Dynamics of Magnetic Materials

June 5-7, 2010
The University of Western Ontario
London, Ontario Canada

Workshop Program

http://www.magnetic-north.ca

Magnetic North I : The Dynamics of Magnetic Materials

June 5 to 7, 2010

University Research Park
University of Western Ontario
London, Ontario, Canada

<u>Scientific Organizing Committee:</u>

M.G. Cottam and A.B. MacIsaac (Co-Chairs)	[University of Western Ontario]
J.P. Whitehead and M. Plumer	[Memorial University of Newfoundland]
Can-Ming Hu	[University of Manitoba]

This first of a series of annual workshops in the area of magnetism will consider research related to the materials properties of magnetic systems, on various aspects of the classical physics of these materials (especially the theoretical modeling of magnetic films, spin transport, and nanomagnetic systems). In addition the workshop will consider problems in quantum magnetism such as quantum spin glasses, frustrated spin liquids, and tunnelling in magnetic molecules. For this inaugural workshop the focus will be on the dynamics of magnetic materials as studied using experimental, theoretical and simulation methods. The dynamics of magnetic materials is a field with growing relevance and enormous potential in technological applications of thin films and nanostructures for sensors and data storage.

This is the first workshop organized under the auspices of "Magnetic North", which is an organization of magnetism researchers in Canada and their international collaborators (see the web site at http://www.magneticnorth.mun.ca/). It is a forum for information exchange on individual and group research activities, providing a list of researchers with links to home pages and recent reprints and preprints. There are a broad range of magnetic researchers in Canada, spanning various academic departments and government laboratories using a variety of experimental, theoretical and computational techniques. A goal of Magnetic North is to facilitate the exchange of ideas between researchers and to reveal overlapping interests that can foster useful collaborations, serving also to strengthen the magnetism research community in Canada as a whole. It is anticipated that the next workshop in this series (Magnetic North II) will take place at Memorial University in St. John's, Newfoundland, in June 2011.

A list of the sponsors of the Magnetic North I workshop is presented at the back of this booklet (on the inside cover).

PROGRAM

There are two types of talks: the invited talks (listed in the Program as I.1 to I.11) and contributed talks (listed as C.1 to C15). The times scheduled are 40 minutes for invited talks (to include 5 minutes for questions) and 15 minutes for contributed talks (to include 3 minutes for questions). The session chairs will ensure that these times are adhered to. All talks (along with the lunches and refreshment breaks that are included in the registration) will take place at the Convergence Centre.

There are two social events in the program, both to be held at Windermere Manor. These are the Welcome Reception on the evening of Saturday June 5 and the Workshop Dinner on the evening of Sunday June 6.

The Workshop will end by the middle of the afternoon on Monday June 7 in order that the participants have the option to transfer to the CAP Annual Congress in Toronto.

<u>Saturday, June 5</u> (at Windermere Manor)

6:00 pm to 9:30 pm	Welcome Reception (with distribution of registration materials for the workshop, free refreshments and drinks).	

<u>Sunday, June 6</u> (at the Convergence Centre)

8:30 am to 9:00 am	Further distribution of workshop registration material (coffee, tea, and light refreshments served)	
SESSION 1	Session chair: Mike Cottam	
9:00 am to 9:05 am	Welcome and opening remarks	
9:05 am to 9:45 am	Paper I.1	Speaker: Bret Heinrich
9:45 am to 10:25 am	Paper I.2	Speaker: Bob Camley
10.25 am to 10:40 am	Paper C.1	Speaker: Rogério de Sousa
10:40 am to 11:00 am	BREAK	
SESSION 2	Session chair: Stephanie Curnoe	
11:00 am to 11:40 am	Paper I.3	Speaker: David Venus
11:40 am to 11:55 am	Paper C.2	Speaker: Lihui Bai
11:55 am to 12:10 pm	Paper C.3	Speaker: Matthew Wismayer
12:10 pm to 12:25 pm	Paper C.4	Speaker: Johan van Lierop
12:25 pm to 1:30 am	LUNCH	
SESSION 3	Session chair: Bret Heinrich	
1:30 pm to 2:10 pm	Paper I.4	Speaker: Gary Wysin

2:10 pm to 2:25 pm	Paper C.5	Speaker: Martin Plumer
2:25 pm to 2:40 pm	Paper C.6	Speaker: Jerzy Mizia
2:40 pm to 2:55 pm	Paper C.7	Speaker: Mangala Singh
2:55 pm to 3:15 pm	BREAK	
SESSION 4	Session chair: John Whitehead	
3:15 pm to 3:55 pm	Paper I.5	Speaker: Can-Ming Hu
3:55 pm to 4:10 pm	Paper C.8	Speaker: Mike Cottam
4:10 pm to 4:25 pm	Paper C.9	Speaker: Jesco Topp
4:25 pm to 5:05 pm	Paper I.6	Speaker: Wayne Saslow
5:15 pm to 5:30 pm	PLANNING SESSION for Magnetic North II workshop (scheduled for St. John's, Newfoundland, June 2011)	

Sunday, June 6 (at Windermere Manor)

7:00 pm to 9:30 pm — Workshop Dinner. [Assemble at the Great Hall Dining Room from 6:45 pm for dinner at 7:00 pm]

Monday, June 7 (at the Convergence Centre)

SESSION 5	Session chair: Allan MacIsaac	
8:30 am to 9:10 am	Paper I.7	Speaker: Mark Freeman
9:10 am to 9:50 am	Paper I.8	Speaker: Byoung Choi
9:50 am to 10:05 am	Paper C.10	Speaker: Kirill Rivkin
10:05 am to 10:20 am	BREAK	
SESSION 6	Session chair: Can-Ming Hu	
10:20 am to 11:00 am	Paper I.9	Speaker: Oleg Petrenko
11:00 am to 11:15 am	Paper C.11	Speaker: Stefan Mendach
11:15 am to 11:30 pm	Paper C.12	Speaker: Jason Mercer
12:30 am to 12:30 pm	LUNCH	
SESSION 7	Session chair: Martin Plumer	
12:30 pm to 1:10 pm	Paper I.10	Speaker: Bruce Gaulin
1:10 pm to 1:25 pm	Paper C.13	Speaker: Guy Quirion
1:25 pm to 1:40 pm	Paper C.14	Speaker: David Ménard
1:40 pm to 1:55 pm	Paper C.15	Speaker: Nilhoufar Faghihi
1:55 pm to 2:35 pm	Paper I.11	Speaker: John Whitehead

INVITED TALKS

I.1

Spin current propagation in magnetic single GaAs/Fe/Au,Ag(001) and magnetic double GaAs/Fe/Au,Ag/Fe/Au(001) structures

B. Heinrich and B. Kardasz

Department of Physics, Simon Fraser University, Burnaby, BC, Canada

New ideas in spintronics are based on nonlocal spinvalves. In this presentation we discuss our recent studies of spin current transport in Au and Ag spacers. Using pure spin currents for information transfer requires understanding several processes: (a) Generation of pure spin currents, (b) propagation of spin currents in normal metals, and (c) coupling of spin currents to magnetization. For the magnetic single GaAs/Fe/Au,Ag(001 layer structures the spin pumping introduces a non-local interface damping following the Gilbert damping phenomenology. This contribution increases with the normal metal (NM) spacer thickness and eventually saturates when its thickness is larger that the spin diffusion length in NM. In magnetic double GaAs/Fe/Au,Ag/Fe/Au(001) layers both spin-pumping and spin-sink effects were present. The spin-sink allows one to detect directly the propagation of spin currents across the Au and Ag spacers. The bottom Fe layer grown at the GaAs(001) interface was employed as a spin pump. Spin currents generated in the Au and Ag spacers were detected by spin dynamics in the top Fe layer which acted as a spin current probe. The spin dynamics in the top Fe layer was detected by ps and submicrometer resolved MOKE (TRMOKE). The magnetic damping was investigated by Ferromagnetic Resonance (FMR) from 10 to 74 GHz. The results from FMR and TRMOKE measurements allowed one to determine the electron momentum and spin flip relaxation rates and the corresponding spin diffusion lengths in Ag and Au spacers. The magnetic single and double layer structures were grown and characterized by MBE techniques.

This work was done in cooperation with the groups of Professor Mark Freeman (U. of Alberta) and Professor Christian Back (U. of Regensburg).

I.2

Nonlinear Amplification and Mixing of Spin Waves: Experiment and Theory

R. E. Camley, Yuri Khivintsev, J. Marsh, V. Zagorodnii, I. Harward, J. Lovejoy, and Z. Celinski

Center for Magnetism and Magnetic Nanostructures, University of Colorado at Colorado Springs, Colorado Springs, CO, USA

In contrast to typical cavity-based ferromagnetic resonance measurements where the oscillating magnetic field has an amplitude of about 0.1 Oe, ultrasmall waveguide geometries can produce very large oscillating microwave fields – up to about 500 Oe for an input power of about 1 Watt. The waveguide is constructed by first growing a sequence of films - 2 microns Cu, 3 microns of SiO_2, 70 or 300 nm of Permalloy and 2 microns of Cu - on a Si substrate. The microstrip waveguide with a length of 6.6 mm and a signal line width of 6 microns is then created using photolithography and ion etching. Using the large fields generated in the structure, we explore nonlinear ferromagnetic dynamics in ferromagnetic ribbons of Permalloy and Fe. In particular if two microwave signals at different frequencies are sent into the waveguide, we can amplify one wave by adding energy to the other wave. We also demonstrate the creation of a number of waves at new frequencies, and the development of a comb of equally spaced frequencies. These experimental results are explained using a macrospin model with perturbation theory and through micromagnetics calculations. The perturbation theory shows that the lowest order nonlinear terms in the Landau Lifshitz equations are cubic and that the nonlinearly generated signals are effectively combinations of three waves. It also gives good insight into both the creation of the new frequencies and the amplification of the spin waves.

I.3

Hierarchy of dynamical processes in perpendicularly-magnetized ultathin films

D.Venus and N. Abu-Libdeh

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Magnetic domain patterns form in perpendicularly-magnetized ultrathin films due to the combination of short-range, attractive magnetic exchange interactions and long-range repulsive magnetic dipolar interactions. The dynamics of these patterns, and the domains within them, are described by the complicated interplay of different relaxation processes that act across many orders of magnitude in temporal and spatial length. Recent measurements of the magnetic susceptibility of Fe/2 ML Ni/W(110) films have permitted the quantitative separation and characterization of these time scales. At low temperature, the domains form a stripe pattern. The oscillatory motion of these domain walls in response to an applied ac field occurs by individual Barkhausen steps with a fundamental time of 10^{-9}s. This magnetic response gives rise to a magnetic susceptibility, c(T), with a characteristic shape. As the temperature is increased, the density of the domains in the pattern increases exponentially. Measurements of c(T) as a function of the heating rate reveal a temporal lag in the domain density that shows quantitatively that it relaxes under the influence of dipolar forces on a fundamental time scale that is $10^{5.5}$ times slower than that for individual Barkhausen steps. Finally, at high enough temperature, the stripe pattern is predicted to disorder through the proliferation of topological pattern defects. This transition can be observed indirectly in c(T) by quenching from sufficiently high temperature. The relaxation of the quenched topological defects causes the entire susceptibility curve to shift to higher temperature with a fundamental time of 10^{0}s. The quantitative temporal analysis of this hierarchy of domain relaxation processes complements an extensive literature that uses microscopy and numerical simulation to characterize the domains spatially.

I.4

Effective potential of a vortex in a cylindrical magnetic dot

Gary M. Wysin

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Vortex states in a thin circular magnetic nanodot are studied using auxiliary constraining fields as a way to map out the potential energy space of the vortex, while avoiding a rigid vortex approximation. In the model, isotropic Heisenberg exchange competes with the demagnetization field caused both by surface and volume magnetization charge density. The system energy is minimized while applying a constraint on the vortex core position, using Lagrange's method of undetermined multipliers. The undetermined multiplier is seen to be the external field needed to hold the vortex core in place at any desired radial distance r from the dot center. This auxiliary field is applied only in the core region of the vortex. For a uniform nanodot, the potential energy is found to be very close to parabolic with r, as in the rigid vortex approximation, while the constraining field increase linearly with r. Effects of nonmagnetic holes in the medium can also be estimated and compared with alternative descriptions. Especially, the local depth of the potential well produced by a hole is found. An externally applied magnetic field is shown to lead to the possibility of a bistable vortex switching.

I.5

From the spin dynamo to spintronic Michelson interferometry

Can-Ming Hu

Department of Physics and Astronomy, University of Manitoba, Canada

Traditionally, the dynamics of magnetic materials are usually measured from its impact on either scattering or absorption of photons. A new approach was recently developed based on the influence of spin dynamics on charge transport. It enables electrical detection of spin resonances under the microwave excitation. As a renaissance of Michael Faraday's idea that magnetism, electricity, and light are interconnected, it reveals the interplay of spins, charges, and photons in magnetic materials at the microscopic level [1]. This talk aims to sketch this new progress of magnetization dynamics by focusing on two perspectives. In the perspective of materials science, by using a microspintronics device called spin dynamo, magnetization dynamics are electrically measured in a variety of materials (Fe, Py, GaMnAs), at different regimes (from linear to nonlinear), and with distinct excitations (ferromagnetic resonance, standing spin waves, dipole-exchange modes, surface, edge and localized magnetostatic modes, etc.). The highlight is the development of a phase-resolved spin resonance spectroscopy, which provides a powerful access to the comprehensive magnetization dynamics. In the perspective of wave physics, the present optical imaging technology is built on digital and on-chip techniques utilizing charge dynamics in microelectronics. It was highlighted by the 2009 Physics Nobel Prize and has led to the household product of digital camera. However, charge-dynamics-based microelectronics work typically within the infrared - optical regime. Utilizing magnetization dynamics, we demonstrate that both the phase and amplitude of microwaves can be directly probed by microspintronics. Spintronic Michelson interferometry is developed which enables on-chip conversion of microwave signals to a DC electrical signal. Thereby, a promising near-field microwave imaging technique is demonstrated which has great potential for industrial and biological imaging applications.

[1] C.-M. Hu, Physics in Canada, 65, No. 1, 29 (2009).

I.6

Continuous Néel-to-Bloch transition in strips whose thickness increases: Statics and dynamics

K. Rivkin, K. Romanov, Y. Adamov, A. Abanov, V. Pokrovsky and **W. M. Saslow**[1]

[1] Department of Physics & Astronomy, Texas A & M University, College Station, TX, USA

For strips of width 2w and height h, with both exchange and the dipole-dipole interaction, we find that Néel and Bloch domain walls are locally stable. As h is increased to h_c, Néel walls evolve continuously to Bloch walls by a second-order transition. It is mediated by a critical mode with $\omega \sim \sqrt{(h_c - h)}$, corresponding to motion of the domain wall center. A uniform out-of-plane rf-field couples strongly to this critical mode only in the Néel phase. Local, but not global stability relative to a crosstie phase was established.

I.7

Nanomagnetomechanical Resonators Applied to Vortex Physics

Mark Freeman with John P. Davis, Ning Liu, Alastair Fraser, Joseph Losby, Jacob A.J. Burgess, David C. Fortin, Doug Vick, Peng Li, Oleksiy Svitelskiy, Vincent Sauer, Wayne K. Hiebert

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Micromechanical resonators have proven to be extremely useful for detection of magnetic torque [1]. We have developed nanoscale torsional resonators fabricated within silicon nitride membranes [2], as a platform for sensitive torque magnetometry of individual nanoscale magnetic elements. An example of such a device is shown below. A study of the transition between the parallel-spin and vortex states in a single magnetic disk, performed using this method, will be presented. The approach furthermore admits complementary transmission electron microscopy of the same structures. This work is part of a larger effort on ultrahigh frequency nanomechanical systems [3,4], motivated in part by information-storage functions that might be enabled by combined nanomechanical and nanomagnetic structures [5]. Work supported by NSERC, CIFAR, iCORE, CRC, and the National Institute for Nanotechnology. Samples were made at the UofA Nanofab and the Integrated Nanosystems Research Facility supported by CFI and nanoAlberta.

[1] M.D. Chabot, J.M. Moreland, L. Gao, S.H. Liou and C.W. Miller, J. MEMS 14, 1118 (2005).
[2] J.P. Davis et al., Appl. Phys. Lett. 96, 072513 (2010).
[3] N. Liu et al., Nature Nanotech. 3, 715 (2008).
[4] O. Svitelskiy et al., Phys. Rev. Lett. 103, 244501 (2009).
[5] A. A. Kovalev, G. E. W. Bauer, & A. Brataas, Phys. Rev. Lett. 94, 167201 (2005).

I.8

Magnetization dynamics in exchange-coupled ferromagnet/antiferromagnet bilayer elements

B.C. Choi[1], H. Xu[1], E. Girgis[1], Th. Speliotis[2], C.A. Ross[3], D. Niarchos[2], and H. Miyagawa[3]

[1] Department of Physics and Astronomy, University of Victoria, Victoria, BC, Canada

[2] Institute of Materials Science, NCSR “Demokritos”, Aghia Paraskevi, Greece

[3] Department of Materials Science and Engineering, Massachusetts Institute of Technology, Cambridge MA, USA

The magnetization dynamics in exchange-coupled $Ni_{80}Fe_{20}/Ir_{20}Mn_{80}$ elements occurring in response to sub-nanosecond transitions of the externally applied magnetic field was investigated using time-resolved scanning Kerr microscope. In experiments, arrays of $Ni_{80}Fe_{20}$ (12nm)/$Ir_{20}Mn_{80}$ (5nm) square elements with the size of 10µm×10µm were fabricated, in which $Ir_{20}Mn_{80}$ layer was used to bias the magnetization configuration of $Ni_{80}Fe_{20}$. The hysteresis measurements revealed the characteristics of exchange-coupling interaction across the interface, *i.e.*, the shifted loops and increased coercive field. The loop shifts, referred to as exchange-bias fields (H_{ex}), were varied from 8 Oe to 12 Oe, in which the strength of H_{ex} was strongly dependent on the magnetic field strength applied during the fabrication process. Upon application of a short magnetic field pulse, the magnetization underwent precessional oscillation with a frequency of ~2 GHz. In addition to the magnetization precession, the magnetic vortex core performed a gyrotropic motion around its initial equilibrium position. Along the pathway of the moving core, strong bursts of spin waves were generated by the creation and subsequent annihilation of a vortex-antivortex pair. An abrupt suppression of magnetization precession occurred subsequently after the vortex-antivortex pair annihilated. The results from micromagnetic modelling implied that the incoherent interaction of the magnetic moments with the propagating spin waves led to an effective suppression of the magnetization precession.

I.9

Low-temperature magnetic properties of $SrEr_2O_4$

O. A. Petrenko, T. J. Hayes, G. Balakrishnan, M.R. Lees (University of Warwick, UK);
L.C. Chapon, P. Manuel, D.T. Adroja, F. Demmel (ISIS, UK) P.P. Deen (ILL, France)

In $SrEr_2O_4$ the magnetic Er ions are linked through a network of triangles and hexagons, where geometrical frustration is likely to arise, provided that the exchange interactions are antiferromagnetic. The talk will describe the low-temperature properties of $SrEr_2O_4$, investigated by neutron diffraction, specific heat and magnetisation measurements. Long range magnetic ordering develops below $T_N = 0.75$ K, identified by magnetic Bragg reflections with propagation vector k = 0 and a lambda anomaly in the specific heat. The structure consists of FM chains running along the c axis, two adjacent chains being stacked antiferromagnetically. The moments point along the c direction, but only one of the two Er sites has a sizeable moment of $4.5\mu_B$. Our latest neutron diffraction measurements reveal the coexistence of long-range and short-range components in the magnetic structure. Unusual behaviour in this compound is observed in an applied field, where for H//c axis, a field of 0.5 T completely destroys long-range magnetic order and introduces instead some sort of state with short-range magnetic correlations. A further increase in magnetic field causes a restoration of the long-range order and a disappearance of the diffuse scattering. We also discuss the low-energy dynamics of $SrEr_2O_4$ probed during our recent inelastic neutron scattering experiments.

I.10

Phase Transitions in Planar Pyrochlores

B. Gaulin

Department of Physics, McMaster University, Hamilton, ON, Canada.

Frustrated pyrochlore magnets with Ising-like moments have attracted much attention due to the spin ice and spin liquid disordered states these materials display at low temperatures. We have recently focussed attention on $Er_2Ti_2O_7$ and $Yb_2Ti_2O_7$ which possess local XY, or planar, moments decorating the pyrochlore lattice - a network of corner sharing tetrahadra. I will mostly describe our neutron scattering experiments in which magnetic long range order is destroyed by application of a (110) magnetic field in the XY antiferromagnetic pyrochlore $Er_2Ti_2O_7$, and experiments in which unexpected field-induced magnetic order is observed in its ferromagnetic counterpart, $Yb_2Ti_2O_7$.

I.11

Spin Wave Dynamics in Magnetic Thin Films

John Whitehead[1], Jason Mercer[1,2], Eric Meloche[3], Trinh Nguyen[1] and Martin Plumer[1]

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[2]Department of Computer Science, Memorial University, St. John's, NL, Canada

[3]Seagate Technology, One Disc Drive, Bloomington, MN, USA

The calculation of spin wave spectra at zero temperature in two dimensional dipole-exchange coupled systems in complex geometries is well established. At finite temperature it has been shown that, for exchange coupled systems, the magnetic excitations at finite temperature can be obtained by numerically integrating the LLG (Landau-Lifshitz-Gilbert) equation in both two and three dimensions. In this talk we present the results our recent work on spin dynamics in planar dipole-exchange coupled systems that combines theoretical results and those obtained from simulations studies to study both ground state and finite temperature magnetic excitations. Extensions of this work to more complex geometries will also be discussed.

CONTRIBUTED TALKS

C.1

Model for twin electromagnons and magnetically induced oscillatory polarization

Rogério de Sousa and Markku P. V. Stenberg

Department of Physics and Astronomy, University of Victoria, Victoria, BC, Canada

We propose a model for the pair of electromagnon excitations observed in the class of multiferroic materials $RMnO_3$ (R is a rare-earth ion). The model is based on a harmonic cycloid ground state interacting with a zone-edge magnon and its twin excitation separated in momentum space by two times the cycloid wave vector. The pair of electromagnons is activated by cross coupling between magnetostriction and spin-orbit interactions. Remarkably, the spectral weight of the twin electromagnon is directly related to the presence of a magnetically induced oscillatory polarization in the ground state. This leads to the surprising prediction that $TbMnO_3$ has an oscillatory polarization with amplitude 50 times larger than its uniform polarization.

C.2

Confined spin waves in a micro strip and the modes evolution

Lihui Bai[1,2], Yongsheng Gui[2], Andre. Wirthmann[2], Makoto Kohda[1], Junsaku Nitta[1], and Can-Ming Hu[2]

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Spin dynamics properties in micron and sub-micron size structures have attracted much attention because of applications in high-speed memory devices and signal preceding devices, such as MRAM, spin wave bus, and spin wave logic device [1]. Spin wave eigen-modes in lateral confined structures have been investigated with both optical and electrical methods [2,3]. Here, the modes evolution between surface mode, edge mode (EM), and central mode (CM) was investigated in a micro $Ni_{0.79}Fe_{0.21}$ (Py) strip by the microwave photo voltage technique [2]. In a permalloy strip with a thickness of 137 nm, a width of 20 mm and a length of 2.45 mm, spin waves were detected electrically with a microwave excitation, while an external magnetic field H was applied in plane. Spin wave modes due to confinement in the strip were well demonstrated. By tuning the angle theta between the external magnetic field and the axis of the Py strip, an evolution between the surface mode, CM and EM were detected. A crossing point between the CM and EM was observed around 78 degree for a 5-GHz microwave, where both modes coexisted but were spatially separated. This work was funded by NSERC and UPGP (C.-M. Hu). Lihui Bai is supported by Tohoku Univ. G-COE Program, and by JSPS and MEXT Japan.

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C3

Magnetic Excitations in Microstrips

M.P. Wismayer, L.E. Hayward and B.W. Southern

Department of Physics and Astronomy University of Manitoba, Winnipeg, MB, Canada

The rising scientific and commercial demand for magnetic sensors with improved field resolution and high operating speeds has renewed interest in the spin wave dynamics of micron-sized magnetic strips. The nature of the spin-wave spectrum across the strip is important for understanding the physics behind a magnetic sensor's operational performance. Theoretical calculations and micromagnetic simulations have been used to investigate the spin-wave dynamics of a rectangular permalloy strip as a function of the direction of an applied in-plane field direction. Theoretical calculations show for fields parallel to the strip ($\varphi = 0^o$) the appearance of forward volume modes (FVM) whereas for fields transverse to the strip ($\varphi = 90^o$), backward volume modes (BVM) are present. There is an apparent crossover from FVM to BVM near $\varphi = 72^o$ accompanied by the appearance of lower frequency modes localized near the edges of the strip.

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C.4

Suppression of blocking behavior in a macroscopic fcc nanoparticle crystal

R. D. Desautels[1], O. Kasyutich[2] and **J. van Lierop**[1]

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[2] H. H. Wills Physics Laboratory, University of Bristol, Bristol, UK

Studying the magnetism of ordered arrays of self-assembled nanoparticles is a highly topical area of research. One of the outstanding challenges in this field of nanomagnetism has been the fabrication of truly three-dimensional (3D) ordered arrays on a macroscopic length scale (e.g. crystals hundreds of microns in size). Such nanomagnetic artificial solids or metamaterials are expected to exhibit properties that are radically different from the individual nanocrystalline components. Recently, we have used a protein crystallization technique to fabricate true 3D ordered arrays of 8 nm diametre magnetoferritin (iron-oxide) nanoparticles between 10 to 100 micrometres in size. We compare the AC and DC susceptibility of a dispersion of uncrystallized nanoparticles and the same nanoparticles in a macroscopic 3D fcc crystal. While the magnetic building blocks of these two systems are identical, completely different magnetism in measured. At temperatures above 50 K the uncrystallized nanoparticle system is superparamagnetic. By contrast, the 3D crystal displays no superparamagnetism. The origin of the unusual nanomagnetism in the 3D nanoparticle crystal is likely from spin-glass-like surface spins and core spin Fe moments in the particles that are being polarized from magnetostatic interactions.

C.5

Micromagnetic simulations of interacting dipoles on a fcc lattice: Application to nanoparticle assemblies

M L Plumer[1], J van Lierop[2], B W Southern[2], and J P Whitehead[1]

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[2] Department of Physics and Astronomy, University of Manitoba, Winnipeg, MB, Canada

Micromagnetic simulations are used to examine the effects of cubic and axial anisotropy, magnetostatic interactions and temperature on M-H loops for a collection of magnetic dipoles on fcc and sc lattices. We employ a simple model of interacting dipoles that represent single-domain particles in an attempt to explain recent experimental data on ordered arrays of magnetoferritin nanoparticles that demonstrate the crucial role of interactions between particles in a fcc lattice. Significant agreement between the simulation and experimental results is achieved, and the impact of intra-particle degrees of freedom and surface effects on thermal fluctuations are investigated. The interplay between thermal fluctuations and dynamics is investigated through the sweep-rate dependent loops.

C.6

Ferromagnetism in the Hubbard Model with Inter-Site Kinetic Correlation

Grzegorz Górski, **Jerzy Mizia** and Krzysztof Kucab

Institute of Physics, University of Rzeszów, Rzeszów, Poland

The ideas of the modified Stoner model [1] are applied to the higher order many body analysis of the Hubbard model. The Hubbard III approximation scheme for the simple Hubbard model [2] is recalled. The chain equation for Green functions which includes the scattering effect and resonance broadening effect is derived. The coherent potential approximation and its relation with the Hubbard III approximation are re-established. The hopping interaction $\Delta t = t - t_1$ and in addition the intersite kinetic correlation functions [1] are added into the Hubbard III scheme. The kinetic correlation was excluded in the original Hubbard III approximation and also in the equivalent coherent potential approximation. Including it brought two spin dependent effects: the bandwidth correction and the bandshift correction, which stimulate the ferromagnetic ground state [3]. Both these factors are enhanced by the hopping interaction. In numerical calculations we have used the bands with symmetrical density of states (semi-elliptic or bcc like DOS) and also with the asymmetrical DOS resembling the fcc DOS. Due to the presence of kinetic correlation and additional Δt interaction we have obtained a ferromagnetic transition in the basic Hubbard model within the broad range of parameters [4]. The strongest decrease of the critical exchange interaction necessary for ferromagnetism was obtained for the asymmetrical fcc like DOS with a high peak at its edge.

[1] J. Mizia and G. Górski, Models of itinerant ordering in crystals: An introduction (Elsevier Ltd. 2007), Chapter 7

[2] J. Hubbard, Proc. Roy. Soc. A 281, 401 (1964)

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C.7

Magnetic and phonon behavior of multiferroic $La_2B'MnO_6$ (B' = Co or Ni) epitaxial films

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Despite its great technological and scientific importance, the presence of a well-controlled strong magnetoelectric coupling in materials remains challenging [1]. Self-ordered $A_2B'B''O_6$ double perovskites provide an alternative avenue to search for innovative multiferroic materials with well-controlled coupled behaviors. We have done a comprehensive study on $La_2B'MnO_6$ (B'= Ni or Co) epitaxial films [2]. These films [2] were grown on $SrTiO_3$ (111) and (001) using a pulsed laser deposition technique. We explored the structure, magnetic, phonon and coupled properties. The phase-stability diagram allows for films containing both B'/Mn ordered and disordered phase in a controlled relative proportion. An ordered phase is obtained by growing the films at relatively high temperature and in a large oxygen partial pressure. Chemical cation ordering has a significant implication on their magnetic, phonon and structural properties. For example, X-ray diffraction study reveals that the B-site Ni/Mn ordering in La_2NiMnO_6 induces superlattice reflections as the crystal symmetry is transformed from a pseudocubic perovskite unit cell in the disordered phase to a monoclinic form with a doubling of the c-axis pseudo-cubic lattice parameter owing to the alternating layer of NiO_6 and MnO_6 octahedra in the ordered phase. We demonstrate that the long range B'/Mn ordering induces a single ferromagnetic-to-paramagnetic transition around room temperature while a randomly distribution reduces the value to ~ 140 K. A partial ordering of B'/Mn leads to two magnetic transitions. The B'/Mn cation ordering influences strongly spin-phonon and spin-polarization coupling. The observed coupling in these systems has been explained within mean field framework.

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C.8

Theory of Dipole-Exchange Spin Waves in Ferromagnetic Nanotubes

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A macroscopic continuum theory is presented for studying the dipole-exchange spin-wave excitations in nanometer-sized ferromagnetic nanotubes. The external field is taken parallel to the longitudinal axis of the cylindrical samples, and a geometry with a large length-to-diameter aspect ratio is considered. The surface and bulk magnetic excitations are studied by including both the long range dipole-dipole interactions and the short range exchange interactions in the spin dynamics, together with general boundary conditions (including effective pinning) at the inner and outer interfaces of the tubes. The situation of the Brillouin light scattering experiments for radially-quantized spin waves in Ni nanotubes [1] can be realized theoretically, by studying both unpinned and pinned cases together with the electromagnetic boundary conditions at both interfaces. For limiting special cases, these calculations also simplify to the one-interface geometries of dipole- exchange spin waves in wires [2] or antiwires. In all cases the theoretical formalism is a generalization of our previous work [3] that was applied to these and other cylindrical magnetic geometries in situations where the dipole-dipole interactions were dominant (as in the magnetostatic regime). The role of exchange in modifying (through hybridization effects) the surface magnetostatic modes of a cylinder is described. Numerical applications are presented, mainly for Ni and EuS nanotubes, including effects of phenomenological damping.

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C.9

A Reconfigurable Artificial Crystal by Ordering Bi-Stable Magnetic Nanowires

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In artificial crystals (ACs) Brillouin zones form and energy gaps in the continuous f(k) dispersion exist at the boundary of the Brillouin zone. The bandstructure is given by the geometry of the AC, in particular, the size and composition of the unit cell. In contrast to ACs for phonons, plasmons or photons, the bandstructure for magnonic crystals can be further tailored by an applied magnetic field and - which is the subject of this contribution - the magnetic ordering of the nanomagnets that compose the AC. We investigated spin waves in a one-dimensional (1D) magnonic crystal fabricated out of planar Ni80Fe20 nanowires and found two different magnon band structures depending on the magnetic ordering of neighboring wires, i.e., parallel and antiparallel alignment. Here, the magnetic order controls the size of the unit cell. At zero in-plane magnetic field H the modes of the antiparallel case are close to those obtained by zone folding of the spin-wave dispersions of the parallel case. This is no longer true for non-zero H which opens a forbidden frequency gap at the Brillouin zone boundary. The 1D stop band gap scales with the external field which generates a periodic potential for Bragg reflection of the magnons [1]. We acknowledge financial support from the DFG via SFB 668, 'Nanosystems Initiative Munich', 'Nano-Spintronics', Australian Research Council and European Community's Seventh Framework Programme (FP7/2007-2013) under Grant Agreement no. 228673 (MAGNONICS).

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C.10

Dynamics of granular magnetic media - damping versus distributions

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It is a well established fact that the material parameters of granular magnetic media determined from FMR experiments, micromagnetic modeling of magnetic recording and simple analytical formulas that describe the process of magnetic recording in a single spin approximation, are different from each other by as much as an order of magnitude. This problem prevents researchers from clearly understanding the limitations of such processes as precessional magnetization reversal, high power microwave absorption and so on. In the present work by using micromagnetic modeling we demonstrate how the assumptions that enter each of these approaches result in such large inconsistencies.

C.11

Spin-Wave Interference in Three-Dimensional Rolled-Up Ferromagnetic Microtubes

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We have investigated spin-wave excitations in rolled-up Permalloy-semiconductor microtubes. We prepare these structures from strained Py / GaAs / InGaAs multilayers which reduce their strain energy by self rolling into rolled-up carpet like micro objects after being released from the substrate [1]. In microwave absorption experiments we find a series of quantized azimuthal modes which arise from the constructive interference of Damon-Eshbach-type spin waves propagating around the circumference of the Permalloy-semiconductor microtubes. The mode spectrum of this novel type of spin wave resonator can be tailored by the rolling radius and number of rolled-up layers as well as by the external magnetic field [2].

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C.12

Building a Smarter Modeller - The LLG Equation

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Standard micromagnetics implementing the Landau Lifshitz Gilbert (LLG) equation is a well defined concept and writing the associated code, while non-trivial, is a task that a graduate student can accomplish in a few months. Creating a high performance, interactive, parallel and adaptable piece of scientific code takes more time and experience. This talk will feature the development of such a piece of micromagnetics code and present novel solutions to computational steering, visualization, parallelism and rapidly changing requirements. The multi-scale problem of Heat Assisted Magnetic Recording (HAMR) is defined and preliminary results using the code will be presented.

C.13

Analysis of the magnetoelastic properties of the multiferroic compound $CuFeO_2$

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There has been a renewed interest in triangular-lattice systems such as $CuFeO_2$ which shows a magnetoelectric effect trigger by geometrical spin frustration. During this presentation we focus our attention on the analysis of the elastic properties of $CuFeO_2$ obtained via ultrasonic velocity measurements as a function of temperature. Within the context of a Landau free energy, our analysis show that the unusual properties of $CuFeO_2$ result from the interplay between magnetism and elastic deformations. Well above the magnetic phase transitions, strong elastic softening, noticeable on the velocity of transverse modes propagating and polarized in the basal plane, suggests that the nature of the structural phase transition at 14 K is primarily *pseudoproper ferroelastic* with the spin acting as a secondary order parameter. Our analysis also indicates that for this multiferroic, the symmetry of the non-magnetic order parameter can be assigned to the two-dimensional $E(x^2- y^2, xy)$ irreducible representation. However, the first order magnetic transition at 11 K is rather associated with a fourth-order Umklapp term of the form $[\mathbf{S}\cdot\mathbf{S}]^2\,\Delta_{4\mathbf{Q},\mathbf{G}}$ where **G** is a reciprocal lattice vector with **Q** representing the wave vector of the spin polarization.

C.14

Effective microwave permeability of ferromagnetic wire arrays

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Arrays of ferromagnetic metallic wires offer increased degrees of freedom for the tailoring of the effective permeability of microwave materials. This flexibility often comes at the cost of higher microwave losses as compared to state-of-the-art ferrites and garnets currently used in devices. Here, we present a multiscale effective-medium model for the permeability tensor of arrays of ferromagnetic wires, which allows us to assess their potential for microwave devices and to highlight the material challenges limiting their use. The model incorporates both the gyromagnetic response and the skin effect exhibited by the individual wires, along with the intrawire and interwire dipolar interactions of finite-size samples. It has been validated by data from a series of ferromagnetic resonance experiments on strongly interacting nanowire arrays, for which the skin effect is not significant [1-3]. The systems studied consist of Ni, CoFeB and NiFe alloys, electroplated into nanoporous alumina membranes. The agreement between model and experiment allows us to quantify the interwire interactions and clarify the magnetization processes, along with providing useful guidance for the tailoring of the microwave response of nanowire arrays. The analysis is further extended to wires of arbitrary diameters under circumstances in which skin effect can no longer be neglected. The emphasis is put on the influence of electromagnetic retardation inside the individual wires and of the geometrical parameters of the array on the ferromagnetic resonance and antiresonance and on the linewidth of the effective permeability spectrum. This allows us to examine the trade-off between the design flexibility permitted by ferromagnetic-metallic inclusions and the limitations imposed by their microwave losses.

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C.15

Field Theoretical Approach to the Solidification of Magnetic Materials

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Many mechanical properties of materials depend on the size and distribution of grain structure. Hence it is important to gain insight into the mechanism of microstructure formation during the solidification. The so called phase-field crystal (PFC) model has recently gained a lot of attention in materials modeling. One of its strengths is that the field to be considered is only averaged in time and not in space. This allows a description of systems on diffusive time scales and atomic length scales so bridges a molecular description and a continuum field theory. Here we present an extension of the PFC model to study how external magnetic field can change microstructures in magnetic materials. We use finite difference method to solve the dynamical equations of motion and Fast Fourier Transform method to calculate the induced magnetic field. Our preliminary results show that the rate of solidification increases in the presence of an external magnetic field.

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