christopher Marrows[1]; [1]University of Leeds, Leeds, United Kingdom; [2]Paul Scherrer Institut, Villigen, Switzerland.

Magnetic quasi-particles such as skyrmions are of importance for novel magnetic information storage designs. In ultrathin multilayer systems skyrmions are stabilised by the interfacial Dzyaloshinskii-Moriya interaction which is present at interfaces between ferromagnets and heavy metals (1). The room temperature stability of skyrmions in these multilayers is a desirable property for technological applications (2-5). Active focal areas are electrical skyrmion detection and manipulation. In the experiment outlined here we stabilized skyrmions in a 2 μm wire of [Pt/CoB/Ir]. Short current pulses (10 ns) were used to move the skyrmions through the wire while a static out of plane magnetic field was applied. Scanning transmission microscopy images were taken after each current pulse. The velocity and Skyrmion Hall angle was evaluated and a field dependence on the Skyrmion Hall angle was observed.

This work was funded by Horizon 2020 MagicSky and has received funding from the EU H2020 research and innovation programme under grant agreement N 654360 having benefitted from the access provided by the Paul Scherrer Institut in Villigen within the framework of the NFFA Europe Transnational Access Activity.

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**9:15 AM *EP02.05.03**
**Skyrmionics with Antiferromagnets** Oleg Tretiakov; Tohoku Univ, Sendai, Japan.

Skyrmions are topologically protected spin textures, which can be used in spintronic devices for information storage and processing. Ferromagnetic skyrmions attracted a lot of attention because they are small in size, better than domain walls at avoiding pinning sites, and can be moved very fast by electric current in ferromagnet/heavy-metal bilayers due to novel spin-orbit torques.

Meanwhile, the ferromagnetic skyrmions also have certain disadvantages to employ them in spintronic devices, such as the presence of stray fields and transverse to current dynamics. To avoid these unwanted effects, we propose a novel topological object: the antiferromagnetic skyrmion. This topological texture has no stray fields and its dynamics are faster compared to its ferromagnetic analogue. More importantly, I will show that due to unusual topology it experiences no skyrmion Hall effect, and thus is a better candidate for spintronic applications. Then I will discuss the lifetimes of both antiferromagnetic and ferromagnetic skyrmions at finite temperatures.

Lastly, I will talk about antiskyrmions -- unusual anisotropic topological objects, which were recently observed in systems with anisotropic Dzyaloshinskii-Moriya interaction. I will explain their lifetimes and current driven dynamics based on the transformation between skyrmion and antiskyrmion. Furthermore, I will make predictions for the antiskyrmion existence and properties in antiferromagnets.

**9:45 AM BREAK**

**10:15 AM *EP02.05.04**
**Skyrmion Dynamics, Nucleation and Stability in Ultrathin Metallic Heterostructures** Geoffrey Beach; Massachusetts Institute of Technology, Cambridge, Massachusetts, United States.

Magnetic skyrmions [1,2] are particle-like chiral spin textures that are topologically protected from being continuously 'unwound'. Their topological nature gives rise to rich behaviors including ordered lattice formation, emergent electrodynamics and robust current-driven displacement by spin-orbit torque. This talk focuses on skyrmions in ultrathin ferromagnetic transition metal multilayers in which interfaces with heavy metals generate a strong Dzyaloshinskii-Moriya interaction (DMI) [3]. Inversion-asymmetric multilayer stacks such as [Pt/CoFeB/MgO]N have been shown to host room-temperature-stable skyrmions and skyrmion lattices, with sizes <50nm and current-driven velocities in excess of 100 m/s [4]. Here, we describe their current-driven creation and dynamics probed with x-ray microscopy, and their stability and materials-based design through an accurate fully-analytical model. Using time-resolved imaging, we demonstrate that in low-pinning CoFeB-based structures, current-induced shifting is repeatable over billions of cycles, and we reveal an analogue to the conventional Hall effect, in which the skyrmion trajectory depends on its topological charge much as a particle in a magnetic field is deflected due to its electric charge [5]. We then demonstrate deterministic current-induced skyrmion writing at sub-nanosecond timescales through the combined action of DMI and spin-orbit torque [6], and show that thermal excitation can drive morphological phase transitions between chiral phases in a controlled way [7]. Finally, we present an analytical framework [8] for computing the energy and structure of any skyrmion in any material, and apply the resulting design principles to experimentally realize room-temperature stable skyrmions with sizes approaching 10nm [9].

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**10:45 AM EP02.05.05**

**Controlling the Dynamical Properties of Single Skyrmions in Magnetic Multilayers by Spin-Orbit Torques** Jan-Philipp Hanke[1, 2], Frank Freimuth[2], Bertrand Dupé[1], Stefan Bluegel[2] and Yuriy Mokrousov[2, 1]; [1]Institute of Physics, Johannes Gutenberg University Mainz, Mainz, Germany; [2]Peter Grünberg Institut and Institute for Advanced Simulation, Forschungszentrum Jülich, Jülich, Germany.

Originating from the interplay of spin-orbit coupling and broken spatial inversion symmetry, the antisymmetric exchange interaction, also known as Dzyaloshinskii-Moriya interaction (DMI), attracts ever-growing attention as it mediates the formation of fascinating chiral spin textures that are perceived to be of great technological relevance, e.g., for future memory devices. Recently, the interfacial DMI was shown to be tunable in magnetic heterostructures of Co sandwiched between different heavy transition metals such as Pt and Ir, heralding bright prospects for the observation of small magnetic skyrmions at room temperature [1,2]. In this context, the phenomenon of current-induced spin-orbit torques (SOTs) can be envisaged to provide a particularly efficient means for controlling and manipulating the dynamical properties of such chiral nano-scale objects. Remarkably, electrically driven switching of the magnetization due to SOTs in inversion-asymmetric crystals has been demonstrated in single ferromagnetic layers [3] and even in antiferromagnets [4].

Here, we apply a recently developed advanced Wannier interpolation for the Berry phase expressions of DMI and SOTs [5,6] to correlate the microscopic origin of these phenomena with the *ab-initio* electronic structure of the considered magnetic trilayers $Ir_{\delta}Pt_{1-\delta}$/Co/Pt and $Au_{\gamma}Pt_{1-\gamma}$/Co/Pt. Strikingly, we find that the DMI changes sign if we tune the chemical composition ratio in these heterostructures, which promotes the corresponding systems as promising candidates for detailed experimental studies of the antisymmetric exchange interaction. While the DMI is nearly isotropic with respect to the orientation of the ferromagnetic Co moments, the current-induced antidamping torques in clean Ir/Co/Pt reveal a particularly pronounced dependence on the magnetization direction according to our density functional theory calculations. Finally, we elucidate how the obtained anisotropy of fieldlike and antidamping SOTs imprints on the general control and manipulation of the dynamical properties of chiral nano-scale spin textures in Co-based trilayers, including in particular magnetic skyrmions and anti-skyrmions. Our *ab initio* results pave the way towards a universal design principle for the skyrmion motion in magnetic multilayers.

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**11:00 AM *EP02.05.06**

**Micromagnetic Simulations of Skyrmion Dynamics at Nonzero Temperature** Jonathan Leliaert; DyNaMat Group, Ghent University, Gent, Belgium.

The dynamics of magnetic skyrmions at nonzero temperatures are governed by the complex interplay between driving forces, thermal fluctuations and material disorder. This interplay leads to rich behavior, e.g. creep , which needs to be fully understood before skyrmions can be reliably used in technological applications like the racetrack memory[1]. Because skyrmions do not always behave as rigid objects, micromagnetic simulations are indispensable to bridge theoretical models and experimental results. To this end, we developed an algorithm offering a twentyfold speedup without a loss of accuracy to perform simulations at nonzero temperatures [2], thus mitigating the problem that large numerical studies were practically infeasible due to the extremely small time steps required. First, a validation of this methodology is shown against theoretical results for skyrmion diffusion [3]. Next, we present a large scale study of the impact of temperature and disorder on the skyrmion motion and compare the results against experimental data of the velocity and skyrmion Hall angle as function of the driving force[4]. [1] A. Fert, et. al, Nat. Nanotech. **8**, 152156 (2013) [2] J.Leliaert, et al,. AIP Adv. **7**, 125010 (2017) [3] J. Miltat, et al., Phys. Rev. B **97**, 214426 (2018) [4] K. Litzius, et al., (under review)

**11:30 AM *EP02.05.07**

**Skrymion Clustering, Creep and Depinning** Charles Reichhardt; Los Alamos National Laboratory, Los Alamos, New Mexico, United States.

We examine skyrmion depinning and sliding dynamics in systems with random and periodic pinning arrays. For finite temperature, we find a skyrmion creep regime where the motion is dominated by thermal jumps or avalanches. In this regime the average skyrmion velocity is finite but the skyrmion Hall angle is zero. At higher drives the skyrmion motion becomes continuous and the skyrmion Hall angle increases from zero to its intrinsic value. In general we find that the skyrmion Hall angle increases with increasing temperature at a fixed drive. We also find that for strong pinning, the moving phases are unstable against the formation of a clustered or segregated state where skyrmions attract one another due to the Magnus force. These results are in agreement with recent continuum based simulations which also show clustering of moving skyrmions when the quenched disorder is strong.

SESSION EP02.06: Emerging Topics in Magnetic Skyrmions
Session Chairs: Shinichiro Seki and Oleg Tretiakov
Friday Afternoon, November 30, 2018
Hynes, Level 2, Room 204

**1:30 PM *EP02.06.01**

**Electric Excitation of Topological Defects in Mott Insulators** Maxim Mostovoy; Zernike Institute for Advanced Materials, University of Groningen, Groningen, Netherlands.

Topological nature of magnetic skyrmions recently observed in chiral magnets is a source of rich and interesting physics. Effective electromagnetic fields acting on electrons and magnons propagating through non-coplanar spin configurations result in unconventional spin, charge and heat transport. Skyrmion dynamics in magnetic conductors under applied electric currents can be used in new magnetic memory and data processing devices.

Mott insulators with competing Heisenberg exchange interactions form a new class of materials where topological magnetic defects, such as skyrmions, can exist in absence of inversion symmetry breaking [1-4]. Skyrmions in centrosymmetric materials have more degrees of freedom and show more complex dynamics than skyrmions in chiral magnets. In addition, the electric polarization induced by non-collinear spin textures couples topological magnetic defects to an applied electric field [5]. The magnetoelectric coupling allows for an electric control of skyrmions in Mott insulators accompanied by low energy losses. In my talk I will discuss stability, dynamics and ferroelectric properties of skyrmions and merons in frustrated magnets. I will also discuss materials that can host these topological defects.

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**2:00 PM EP02.06.02**
**Twisted Domain Walls in Perpendicularly Magnetized Multilayers** Ivan Lemesh and Geoffrey Beach; Materials Science and Engineering, Massachusetts Institute of Technology, Cambridge, Massachusetts, United States.

Multilayer films with perpendicular magnetic anisotropy (PMA) are highly active media in modern magnetic technologies and research. Domain walls in such materials are usually treated either in 2D, similarly to homogeneous magnetic layers (via the so-called effective medium model, in which all the magnetic constants are effectively scaled), or as in multilayers, but with a trivial assumption of a fixed domain wall width $\Delta$ and angle $\psi$ across the layers. However, recently it has been argued that the actual equilibrium configuration of the domain walls in multilayers is rather different. Both $\Delta$ and $\psi$, as revealed from the explicit multilayer simulations in these studies, vary from layer-to-layer, with the Néel-like caps of opposite chirality developing at the bottom and the top layers.

In this work, we rigorously prove that such a twist is indeed a ground state in PMA multilayers and find that it persists even for films with high Dzyaloshinsky-Moriya Interaction (DMI). The key aspect of our work is that it — for the first time — provides an accurate and complete calculation of the magnetostatic energy in multilayers, including the contributions that were inherently ignored in the well-known effective medium model.

By solving the exact magnetostatic integrals, we evaluate the total micromagnetic energy density of the domain walls in multilayers analytically and derive the equilibrium $\Delta$ and $\psi$ in every magnetic layer. We find that the value DMI at which all the layers become Néel (threshold DMI) is underestimated by the earlier 2D model and provide the exact numerical relations for the new 3D model that contains the wall twist. We analyze the exact influence of this twist on the size of the domains and skyrmions and detect notable differences from the expressions provided by the 2D model. We also find that the extraction of DMI from the domain width measurements is highly inaccurate in the region of small and intermediate values of DMI, where the wall twist usually persists.

Finally, we identify the impact of the domain wall twist on the dynamics of skyrmions in multilayers under the influence of injected currents carrying the spin-orbit torque. We show that the skyrmion velocity and skyrmion hall angle derived from the exact multilayer theory can vary significantly compared with the predictions of the 2D model. We provide the numerical multilayer relations that are valid at low and intermediate values of current density (j). We also explore the high-j regime with the help of multilayer micromagnetic simulations and reveal new physical phenomena, such as the domain wall precession that result in the impeded skyrmion motion.

Our findings are confirmed with explicit multilayer micromagnetic simulations. The corresponding paper is under the preparation to be submitted to Physical Review Letters journal.

**2:15 PM *EP02.06.03**
**X-Ray Spectromicroscopy of Non-Trivial Spin Textures and Their Ultrafast Dynamics** Peter Fischer[1, 2]; [1]Lawrence Berkeley National Lab, Berkeley, California, United States; [2]Physics Department, University of California, Santa Cruz, Santa Cruz, California, United States.

Spin textures and their dynamics hold the key to understand and control the properties, behavior and functionalities of novel magnetic materials, which can impact the speed, size and energy efficiency of spin driven technologies. Advanced characterization tools that provide magnetic sensitivity to spin textures at high spatial resolution, ultimately at buried interfaces and in all three dimensions, and at high temporal resolution to capture the spin dynamics across scales, are therefore of large scientific interest.
Magnetic soft X-ray spectro-microscopies [1] provide unique characterization opportunities to study the statics and dynamics of spin textures [2,3] in magnetic materials combining X-ray magnetic circular dichroism (X-MCD) as element specific, quantifiable magnetic contrast mechanism with spatial and temporal resolutions down to fundamental magnetic length and time scales.
Current developments of x-ray sources aim to increase dramatically the coherence of x-rays opening the path to new techniques, such as ptychography [4] or x-ray interferometry that will allow unprecedented studies of nanoscale heterogeneity, complexity, and fluctuations.
We will report a recent study of topological spin textures [5] that were imprinted from the vortex state in a 30nm thin permalloy (Py) nanodisk with diameters from 250-1000nm into a multilayer Ir/Co/Pt film with strong DMI. Using element-specific magnetic soft x-ray microscopy we were able to image the magnetic structure of the Py nanomagnets and the spin texture in the DMI film independently. We found a significant increase of the imprinted domain period (240nm) in the DMI film compared to the free film (180nm). Depending on the size of the nanodisks, we observed a change of the skyrmion diameter, and we found evidence for target Neel skyrmions due to an asymmetric expansion of the domain walls as a function of applied magnetic fields. Further, we will show results from a study at LCLS using x-ray photo correlation spectroscopy (XPCS) with a novel 2-pulse scheme that allowed us to discover an unexpected and drastic change of the correlation times in nanoscale spin fluctuations near phase boundaries, i.e., in the skyrmion phase, and near the boundary with the stripe phase of a multilayered Gd/Fe system [6].

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**2:45 PM BREAK**

**3:15 PM *EP02.06.04**

**Reservoir Computing with Skyrmion Fabrics** Daniele Pinna[1], George Bourianoff[2] and Karin Everschor-Sitte[1]; [1]Johannes Gutenberg University, Mainz, Germany; [2]Intel Corporation (Retired), Austin, Texas, United States.

The topologically protected magnetic spin configurations known as skyrmions offer promising applications due to their stability, mobility and localization. Thanks to their many nanoscale properties, skyrmions have been shown to be promising in many applications ranging from non-volatile memory and spintronic logic devices, to enabling the implementation of unconventional computational standards such as Stochastic computing and Reservoir Computing. Particularly, Reservoir Computing is a type of recursive neural network commonly used for recognizing and predicting spatio-temporal events. Its basic functioning does not require any knowledge of the reservoir topology or node weights for training purposes and can therefore utilize naturally existing networks formed by a wide variety of physical processes.

In this talk we will discuss how a random skyrmion "fabric" composed of skyrmion clusters embedded in a magnetic substrate can be effectively employed to implement a functional reservoir. This is achieved by leveraging the nonlinear resistive response of the individual skyrmions arising from their current dependent anisotropic magneto-resistance effect (AMR). Complex time-varying current signals injected via contacts into the magnetic substrate are shown to be modulated nonlinearly by the fabric's AMR due to the current distribution following paths of least resistance as it traverses the geometry. By tracking resistances across multiple input and output contacts, we show how the instantaneous current distribution effectively carries temporally correlated information about the injected signal. This in turn allows us to numerically demonstrate simple pattern recognition. We argue that the fundamental ingredients for such a device to work are threefold: i) Concurrent probing of the magnetic state; ii) stable ground state when forcings are removed; iii) nonlinear response to input forcing. Whereas we demonstrate this by employing skyrmion fabrics, the basic ingredients should be general enough to spur the interest of the greater magnetism and magnetic materials community to explore novel reservoir computing systems.

**3:45 PM DISCUSSION TIME**

**4:00 PM EP02.06.06**

**Non von Neumann Computing with Skyrmion Diode and Skyrmion Transistor** Linjie Liu, Weijin Chen, Ye Ji and Yue Zheng; State Key Laboratory of Optoelectronic Materials and Technologies, Sun Yat-Sen University, Guangzhou, China.

Magnetic skyrmions are a class of topological defects with non-coplanar swirling spin structure. Recently, they attracted intensive attention for their non-trivial physical properties and potentials in high-density memory and new type spintronic devices. Importantly, latest studies indicate that devices based on skyrmions are particular suitable for so-called Non von Neumann devices, which combine the processing and memory units and avoid large communication cost between them. However, there are few concepts about new types of skyrmion devices until now. This work demonstrates new types of skyrmion devices, which are termed as *skyrmion diode* and *skyrmion transistor*. These devices are based on the interaction between terrace-like structures and skyrmions. Micromagnetic simulation indicates that terrace-like structures can effectively modulate the velocity of skyrmions (in both the directions and the speed), due to the potential energy changes of skyrmions. Further investigation shows that output characteristics of skyrmion diodes are tunable by changing the geometry. Moreover, as a type of basic devices, skyrmion diodes can be coupled with each other to form a new devices with more complex functions. Based on these ideas, we design a skyrmion transistor by coupling two skyrmion diodes. In the transistor, transport characteristics of skyrmions can be controlled by other skyrmions on the gate line. Our study for the first time proposes the concept about skyrmion diodes and their important implication on the design of complex skyrmion devices.

**4:15 PM EP02.06.07**

**Controlling the Configuration of Magnetic Skyrmions Visualized by Full-Field Soft X-Ray Microscopy** Mi-Young Im[1], Soong-Geun Je[1], Jung-Il Hong[2] and Anjan Soumyanarayanan[3]; [1]Lawrence Berkeley National Laboratory, Berkeley, California, United States; [2]DGIST, Daegu, Korea (the Republic of); [3]Data Storage Institute, Singapore, Singapore.

Magnetic skyrmion is a spin structure stabilized by Dzyaloshinskii- Moriya interactions and/or dipolar interactions. Magnetic skyrmions have attracted enormous interests not only because of their fascinating topological character but also due to their potentials in a wealth of technological applications such as high efficient storage and computational devices. In the past couple of years, generating skyrmions at room temperature and realizing their movements have been main research directions and soft X-ray microscopy has been a vital role in such researches [1,2]. Another critical issue in the study of skyrmions has been to tune the topological properties of skyrmions and skyrmion configurations. In our works, we experimentally addressed the issue by direct observation of skyrmions and skyrmion configurations in Pt/Co/Fe/Ir and Pt/Co/Pt multilayered heterostructures utilizing a soft X-ray transmission microscope at Advanced Light Source (XM-1, BL6.1.2), enabling the direct observation of in-plane and out-of-plane magnetic components with a high spatial resolution down to 25 nm. We demonstrated that the properties of skyrmions such as size and density of skyrmions could be controlled by varying Co and Fe thicknesses in Pt/Co/Fe/Ir [3]. Through the work, a platform for investigating functional room temperature skyrmions for the development of skyrmion-based memory devices was established. In Pt/Co/Pt systems, the controllability of skyrmion configurations was investigated. We observed that skyrmion configuration significantly changes by injecting current pulses. Skyrmions could be either created or annihilated by the injected current pulse depending on the strength of applied magnetic field [4]. Our results suggest that the Joule heating plays a critical role in the formation and/or elimination of the bubbles and skyrmions. In the work, the schematic phase diagram for the creation and annihilation of bubbles is presented, suggesting an optimized scheme with the combination of magnetic field and electric current necessary to utilize skyrmions in the practical devices.

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**4:30 PM *EP02.06.08**

**Chiral Domain Walls and Skyrmions in Co/Pd Exchange Coupled Multilayers—Statics and Dynamics** Shawn D. Pollard[1], Joseph Garlow[2], Marco

Beleggia[3], Kaiming Cai[1], Yimei Zhu[2, 4] and Hyunsoo Yang[1]; [1]Department of Electrical and Computer Engineering, National University of Singapore, Singapore, Singapore; [2]Materials Science and Engineering, Stony Brook University, The State University of New York, Stony Brook, New York, United States; [3]Center for Electron Nanoscopy, Technical University of Denmark, Kgs Lyngby, Denmark; [4]Condensed Matter Physics and Materials Science, Brookhaven National Laboratory, Upton, New York, United States.

Magnetic skyrmions in multilayer geometries have gained significant attention in recent years, as they provide the opportunity to simultaneously tune demagnetization, anisotropy, exchange, and interfacial Dzyaloshinskii-Moriya interaction (DMI) energies by varying layer thicknesses and compositions. Here we demonstrate the presence of zero field, room temperature Néel skyrmions in Co/Pd multilayers using Lorentz transmission electron microscopy (L-TEM), investigate their nucleation and annihilation processes [1]. We show this to be a consequence of the strong DMI associated with the Co/Pd multilayer geometry, confirmed with MOKE microscopy imaging of asymmetric bubble expansion. This structure differs from conventional multilayer geometries as, traditionally, a multilayer stack is composed of three different materials, HM1/FM/HM2, where HM1 and HM2 are heavy metals with varying signs of DMI, to prevent cancelation from top and bottom interfaces. Further, due to orbital hybridization of Pd with Co, the entire layer is exchange coupled. Using micromagnetic simulations, we show that this has important consequences in the domain wall structure and can play a role in the dynamics of magnetic skyrmions in magnetic multilayers.

We further extend previous studies using L-TEM to quantify the thickness-averaged domain wall deviation from pure Bloch or Néel states, which originates from the completion between demagnetization and DMI energies. This technique complements measurements such as X-ray resonant magnetic scattering [2] by providing nanoscale maps of the local domain structure. Further, it is sensitive to the magnetization of the entire multilayer stack, allowing for full determination of the averaged structure, unlike various surface sensitive techniques (i.e. photoemission electron microscopy or SEMPA) [3,4]. Using L-TEM, we determine the nature of the domain wall as a function of Co thickness and repetition number. This technique is extendable to other multilayer systems and could allow for the determination of a full magnetic phase diagram of systems with strong interfacial DMI.

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