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Frontiers in Artificial Spin Ice
FASI 2023

Abstracts

Correlations I – Wednesday, 14th June 13:30 – 15:00

Chair: Kevin Hofhuis

Time: 13:30 – 14:00

Square Artificial Spin Ice: New Physics From an Old System

Presenter: Peter Schiffer[1]

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Square ice has been one of the most basic structures for artificial spin ice studies. With its robust ordered ground state, the physics of square ice in zero field is fairly simple and yet its simplicity opens doors to studies of new phenomena. For example, the application of a magnetic field leads to a range of interesting collective behavior. First, I will discuss studies of field-induced avalanches in artificial spin ice, which show that square ice in a field is a good manifestation of the one-dimensional random field Ising model. [1] I then will discuss magnetometry studies of square ice that explore the interplay between the ferromagnetism of the material, the intrinsic behavior of isolated islands, and the interactions among islands. [2] I will conclude with some recent developments on square ice, showing that it still has much to teach us.

References

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Time: 14:00 – 14:30

Dynamic transitions in the vertex-frustrated Apamea lattice

Presenter: Alan Farhan[1]

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Ever since the introduction of thermally-activated artificial spin ice systems, almost exactly a decade ago [1], an initial surge ensued in addressing multiple outstanding questions such as the spin ice ground state [2,3] or emergent magnetic monopoles and their dynamics [4]. This was accompanied by an increasing number of efforts combining creative design with real-time magnetic imaging, to directly visualize a variety of emergent phenomena ranging from polaronic states, reduced and enhanced effective dimensionality to spin glass behavior [5-8]. In my presentation, I aim to demonstrate how basic concepts of thermodynamics such as ergodicity, influenced by interplay of temperature and frustrated interactions, can be directly visualized and tested via real-space imaging of thermal fluctuations in a vertex-frustrated geometry, the Apamea lattice.

References

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Time: 14:30 – 15:00

Artificial magnets as experimental simulators of classical spin liquids and seminal vertex models

Presenter: Nicolas Rougemaille [1]

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Artificially made, geometrically frustrated arrays of interacting magnetic nanostructures offer a remarkable playground for exploring spin ice physics experimentally. Initially designed to capture the low-energy properties of highly frustrated magnets, artificial spin ices provide a powerful lab-on-chip platform in which to study cooperative magnetic phenomena and exotic states of matter.

Recently, we showed that the thermodynamics of the F model can be approached very closely in a purely two-dimensional system, including its macroscopically degenerate, high-temperature ice regime [1]. The F model has rather unusual properties [2,3]: (i) it is characterized by an infinite order phase transition separating a high-temperature critical phase (the so-called square ice) from an antiferromagnetic order, and (ii) the configurational space is divided into topological sectors. These properties are inherited from the constraints of the six vertex model, which allows only loop excitations to develop on an antiferromagnetic background consisting of a tessellation of type I vertices. These loops are made of type II vertices, whose magnetic moments can be joined into lines, the so-called Faraday lines [2]. They carry the system energy and are thus the elementary excitations of the F model. They are of two kinds: magnetization-free, chiral closed loops extending within the bulk of the lattice, and system-spanning windings, hosting a net magnetization. Only closed loops can be contracted to zero, but they do not couple with an external field, as they carry no net magnetization. Instead, system-spanning windings cannot be contracted, forcing the system to fluctuate within a given topological sector.

Interestingly, the topological properties of the F model can be probed experimentally, at least to some extent, by a careful control of the vertex energies and the reduction of ice-rule defects to a marginal contribution. This was made possible by replacing the spin degree of freedom used in conventional artificial spin ice systems by a micromagnetic knob, which can be finely tuned to adjust the vertex energy directly, rather than modifying the two-body interactions. This strategy allowed us to visualize the proliferation of Faraday loop excitations developing on the antiferromagnetic ground state as our system is brought to higher-energy configurations. Faraday lines carrying a net magnetization and chiral Faraday loops characterized by a zero magnetic susceptibility have been imaged in real space, giving access to the topological properties of the F model experimentally. In this contribution, our main findings on the F model will be presented and other routes pursued in our group will be briefly introduced.

References

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Neuromorphic Computing & Nanomagnetic Logic

Wednesday, 14th June 16:00 – 18:00

Chair: Bartel Van Waeyenberge

Time: 16:00 – 16:30

Generalisation and Few-shot Learning with Interconnected ASI Neuromorphic Reservoirs

Presenter: Will R. Branford[1,2]

Authors: Will R. Branford[1,2], Kilian D. Stenning[1,3], Jack C. Gartside[1], Luca Manneschi[4], Christopher T. S. Cheung[1], Tony Chen[1], Alex Vanstone[1], Holly H. Holder[1], Francesco Caravelli[5], and Eleni Vasilaki[4]

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Neuromorphic computing leverages the complex dynamics of physical systems for computation. The field has recently undergone an explosion in the range and sophistication of implementations, with rapidly improving performance. Neuromorphic schemes typically employ a single physical system, limiting the dimensionality and range of available dynamics - restricting strong performance to a few specific tasks. This is a critical roadblock facing the field, because modern AI and machine-learning provide striking performance, where typically larger models with more dimensions and parameters yield better results. This trend has found empirical support in the study of 'over-parameterised' regimes [1], where the number of network parameters greatly surpasses the size of the training dataset. In this regime, models avoid overfitting, generalise well and learn with few training data.

Here, we engineer a diverse suite of ASI nanomagnetic arrays and show how tuning microstate space and geometry enables a broad range of dynamics and computing performance [2]. We interconnect arrays in parallel, series and multilayered neural network architectures, where each network node is a distinct physical system. This networked approach grants extremely high dimensionality and enriched dynamics enabling meta-learning to be implemented on small training sets and exhibiting strong performance across a broad taskset. We showcase network performance via few-shot learning, rapidly adapting on-the-fly to previously unseen tasks.

We employ ordered and disordered ASI arrays with nanomagnet dimensions on the crossover from single ferromagnetic domain (macrospin) to vortex states [3-5]. Magnetic force microscopy reveals a ratchet-like transformation of macrospins into vortices, during minor loop magnetic reversals. Interacting neighbouring magnets play an important role, giving cooperative growth of macrospin and vortex chains. This gradual evolution of linkages is neuromorphic in character, and interesting for both neurally-inspired computation [3] and self-assembly of magnonic circuits [5]. We employed spin-wave microstate fingerprinting [6] for rapid, scalable readout of vortex and macrospin populations, and leveraged this for spin-wave reservoir computation. We benchmark the computation using non-linear mapping transformations of diverse input and target signals in addition to chaotic time-series forecasting.

References

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Time: 16:30 – 17:00

Astroid Clocking: A New Scheme for Stepwise Field-Driven Evolution of an Artificial Spin Ice

Presenter: Erik Folven[1]

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Artificial spin ice (ASI) systems with their rich behavior and potential for fundamental physics exploration, have long intrigued the research community. More recently, novel ASI device applications, such as reconfigurable magnonic devices [1] and hardware for neuromorphic computing [2], have also been proposed. In this context, establishing efficient schemes for controlled reconfiguration and input encoding in ASI using external stimuli is essential. Here, we present a new global field protocol called astroid clocking that enables stepwise, gradual evolution of spin states in ASI and offers unprecedented control of the dynamical process in both time and space.

The use of an external field remains the primary means of controlled interaction with ASI. An issue with typical protocols, is that they often yield uncontrolled spin-flip dynamics. Crossing a critical field strength triggers a sudden avalanche of spin flips, erasing previous input information—a concern for ASI computing applications. Astroid clocking, however, results in fundamentally different spin flip dynamics. By exploiting the shape and orientation of the nanomagnet switching astroids, specific field angles are employed to selectively address different parts of the ASI array.

Here, we demonstrate controlled growth and reversal of ferromagnetic domains in 45-degree pinwheel ASI. Using our open-source simulation software flatspin [3] we elucidate the underlying mechanism of the asteroid clocking. The stepwise evolution of the ASI spin configuration is directly imaged using XMCD-PEEM and MOKE microscopy. We believe that the asteroid clocking protocol holds the potential to unlock new avenues of exploration in both fundamental and applied ASI studies.

References

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Time: 17:00 – 17:30

Multipolar analysis of the relaxation pathway in nanomagnetic clusters

Presenter: Paula Mellado[1]

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Arrays of single-domain nanomagnetic islands are potential building blocks for logic gates to implement probabilistic computation using artificial spin ice. In clusters made out of lithographically prepared nanomagnets, the anisotropy of magnetic interactions and the symmetry of the magnetic array combine to give rise to several output magnetic states. The probability of obtaining a particular magnetic configuration in finite clusters has been experimentally manipulated by implementing energy barriers in the relaxation pathway. Here, by considering a single nanomagnet as a dumbbell, a bar magnet of finite length with two magnetic charges at their ends, we study the effect of interactions and symmetry in the entropy staircase associated with the relaxation process of small clusters of nanomagnets. We show that the hierarchy of energy scales associated with their relaxation can be analytically captured by extending the monopole theory for spin ice to a multipole one, which exposes metastability's origin and analytically captures all the magnetic regimes in the relaxation process.

Time: 17:30 – 18:00

Applications of thermoplasmonics to nanomagnetic logic

Presenter: Paolo Vavassori[1,2]

Authors: Paolo Vavassori[1,2], Matteo Menniti[1], Pieter Gypens[3], Jonathan Leliaert[3], and Naëmi Leo[4]

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Single-domain nanoscale magnets interacting via magnetostatic interactions are potentially key metamaterials for low-power information processing [1]. Their properties and functionality are determined by the capability to reverse the moment of each nanomagnet to minimize the mutual dipolar interactions, which happens more quickly at elevated temperatures. We propose and demonstrate an approach in which the nanomagnetic arrays are made of hybrid nanostructures that combine a plasmonic nano-heater with a magnetic element. We achieve the reliable and contactless plasmon-assisted optical heating of nanomagnets with a flexible control of length (down to the micrometer) and time (down to sub-ns) scales of the thermal excitation [2]. Furthermore, the polarization-dependent absorption cross section of elongated plasmonic elements enables selective heating of a desired subset of nanomagnets within the illuminated area depending on their in-plane, which is not possible with conventional heating schemes [3]. This provides the spatial discrimination and speed required for their integration with CMOS technology. Furthermore, the here presented concept of plasmon-assisted optical heating offers powerful prospects for novel functionalities and applications in the fields of magneto-calorics, spintronics, magnonics.

References

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Correlations II – Thursday, 15th June 08:30 – 10:00

Chair: Björgvin Hjörvarsson

Time: 08:30 – 09:00

Dynamics and emergence in magnetic metamaterials: The quest for the missing mesospin moment

Presenter: Vassilios Kapaklis[1]

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Magnetic metamaterials offer an interesting playground for the study of collective magnetic ordering and dynamics. The building blocks—mesospins—of these are often treated as point-like magnetic dipoles and, more recently, as artificial magnetic atoms. These analogies only hold to a certain point when describing thermal fluctuations, transitions and dynamics in mesoscopic systems. Furthermore, it has become evident that the analogy to a point-like dipole can even be misleading, resulting in misinterpretations and quantitative discrepancies between observations and calculations. The formation and evolution of magnetization textures inside mesospins has to be considered in order to rationalize these discrepancies. Such textures are defined by inter- and intra-mesopin effects, highlighting the importance of understanding the role of the multiple length- and energy-scales relevant in magnetic metamaterials. An overview of some recent developments in this direction will be presented and discussed.

Time: 09:00 – 09:30

Static and Tunable Modifications to Perpendicular ASI

Presenter: Susan Kempinger[1]

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Perpendicular implementations of Artificial Spin Ice are attractive due to their intrinsically isotropic interactions between neighboring elements. Also, the magnetic states of elements in the array can be accessed using polar magneto-optical Kerr effect microscopy, allowing for complete microstate characterization in situ with an applied field. Symmetry breaking modifications can be used to expand the usefulness of perpendicular ASI by allowing additional control over the preferred state of the system. Modifications to interactions are introduced either statically by modifying the pattern during the fabrication process, or tunably by some external parameter after fabrication. Connecting neighboring islands with thin necks statically modifies the interaction strength between select pairs of nearest neighbors in an ASI array. The thickness and orientation of the necks determines the adjusted interaction strength. Fabricating perpendicular ASI arrays on a soft magnetic $Ni_{80}Fe_{20}$ (Py) underlayer allows for tunably breaking the lateral symmetry using an in-plane magnetic field. Previous studies have shown that soft magnetic underlayers increase the interaction strength between islands. We use micromagnetic characterizations to quantify the impact of combining these two modifications on the interaction strength, and will present on simulation results and the status of fabricated samples with these two modifications.

Work performed at the Center for Nanoscale Materials, a U.S. Department of Energy Office of Science User Facility, was supported by the U.S. DOE, Office of Basic Energy Sciences, under Contract No. DE-AC02-06CH11357.

Time: 09:30 – 10:00

Designing Emergence with Vertex-Frustration

Presenter: Cristiano Nisoli[1]

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In the first seven minutes and a half—for the benefit of broader dinner conversations—we shall describe how so many ideas in artificial spin ice can be exported to different platforms, e.g. meta-elasticity, colloids, networks, or quantum annealers, with a list of recent examples. Then, we will report of recent results on vertex frustrated spin ices and use them to conceptualize their framework. In vertex-frustration it is important to distinguish between structure and description. The structure can be very complex, but the goal should be to obtain a simple emergent description. Then one forgets the complex underlying binary structure. For instance: Shakti spin ice can be described as the problem of fully covering a chessboard with construction blocks for toddlers; and Santa Fe spin ice, by wiggling strings. "Simple" should not mean, however, "trivial". The idea is to generate these emergent mathematical objects to reveal new physics: for instance Tetris spin ice can order by raising its total entropy, at equilibrium; Santa Fe spin ice can be partitioned into topological sectors and thus reveal a topological kinetic crossover. We will conclude by discussing new directions within this framework.

New Frontiers – Thursday, 15th June 11:00 – 12:30

Chair: Gavin Macauley

Time: 11:00 – 11:30

The self-induced spin glass: the perplexing magnetism of elemental neodymium

Presenter: Alex Khajetoorians[1]

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Spin glasses are a class of disordered magnetic materials characterized by a flat multi-well energy landscape that exhibits aging dynamics. Spin glass behavior is often described by two key ingredients: (a) competing spin interactions, and (b) external disorder. It was recently proposed that a special type of spin glass can be realized, solely by competing interactions. [1] In 2020, we discovered that the controversial and perplexing magnetic state of elemental Nd(0001) is a self-induced spin glass. [2] Using spin-polarized scanning tunneling microscopy/spectroscopy (SP-STM/STS), we found that the zero-field state shows a multiplicity of favorable short-range ordered Q-states, but in the absence of long-range order. The magnetic state shows aging dynamics, and it stems from frustrated indirect exchange. More recently, we showed that with increasing temperature, frustration is broken leading to a long-range ordered multi-Q state. [3] In this talk, I will review the concept of the self-induced spin glass in Nd. Moreover, I will discuss new results concerning the aging dynamics and magnetic phase diagram of the material, as well as perspectives to use such multi-well systems for new memory and computing applications.

References

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Time: 11:30 – 12:00

Emergent Disorder and Mechanical Memory in Periodic Metamaterials

Presenter: Yair Shokef[1]

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Inspired by the topological structure of frustrated artificial spin ices, we introduce an approach to design ordered, periodic mechanical metamaterials that exhibit an extensive set of spatially disordered states. We show how such systems exhibit irreversible, non-Abelian, and history dependent responses, as their state may depend on the order in which external manipulations were applied. We use this behavior to demonstrate how the static state of a system encodes information about the dynamical sequence of operations that the system underwent. Thus, multistability and potential to store complex memory emerge from geometric frustration in ordered mechanical lattices that create their own disorder.

Time: 12:00 – 12:30

Structural Spin-Ice Analogues

Presenter: Andrew L. Goodwin[1]

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We are interested in solid phases that support correlated disorder of the kind found in spin-ices, where complexity arises from geometric frustration of relatively simple interactions. This talk will cover some recent examples of structural-spin-ice analogues from our own group based on cyanide and metal-organic framework chemistry [1,2], and will discuss generalisations of the spin-ice concept to the broader class of Truchet tilings [3].

References

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3D Nanomagnetism – Thursday, 15th June 13:30 – 15:00

Chair: Valerio Scagnoli

Time: 13:30 – 14:00

Tuning the properties of nanomagnets by exploiting three dimensional effects

Presenter: Amalio Fernández-Pacheco[1]

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The expansion of nanomagnetism to three dimensions provides exciting opportunities to explore new physical phenomena and opens great prospects to create 3D magnetic devices for green computing technologies. [1] In this talk, I will first present the recent work of our group on fabrication and magneto-optical characterization of 3D nanomagnets. [2,3] Then, I will discuss new opportunities provided by 3D geometries to tune intra- and inter- properties in nanomagnets, including the formation of complex spin textures and topological stray fields. [4,5]

References

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Time: 14:00 – 14:30

Magnetic High-Frequency Modes in Three-Dimensional Interconnected Nanowire Arrays

Presenter: Riccardo Hertel[1]

[1] Université de Strasbourg, CNRS, Institut de Physique et Chimie des Matériaux de Strasbourg, F-67000 Strasbourg, France

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Recent progress in the nanofabrication of three-dimensional magnetic nanostructures [1] has opened the opportunity to generate arbitrarily shaped artificial magnetic samples whose properties are governed by their geometric features. Three-dimensional magnetic objects with a suitably tailored microstructure may effectively represent novel types of magnetic materials with unique magnetic properties. In this context, extended arrays of interconnected soft-magnetic nanowires have recently emerged as a category of particular interest. Such systems display features of three-dimensional artificial spin-ice systems and exhibit a wide variety of nearly degenerate magnetization states, which can include defect-like magnetic structures forming at the intersection points.

By using advanced finite-element micromagnetic simulation methods [2], we investigate high-frequency magnetization oscillations in different types of magnetic nanoarchitectures consisting of interconnected soft-magnetic nanowires, ranging from buckyball-type geometries [3] to cubic arrays and diamond-type artificial magnetic crystals [4]. In all cases, we find distinct resonance peaks in the absorption spectra, which can be attributed to specific geometric and micromagnetic features within the lattice. The magnetic high-frequency dynamics depends particularly sensitively on the micromagnetic structure developing at the nanowires' intersection points. Moreover, at higher frequencies, characteristic standing-spin wave modes develop within the individual nanowires. The sensitivity of the high-frequency oscillation modes to nanoscale micromagnetic and geometric features, in combination with the high precision of modern sample fabrication methods, underlines the potential of these magnetic systems for three-dimensional magnonic applications with tunable and reconfigurable properties.

References

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Time: 14:30 – 15:00

Magnetic Charge Ordering in 3D Artificial Spin Ice

Presenter: Sam Ladak [1]

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In this talk, I will outline experiments and modelling carried out upon a 3D artificial spin-ice system [1,2,3,4] which takes the geometry of a diamond-bond lattice, capturing the arrangement of spins in bulk pyrochlore systems. Monte-Carlo simulations of such structures, predict a rich phase diagram with a number of charge-ordered phases including a single and double charged monopole crystal [5]. By using magnetic force microscopy, I will show that the vertex states in experimental systems can be determined, and monopole transport upon the lattice surface can be directly visualised [2]. I will show that experimental demagnetised systems are found to host ferromagnetic stripes upon the surface, a configuration that forbids the formation of the expected double-charge monopole crystal ground state [5]. Instead, the system forms crystallites of single magnetic charge, superimposed upon an ice background. I will move onto discuss how the measured configuration can be understood in terms of an enhanced monopole chemical potential upon coordination-two vertices at the surface, and how this may be controlled with intricate 3D nanostructuring to realise the expected double-charge crystal ground state.

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Correlations III – Thursday, 15th June 16:30 – 18:00

Chair: Lance De Long

Time: 16:30 – 17:00

Control Processes and State Selection Using Artificial Spin Ice

Presenter: Bob Stamps[1]

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As models in experiment, Artificial Spin Ice allow for flexible adjustment of coupling parameters via geometric constraints placed on interactions. This flexibility facilitates their use in fundamental studies of ordering processes on mesoscopic length scales. Recent advances in fabrication now enable creation of complex two- and three-dimensional structures that have opened new possibilities for structural design and exciting new potentials for application in practical devices. In this talk, novel mechanisms for the control of configurational states and magnetic ordering processes using new geometries are discussed. [1,2] A rudimentary 'smart ASI' is described whose design is based on state optimization principles as in some models used for neurological processes. [3,4] Finally, preliminary results from an exploration of state classification and analysis of inverse problems using Artificial Spin Ice are discussed.

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Time: 17:00 – 17:30

Controlling Local Interactions in Artificial Spin Ices: Customising Ground States

Presenter: Yong-Lei Wang[1]

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Artificial spin ice (ASI) has emerged as a promising platform for investigating fascinating collective behaviors. Understanding and controlling the ground state of these systems are crucial for both fundamental research and technological applications. However, accessing the ground state of artificial spin ice, especially in Kagome ASI, presents a significant challenge due to its high degeneracy and frustration. In experimental settings, the low-energy states accessible primarily arise from short-range interactions, as long-distance interactions tend to be weak and difficult to observe. Therefore, a feasible approach is to modify the local interactions to customize the experimentally accessible low-energy states.

In this presentation, we introduce a convenient approach to manipulate the competing dipolar interactions between neighboring nanomagnets, thereby enabling the customization of vertex degeneracy and ground state. [1] By adjusting the length of selected nanobar magnets in the Kagome spin ice lattice, we successfully realize multiple low-energy microstates, including the elusive long-range ordered state known as the spin crystal state in Kagome ASI. Unlike the ground state of a regular Kagome ASI, where the spin crystal state emerges from long-range interactions, our strategy establishes the spin crystal state through nearest neighbor interactions. This approach can be directly applied to other artificial spin systems, providing opportunities to achieve exotic phases and explore emergent collective behaviors.

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Time: 17:30 – 18:00

Tensor-network approach to frustrated Ising models: an alternative to Monte Carlo

Presenter: Frédéric Mila[1]

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The numerical investigation of classical models with discrete degrees of freedom such as the Ising model or ice models is usually done with Monte Carlo simulations. However, for powerful that they are, these simulations have difficulties to answer some questions in very frustrated systems, in particular when it comes to models with a small but non-vanishing residual entropy. In this talk, I will show that the formulation of the partition function as the contraction of a tensor network is competitive when it comes to the low or zero temperature physics of very frustrated models [1]. This will be illustrated on the Ising model on the kagome lattice with coupling up to the third neighbour [2,3], a model where the residual entropy is only progressively lifted when including farther couplings, resulting in phases with very small residual entropies that we could calculate very accurately with tensor networks.

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(Artificial) Spin Ice Phenomena – Friday, 16th June 08:30 – 10:00

Chair: Aleksandr Kurenkov

Time: 08:30 – 09:00

Geometric Control of Emergent Antiferromagnetic Order in Coupled Artificial Spin Ices

Presenter: CD Phatak[1]

[1] Materials Science Division, Argonne National Laboratory, Lemont, IL USA.

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Artificial spin ices (ASIs) composed of coupled nanomagnets offer the possibility to create designer geometrical frustration and manipulate inter-nanomagnet interactions [1,2]. In particular, by using a dimer motif consisting of two strongly coupled single-domain nanomagnets as a building block, we can control and realize intriguing antiferromagnetic physical states in which the magnetic charge is not conserved. Here we create a dimer Kagome ASI (DK-ASI) system within which the antiferromagnetic order is controlled by tuning lattice geometry. We use MuMax3 [3] micromagnetic simulations to predict the complex energy landscape of the demagnetized DK-ASI systems and experimentally verify the real-space magnetic ordering in the system using high-resolution Lorentz transmission electron microscopy. In addition, by combining the experimental data with a Heisenberg Hamiltonian model and Monte Carlo simulations, we have derived key insights into the governing inter-island coupling. We show that the collective ground state consists of disordered antiferromagnetic dimers across the lattice when the intradimer interaction is dominant. However, for lattices governed by intra-triad-unit interactions, the ground state exhibits a long-range spin-ordered state in which the vertex magnetic charge is uniform across all triads. These findings provide an insight and a pathway into tunable antiferromagnetic coupling of artificial lattices with implications for natural antiferromagnets as well as frustrated spin-liquid materials.

This work was supported by the U.S. Department of Energy, Office of Science, Office of Basic Energy Science, Materials Sciences and Engineering Division.

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Time: 09:00 – 09:30

Active Matter Realizations of Commensurate and Artificial Ice Systems on Ordered Substrates

Presenter: Charles Reichhardt[1]

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Active matter describes systems with some form of self-propulsion, such as found in biological systems for bacteria, motor protein filaments, synthetic active systems such as colloids, and assemblies of self-mobile robots [1,2]. These systems can exhibit a variety of phases that, in some cases, show similarities to equilibrium phases but can also exhibit phases with no equilibrium counterpart. An open question is how the activity or non-equilibrium fluctuations affect known equilibrium phase transitions and statistical mechanics models. Here we look at several active matter realizations of continuum models interacting with ordered substrates, which can capture behavior found in spin-like models. For periodic obstacle arrays, we find that an activity-induced ordering transition can occur to create an active Mott phase with long-range order, while at other fillings, the configurations are frustrated but can have local vertex order. For active nematics interacting with periodic substrates, the curvature of the obstacles can induce topological defects so that the defects can form ordered patterns similar to the square ice system. For increasing activity, the defects can show various dynamic behaviors and dynamic transitions. We also discuss how an effective ice rule could arise for topological dynamics. We also discuss other realizations that could be made for robotic systems. Our work suggests a new area to apply concepts from artificial spin ice to intrinsically non-equilibrium systems.

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Time: 09:30 – 10:00

Seeing Magnetic Monopoles

Presenter: Ludovic Jaubert[1]

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Even if magnetic monopoles have been extensively studied in spin-ice systems, their signatures have been indirect in solid-state materials so far, leaving their direct observation an open challenge. One such technique that could realize this direct observation is electron holography. In this seminar, we shall explore the possibility of imaging monopoles via electron holography through experimental measurements of artificial spin ice, and computational simulation of how monopoles would appear in a pyrochlore spin ice thin film [1].

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Dynamics in Artificial Spin Ice – Friday, 16th June 10:30 – 12:00

Chair: Aleš Hrabec

Time: 10:30 – 11:00

Nonlinear Multi-Magnon Scattering in Artificial Spin Ice

Presenter: M. Benjamin Jungfleisch[1]

Authors: Sergi Lendinez[1], Mojtaba T. Kaffash[1], Olle G. Heinonen[2,3], Sebastian Gliga[4], Ezio Iacocca[5], and M. Benjamin Jungfleisch[1]

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Artificial spin ice systems have recently been discussed in the context of functional magnonic materials, where an interplay between geometry, material properties, and reconfigurability determines the magnon spectrum. Magnons are the fundamental quantum-mechanical bosonic excitations of magnetic solids, whose number does not need to be conserved in scattering processes. Microwave-induced parametric magnon processes have been believed to occur in magnetic thin films only, where quasi- continuous magnon bands exist.

Here, we reveal the existence of such nonlinear multi-magnon scattering processes and their coherence in artificial spin ice [1]. The experimental investigations using microwave and Brillouin light scattering spectroscopy are combined with numerical simulations to understand the evolution of modes. Our results show that harmonic magnon modes can be excited in artificial spin ice subject to sufficiently strong microwave power. This excitation leads to a spatial modification of modes enabling nonlinear processes that is unique to artificial spin ice. Comparison with numerical simulations reveals that frequency doubling is enabled by exciting a subset of nanomagnets that, in turn, act as nanosized antennas, an effect that is akin to scattering in continuous films. Our results suggest that tunable directional scattering is possible in these structures opening new avenues for manipulating magnon populations in reconfigurable nanomagnetic networks.

This work was supported by the U.S. Department of Energy, Office of Basic Energy Sciences, Division of Materials Sciences and Engineering under Award DE-SC0020308.

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Time: 11:00 – 11:30

Deconstructing Magnetization Noise: Degeneracies, Phases, and Mobile Fractionalized Excitations in Tetris Artificial Spin Ice

Presenter: Mateusz Goryca[1,2]

Authors: M. Goryca[1,2], X. Zhang[3], J. D. Watts[4], C. Nisoli[2], C. Leighton[4], P. E. Schiffer[3], and S. A. Crooker[2]

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[2] Los Alamos National Laboratory, Los Alamos, NM 87545, USA
[3] Department of Applied Physics, Yale University, New Haven, CT 06511, USA
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Direct detection of spontaneous spin fluctuations, or "magnetization noise", is emerging as a powerful means of revealing and studying magnetic excitations in both natural and artificial frustrated magnets. Depending on the lattice and nature of the frustration, these excitations can often be described as fractionalized quasiparticles possessing an effective magnetic charge. These fractionalized excitations are topologically protected, can diffuse through the crystal lattice in thermal equilibrium, and can move in response to applied magnetic fields, motivating studies of "magnetricity" in analogy to electricity. In archetypal square ASI lattices, magnetization noise from quasiparticle kinetics was detected at room temperature via optical magnetometry [1, 2] and the sudden appearance of excess noise at certain applied magnetic fields revealed the presence of phases rich in mobile magnetic charges.

Motivated by these studies, here we use optical magnetometry of spontaneous noise to reveal new families of fractionalized excitations in the low-symmetry frustrated ASI known as "tetris ice" (Fig. 1a). By applying small magnetic fields, tetris ice can be tuned through a variety of complex spin configurations, whose degeneracies and boundaries are directly revealed by noise. In particular, we find particularly intense and narrow bands of noise for certain directions and ranges of applied field (Fig. 1b,c). Using Monte Carlo simulations to deconstruct these noise signatures, these bands are shown to herald novel regimes wherein magnetic quasiparticles delocalize and proliferate, without cost in energy, along extended quasi-1D spin chains in the lattice. These results demonstrate the power of noise-based studies to probe microscopic details of complex magnetic phenomena, in this case the equilibrium kinetics driven by fractionalized magnetic excitations.

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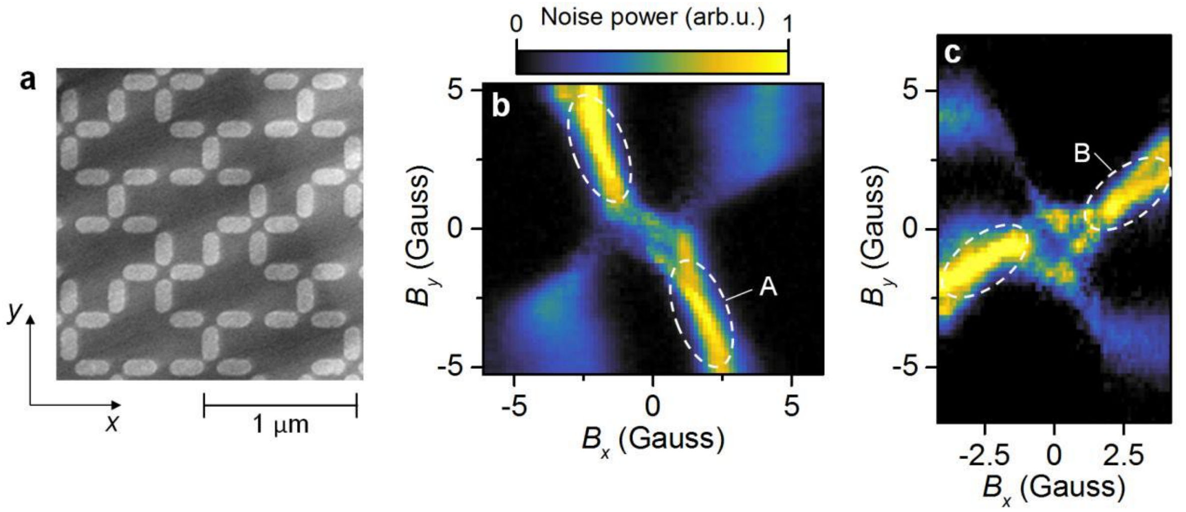

Figure 1 | a, SEM image of tetris ice. **b,** A map of the measured noise power from the horizontal islands, in thermal equilibrium, vs. in-plane magnetic fields B_x and B_y. **c,** Same, but for the vertical islands. Intense noise along bands A and B herald the proliferation of fractionalized magnetic excitations.

Time: 11:30 – 12:00

Spin Dynamics in Magnetochiral Nanotubes and 3D Tubular Nanonetworks Created by Conformal Ferromagnetic Coating of 3D Nanotemplates

Presenter: Dirk Grundler[1,2]

Authors: M. C. Giordano[1], H. Guo[1], M. Hamdi[1], A. Mucchietto[1], A. J. M. Deenen[1], M. Xu[1], and D. Grundler[1,2]

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Three-dimensional (3D) nanoarchitectures prepared from materials with magnetic order are expected to give rise to nanoscale functional materials with unique features [1]. Particular interest has been generated by 3D assemblies of interconnected ferromagnetic nanowires and nanotubes [2,3,4]. Their prospects reach from magnetically frustrated states which are reversibly created and dissolved to 3D magnonic crystals with magnetochiral properties at GHz frequencies. However, fabrication technologies for complex architectures of 3D interconnected ferromagnetic nanotubes are still under development.

We further optimized atomic layer deposition (ALD) of ferromagnetic Ni (Fig. 1a) [5] and Ni80Fe20 (Permalloy, Py) [6] to obtain nanotubular ferromagnets with radii on the order of 100 nm (Fig. 1a). The conformal coating allowed us to create individual nanotubes prepared as ferromagnetic shells around micro-meter-long single-crystalline semiconductor (GaAs) nanowires. We explored their spintronic properties [7] and, when exciting spin waves (magnons) at GHz frequencies [5,6], we identified magnetochiral properties [8]. Our current work concerns interconnected Ni nanotubes for 3D nanomagnonics (Fig. 1b). Here, we use a polymeric 3D nanoscaffold produced by two-photon lithography and prepare 10 to 30 nm thick Ni shells by means of ALD. Magnon spectra are obtained by micro-focus inelastic light scattering (BLS) spectroscopy performed from the top (Fig. 1c). In our talk, we will report our recent experimental data and compare them with micromagnetic simulations of 3D ferromagnetic nanoarchitectures. The work is funded by SNSF via grants 177550 and 197360.

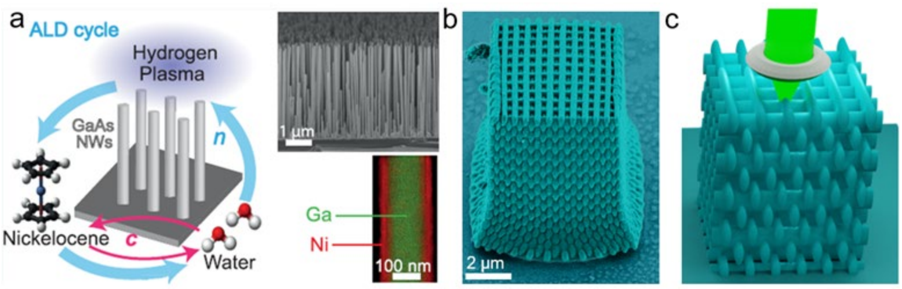

Figure 1 | a, ALD process for Ni (left) applied to vertically standing GaAs nanowires (right) [5]. **b,** Polymeric nanoscaffold overgrown with a Ni shell (blue) by ALD. **c,** Sketch of BLS spectroscopy.

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