Skyrmions 2015

Hefei Mini-Workshop on Skyrmions

Program & Abstracts

18th-19th May 2015

Hefei, China

The workshop on magnetic skyrmions

Hefei, China, 18th-19th May 2015

Sponsored by

High Magnetic Field Laboratory of the Chinese Academy of Sciences

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Lecture Program

May 18 (Monday)		
8:30-8:50	Conference Remarks (Mingliang Tian, and Axel Hoffmann)	
8:50-9:25	Chialing Chien	Broken Symmetry, Spin Helix, and Skyrmion in BA20 Magnets
9:25-10:00	Avadh Saxena	Skyrmions, Merons and Monopoles: Topological Excitations in Chiral Magnets
10:00-10:30	Visit the HMFL Lab and Coffee Break (Avadh Saxena)	
10:30-11:05	Youquan Li	Exotic spin orders and their manipulation
11:05-11:40	Gen yin	Coherent itinerant spin transport in a skyrmion spin texture
	Lunch (Haifeng Ding)	
13:30-14:15	Axel Hoffmann	Electric Manipulation of Skyrmions in Metals and Insulators
14:15-14:50	Renchao Che	Tomography, holography and EELS under Lorentz transmission electron microscopy
14:50-15:25	Gong Chen	Imaging and tailoring chirality of domain walls in magnetic films
15:25-15:50	Coffee Break (Yan Zhou)	
15:50-16:25	Haifeng Ding	Two-Dimensional Artificial Skyrmion Crystal Stabilized by Nanopatterning
16:25-16:50	Qingfang Li	Current-induced magnetic skyrmions oscillator
16:50-17:25	Guoping Zhao	Skyrmion-skyrmion and skyrmion-edge repulsions in skyrmion-based racetrack memory
Dinner		
May 19 (Tuesday)(Youquan Li)		
8:30-9:05	Naoya Kanazawa	Skyrmions in bulks and films of B20-type compounds
9:05-9:40	Andreas Bauer	Spin dynamics of skyrmions in chiral magnets
9:40-10:15	Jiadong Zang	Symmetry Analysis of Skyrmionic Helimagnets
10:15-10:45	Coffee Break (Renchao Che)	
10:45-11:20	Yan Zhou	Micromagnetics simulations of magnetic droplet soliton and dynamical magnetic skyrmions
11:20-11:55	Mingliang Tian	Skyrmions in confined geometry
Lunch		

(***) represents the sections chairman

A bus will be used to pick up the customers at 8:10 in the hotel

Broken Symmetry, Spin Helix, and Skyrmion in B20 Magnets

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Traditional magnets with a ferromagnetic ground state are well known scientifically and exploited extensively for technological applications. The cubic B20 magnets with broken inversion symmetry and Dzyaloshinskii-Moriya interaction (DMI) exhibit new magnetic spin helix and Skyrmion states as revealed by neutron diffraction and Lorenz TEM. Using magnetometry and transport measurements we have observed signatures of broken C_4 symmetry and the unique spin helix resistance, revealing the central role of the substantial spin-orbit interaction for the intriguing physics. Skyrmions may be explored for future memory applications as in Skyrmionics.

Skyrmions, Merons and Monopoles: Topological Excitations in Chiral Magnets

Avadh Saxena
(Los Alamos National Lab)

Stable topological excitations such as domain walls and vortices are ubiquitous in condensed matter as well as high energy physics and are responsible for many emergent phenomena. In 2009 a new mesoscopic spin texture called skyrmion was discovered experimentally in certain conducting and insulating magnets. It is now believed to exist in Bose-Einstein condensates, 2D electron gases, superconductors, nematic liquid crystals among many other systems. This topological excitation was originally proposed by Tony Skyrme in 1958 in a nonlinear field theory of baryons. In the temperature-magnetic field phase diagram of chiral magnets, skyrmions form a triangular lattice in the low temperature and intermediate magnetic field region (in thin films). In metallic magnets, skyrmions can be driven by a spin polarized current while in insulating magnets by magnons. The threshold current density to depin skyrmions is 4 to 5 orders of magnitudes weaker than that for magnetic domain walls. The low depinning current makes skyrmions extremely promising for applications in spintronics. I will first attempt to summarize the experiments and present an overview on skyrmions. Then I will demonstrate how increasing the easy-plane anisotropy results in a transition from a triangular lattice of skyrmions to a square lattice and eventually to merons. The latter are essentially half-skyrmions and with half the topological charge. Finally, I will show that under current driving skyrmions tubes can split or merge at certain points leading to the formation of magnetic monopoles and anti-monopoles connected by a Dirac string.

Exotic spin orders and their manipulation

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There has been spectacular progress in the study on multiferroics, which is expected to make a realistic step toward an electrical control of magnetism or four state memories. We propose a tilt Heisenberg model of which the continuum limit is a gauge Landau-Lifshitz equation that provides a unified description for various spin orders appeared. We also propose a mechanism to pin skyrmions in chiral magnet, and find that the position-dependent electric field can induce the Hall motion of the skyrmion. Our studies on electromagnon and the motion of multiferroics domain wall will also be briefly presented, where we demonstrate an electric-field control of spin-wave injection which is expected to offer new opportunities for spin-wave injection, conversion and control by using electric field. Finally, we show the main results of our recent study on the micro-mechanism: spin-orbital driven ferroelectricity; spin-orbital coupling and charge effect in Mott insulators.

Coherent itinerant spin transport in a skyrmion spin texture

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The intrinsic spin Hall effect (SHE) originates from the topology of the Bloch bands in momentum space. The duality between real space and momentum space calls for a spin Hall effect induced from a real-space topology in analogy to the topological Hall effect (THE) of skyrmions. As a Barry’s phase induced Hall effect, the carrier transport within the scale of each magnetic skyrmion cannot be captured using a semi-classical picture. In this study we use the nonequilibrium Green’s function theory (NEGF) to demonstrate the topological spin Hall effect (TSHE) in which a pure transverse spin current is generated from a skyrmion spin texture. When the skyrmion size is smaller than the mean free path of the itinerant spin, the skyrmion dynamical behavior is also dominated by the coherent spin current. At this limit, the itinerant spin does not follow the local spin adiabatically. As a result, the skyrmion dynamics such as the acceleration, skyrmion Hall angle and the interaction to the open boundaries are quite different from the adiabatic picture.

Electric Manipulation of Skyrmions in Metals and Insulators

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In this presentation, two recent examples of electrically manipulating skyrmions are discussed for magnetic multilayer systems, where the skyrmions can be stabilized at room-temperature. The first example is related to skyrmion generation in a metallic multilayer system. Magnetostatically stabilized skyrmion structures, magnetic bubbles, can form in magnetic thin films with perpendicular magnetic anisotropy. By adding an additional layer with strong spin-orbit coupling to the ferromagnet, it is possible to generate an interfacial chiral Dzyaloshinskii Moriya interaction, which stabilizes chiral magnetic domain walls around the bubble, resulting in a skyrmion spin structure. These skyrmion bubbles can then be electrically manipulated utilizing spin Hall effects [1]. This is demonstrated for a Ta/CoFeB/TaO_x trilayer, where skyrmions can be generated via diverging electric charge currents in a process that is similar to droplet formation in surface-tension-driven fluid flow [2]. This provides a practical approach for skyrmion formation on demand. Experimentally we determined the electric current vs. magnetic field phase diagram for the skyrmion formation and we demonstrated the manipulation of the dynamically created skyrmions. The resultant motion of the skyrmion bubbles is characterized by stochastic depinning due to random pinning sites.

Furthermore, the second example shows electric manipulation of skyrmions for an insulating system. The large charge gap makes direct electric manipulation in these materials impossible. Nevertheless, spin Hall effects again provide a pathway for electrical manipulation of skyrmions even for insulators. This was demonstrated for bilayers consisting of $(Y.Bi)_3Fe_5O_{12}$ (YIG:Bi) combined with Pt or W layers. Utilizing magneto-optic imaging □m-sized skyrmion bubbles were observed in these bilayers. Upon subsequent current pulses some of the skyrmion bubbles move, while others are stationary, but reduced their size. This is consistent with different structures of the bubble domain-walls resulting in different topological charges and skyrmion numbers. In addition, distinct features were observed in Hall effect measurements, which directly correlate with changes of the magnetic domain structures.

Work at Argonne was supported by the DOE-OS, MSE. Lithographic patterning was carried out at the Center for Nanoscale Materials, which is supported by DOE-OS, BES (#DE-AC02-06CH11357). Work at UCLA was partially supported by the NSF Nanosystems Engineering Research Center for Translational Applications of Nanoscale Multiferroic Systems (TANMS).

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Tomography, holography and EELS under Lorentz transmission electron microscopy

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Magnetic nanoparticle is important both scientifically and technologically. However, to deeply understand the physical association between microstructure and magnetic property is still in lack. Herein, via a series of advanced transmission electron microscopy (TEM), such as 3-D electron tomography, off-axis electron holography, and electron energy loss spectroscopy (EELS), the microstructure and magnetic property of manganese selenide (MnSe), $L1_0$-FePt, α-Fe/CNTs are comprehensively investigated. (1) Wurtzite MnSe nanocrystals with uniform sizes and tailored shapes were obtained via colloidal approach. The 3-D morphology of the bullet-shaped nanorods has been demonstrated by the advanced TEM 3D-tomography technology. Examinations with HRTEM and EELS show that planar-defect structures such as stacking fault and twin along [001] direction are formed during the bullet-shapes growth. According to careful HRTEM observations, we propose a "quadra-twin core" growth mechanism for the formation of wurtzite MnSe nanotetrapods. Furthermore, the wurtzite MnSe nanocrystals show low-temperature surface spin-glass behavior due to their noncompensated surface spins and the blocking temperatures increase from 8.4 K to 18.5 K with higher surface area/volume ratio of the nanocrystals.

Our results provide a systematical study of wurtzite MnSe nanocrystals. (2) Well-aligned, ferromagnetic FePt nanorods have been fabricated by electron beam-induced deposition using an ultrahigh-vacuum scanning electron microscope. The nanoparticles were identified to be face centered tetragonal fct $L1_0$-FePt phase by electron diffraction and high-resolution transmission electron microscopy. The residual magnetic flux density Br of the nanorods was evaluated to be about 1.53 T via off-axis electron holography, showing a strong ferromagnetic character. (3) The differences of structure and composition between the Fe/CNxnanotubes and Fe/C nanotubes were investigated by EELS. It was found that the morphology of Fe/CNx nanotubes is more corrugated than that of the Fe/C nanotubes due to the incorporation of nitrogen. By comparing the $FeL_{2,3}$ electron energy-loss spectra of Fe/CNx nanotubes to those of the Fe/C nanotubes, the electron states at the interface between Fe and the tubular wall of both Fe/CNx nanotubes and Fe/C nanotubes were investigated. At the boundary between Fe and the wall of a CNx nanotube, the additional electrons contributed from the doped 'pyridinic-like' nitrogen might transfer to the empty 3d orbital of the encapsulated iron, therefore leading to an intensity suppression of the iron $L_{2,3}$ edge and an intensity enhancement of the carbon Kedge.

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Imaging and tailoring chirality of domain walls in magnetic films

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Chirality in magnetic materials is fundamentally interesting and holds potential for logic and memory applications [1,2]. Using spin-polarized low-energy electron microscopy at NCEM, we recently observed chiral domain walls in thin films [3,4]. We developed ways to tailor the Dzyaloshinskii-Moriya interaction, which drives the chirality, by interface engineering [5] and by forming ternary superlattices [6]. We find that spin-textures can be switched between left-handed, right-handed, cycloidal, helical and mixed domain wall structures by controlling uniaxial strain in magnetic films [7]. We also demonstrate an experimental approach to stabilize skyrmions in magnetic multilayers without external magnetic field [8]. These results exemplify the rich physics of chirality associated with interfaces of magnetic materials. This work was done in collaboration with A.T.N'diaye, T.P.Ma, A.Mascaraque, C.Won, Z.Q.Qiu, Y.Z.Wu, and A.K.Schmid.

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Two-Dimensional Artificial Skyrmion Crystal Stabilized by Nanopatterning

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The skyrmion crystal carries a topological charge and a Berry phase in real space and is anticipated to produce unconventional spin-electronic phenomena, such as the topological Hall effect and to exhibit spectacular dynamic properties. Technologically, skyrmion crystal may be exploited as a new class of spintronic material due to its unusual response to an electric charge current and spin current. A skyrmion crystal typically arises from helical spin structures induced by the Dzyaloshinskii–Moriya (DM) interaction. Experimentally, what has impeded its property exploration is that it is only to be found in few systems and within a narrow temperature and magnetic field range.

In this talk, we present a micromagnetic simulation and experimental realization of of a 2D skyrmion crystal, which completely by-passing the need for strong (or, indeed, any) DM interaction[1,2]. The methodology is demonstrated with the computed skyrmion number per unit cell. The samples are fabricated by embedding lithography-patterned arrays of micron-sized Co disks onto Co/Pt multilayer films that have perpendicular magnetic anisotropy. Kerr microscopy reveals that the disks are in the vortex state with controllable circulation. Through comparison of simulated and measured hysteresis loops, we find that the sample can be configured into either skyrmion or non-skyrmion state. The demonstration of a skyrmion crystal at room temperature provides an interesting playground to further explore the unique properties of skyrmion crystals.

1 Sun, L. *et al.* Creating an Artificial Two-Dimensional Skyrmion Crystal by Nanopatterning. *Phys. Rev. Lett.* **110,** 167201 (2013).

2 Miao, B. F. *et al.* Experimental realization of two-dimensional artificial skyrmion crystals at room temperature. *Phys. Rev. B* **90,** 174411 (2014).

Current-induced magnetic skyrmions oscillator

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Spin transfer nano-oscillators (STNOs) are nanoscale devices which are promising candidates for onchip microwave signal sources. For application purposes, they are expected to be nano-sized, to have broad working frequency, narrow spectral linewidth, high output power and low power consumption.In this paper, we demonstrate by micromagnetic simulation that magnetic skyrmions, topologically stable nanoscale magnetization configurations, can be excited into oscillation by a spin-polarized current. Thus, we propose a new kind of STNO using magnetic skyrmions. It is found that the working frequency of this oscillator can range from nearly 0Hz to gigahertz. The linewidth can be smaller than 1 MHz. Furthermore, this device can work at a current density magnitude as small as $10^8 Am^{-2}$, and it is also expected to improve the output power. Our studies may contribute to the development of skyrmion-based microwave generators.

Skyrmion-skyrmion and skyrmion-edge repulsions in skyrmion-based racetrack memory

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Magnetic skyrmions are promising for building next-generation magnetic memories and spintronic devices due to their stability, small size and the extremely low currents needed to move them. In particular, skyrmion-based racetrack memory is attractive for information technology, where skyrmions are used to store information as data bits instead of traditional domain walls. Here we numerically demonstrate the impacts of skyrmion-skyrmion and skyrmion-edge repulsions on the feasibility of skyrmion-based racetrack memory. The reliable and practicable spacing between consecutive skyrmionic bits on the racetrack as well as the ability to adjust it are investigated for the first time as we know . Clogging of skyrmionic bits is found at the end of the racetrack, leading to the reduction of skyrmion size. Further, we demonstrate an effective and simple method to avoid the clogging of skyrmionic bits, which ensures the elimination of skyrmionic bits beyond the reading element. Our results give guidance for the design and development of future skyrmion-based racetrack memory.

Skyrmions in bulks and films of B20-type compounds

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A magnetic skyrmion is a nanometer-scale vortex-like spin structure with topological stability. Since discovery of skyrmions in a B20-type compound of MnSi [1], various properties have been revealed: Lorentz transmission-electron-microscopy (TEM) studies provided firm evidences of skyrmion formation and also found that thin films of B20-type compounds ubiquitously host stable skyrmions over a wide temperature - magnetic field region [2]. Near room-temperature formation of skyrmion crystal was observed in B20-type FeGe [3]. Moreover, motions of skyrmions at low current density (10^5 - 10^6 A/m^2) indicate possible electrical manipulation [4]. Such electrical controllability as well as their stable particle nature highlights potential applications for novel spintronic devices.

In this talk, I will present skyrmion formations in bulks and films of B20-type compounds. Following topics are mainly discussed: (i) Skyrmion formation in a series of B20 germanium compounds [5], (ii) Emergence of 3-dimensional skyrmion crystal state in MnGe [6], (iii) Detection of skyrmions in epitaxial thin films of B20-type compounds [7]. This work was done in collaboration with Center for Emergent Matter Science (CEMS) led by Yoshinori Tokura.

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Spin dynamics of skyrmions in chiral magnets

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In MnSi – the most-investigated Dzyaloshinskii-Moriya-driven chiral magnet – the transition from paramagnetism to helimagnetism in zero field is driven fluctuation-induced first-order by strongly interacting chiral fluctuations as described in the Brazovskii scenario [1]. Magnetic fields quench these fluctuations leading to a field-induced tricritical point (TCP) where the transition becomes mean-field second-order [2]. In addition, MnSi was the first compound, in which a regular arrangement of spin whirls, the so-called skyrmion lattice, was identified in finite fields just below the helimagnetic ordering temperature [3]. Each skyrmion is associated with one quantum of emergent flux resulting in emergent electrodynamics [4] and the possibility to manipulate the magnetic structure using electrical currents at ultra-low densities [5]. While it was established that the unwinding of these topologically non-trivial objects into a helimagnetic state is accomplished via emergent magnetic monopoles [6], it is still unknown how they crystallize from a paramagnetic state.

In order to address this question, we report a comprehensive study combing small-angle neutron scattering and neutron spin echo spectroscopy using the MIEZE technique, which allows to measure under applied magnetic field without loss of energy resolution. The quasi-elastic linewidth recorded by means of MIEZE shows a change of the characteristic spin fluctuations at the TCP, providing microscopic evidence for its existence and hence the Brazovskii scenario. In the field range of the skyrmion lattice, our data suggest the presence of fluctuations with a skyrmionic character already above the onset of static order. These findings are supported by high-resolution specific heat data, measurements of the longitudinal and the transversal ac susceptibility, as well as by all-electrical broadband spectroscopy showing excitations in the GHz range that may be attributed the gyration of skyrmion-like objects [7].

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Symmetry Analysis of Skyrmionic Helimagnets

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Magnetic skyrmion is a topological spin texture observed in several helimagnets. Inspired by the novel physics tracing back to its nontrivial topology and promising applications in next generation memory device and ultra-dense data storage, a full understanding of these materials is an urgent subject. We have analyzed the symmetry of a typical helimagnet family, the B20 compounds, and derived an effective description of the electron conduction therein, which explains recent experiments and suggests other predictions. On the other hand, a similar symmetry analysis leads to a full classification and search strategy of helimagnets. Based on this guideline, we discovered a new helimagnet family, the molybdenum nitride, harboring skyrmions, which is confirmed by magnetic imaging.

Micromagnetics simulations of magnetic droplet soliton and dynamical magnetic skyrmions

YanZhou
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Nanocontact–based (NC) spin-torque oscillators (STO) provide an excellent environment for studying a wide range of exotic nano-magnetic phenomena including localized and propagating spin wave (SW) modes, SW multi-mode coupling, vortices, and antivortices [1-3]. Recent experimental observation of magnetic droplet solitons and skyrmions in NC-STOs and ferromagnetic thin film with perpendicular magnetic anisotropy (PMA) add two new members to the family of distinct and useful nanoscale magnetic objects [2,4]. More recently, creation, control and propagation of skyrmions in magnetic nanostructures with constricted geometries by spin transfer torque (STT) have been studied theoretically and numerically by two independent groups [5-6]. Due to the competition of ferromagnetic exchange coupling, anisotropy energy and Dzyaloshinskii-Moriya interaction (DMI), the droplet and the skyrmion are extremely compact, on the order of 10-100 nm, compared to conventional micrometer sized magnetic bubbles stabilized by dipolar interaction. Spin current injection and applied magnetic fields can further tune the energy landscape to create and control such objects.

In this talk, I will present some of our recent work on micromagnetics simulations of magnetic droplet solitons and skyrmions in constricted geometries. We demonstrate, through numerical simulations and theory, how an magnetic droplet soliton can be nucleated and manipulated in NC-STO, and how an isolated skyrmion can be created and controlled in nanowire geometry. We furthermore propose some new mechanisms for skyrmion creation and manipulation in nanostructures. Our simulations include spin transfer torque, perpendicular magnetic anisotropy and DMI terms and we have mapped out the parameter space spanned by applied magnetic field, current, DMI, exchange, and PMA. The radius of the NC and the disk are found to play important roles due to the confining forces from the boundary. We believe our study is fundamentally important for a better understanding of how to inject and control skyrmions as information carriers in nanoscale hybrid spintronic and magnonic devices.

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Skyrmions in confined Geometry

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In this talk, I will present some of our recent work on the formation and magnetization dynamics of skyrmions in constricted geometries. By using numerical simulations and calculations, we predicted a new magnetic vortexand the field-driven evolution of spin textures in nanodisk of chiral magnets. This theoretical predictions are directly observed in FeGe nanodisk by using high resolution Lorentz TEM. Beyond,

Experimentally, we report the first experimental demonstration of such scheme, where magnetic field-driven skyrmion cluster (SC) states with small numbers of skyrmions were demonstrated to exist on the cross-sections of ultra-narrow single-crystal MnSi nanowires (NWs) with diameters (40 – 60 nm) comparable to the skyrmion lattice constant (18 nm)[3.4]. In contrast to the skyrmion lattice in bulk MnSi samples, the skyrmion clusters lead to anomalous magnetoresistance (MR) behavior measured under magnetic field parallel to the NW long axis, where quantized jumps in MR are observed and directly associated with the change of the skyrmion number in the cluster, which is supported by Monte Carlo simulations. In addition, we report the observation of high resolution Lorentz TEM on the skyrmion chain in FeGe nanostripe. Under the action of applied field, we find that the edge spin distortion originating from the termination of the spin helix at the boundary evolves into highly stable skyrmion chain with controllable position. Accordingly, the width of the nanostripe for hosting single skyrmion chain is significantly extended. These findings demonstrates the geometry defects can be used to control the formation of topologically nontrivial objects. Magnetic vortex with skyrmionic core in a thin nanodisk of chiral magnets.