Review Report on PhD Thesis

Faculty: **Central European Institute of Technology** Academic year: **2022/2023**
Brno University of Technology in Brno

Student: **Ing. Vojtech Schanilec**

Doctoral study program: **Advanced Materials and Nanosciences**

Field of study: **Advanced nanotechnologies and microtechnologies**

Supervisor: **prof. RNDr. Tomas Sikola, CSc.**

Reviewer**:** **Dr. Alexandra Mougin**

PhD thesis title: Artificial arrays of magnetic nanostructures

Topicality of doctoral thesis:

The idea of the thesis was to fabricate and test new designs of artifical kagome and square arrays, including notches and holes as tuning defects, to be compared with the existing theoretical expectations of spin ice and liquid physics

Meeting the goals set: yes

Problem solving and dissertation results:

Chapter 1 provides a basis of magnetism including background in geometrical frustrated systems. The thesis content is positioned in relation to the state of the art, starting from the water ice problem towards the spin ice one. Pioneering works on two-dimensional lithographically fabricated lattices composed of interacting nanomagnets called artificial spin ices started around 2005. Artificial spin ice lattices are fabricated by a pattern of elongated nano- or micromagnets. These nanomagnets need to be small enough to be a single domain. The magnetisation of these single-domain macrospins always points along the long axis of the nanomagnet and such patterns therefore are a good approximation of Ising-like spins in spin ices. The different kind of possible arrays geometry are then reviewed (artificial kagome and artificial square) and motivated as playgrounds in real life for capturing the physics of spin liquids. Both systems are the results of the projections of the natural three-dimensional pyrochlore crystals onto a plane. A large variety of models and simulations exist to describe the physics of each geometry (described in more details in chapter 3 and 4). At this stage, I understood that the idea of the thesis was to fabricate and test new designs of artifical arrays to be compared with the existing theoretical expectations of spin liquid physics. The original idea is to tune the lattices by connecting some nanomagnets instead of relying on disconnected ones whose behavior is governed by dipolar interactions. The properties of these arrays are then driven by the micromagnetic energies at the connection that can be changed by notches or holes. Doing so, the systems ground and excited states can be changed and new comparisons can be performed.

Ebeam lithography, evaporation, MEB imaging were used to fabricate the networks of nanoislands. The magnetic states were obtained by controlled demagnetization procedures (field driven in a rotating field) and imaged by MFM. In modified arrays, the MFM images provide information on the DW at each vertex site from which the spin configuration at the connected vertex nanomagnets is deduced by comparison with µMax simulations. The analysis is done using an home-built software for square lattice. All are described in chapter 2.

The originality of the PhD work of Vojtěch SCHÁNILEC lies in the samples concept. He designed and realized a micromagnetic knob, a notch in the kagome arrays or a hole in the square arrays, used to tune the connection energy in his nanomagnets connected in one macro lattice. With this trick, he could revisit problems investigated since 20 years. Two publications (Phys Rev Lett) as first author attest the importance of his results reported in Chapters 3 and 4.

Chapter 3 focuses on artificial Kagome ice and its potential use to test spin liquids models. Spin liquids are correlated, disordered states of matter that fluctuate even at low temperatures. Experimentally, the degeneracy characterizing their low-energy manifold is expected to lifted because of dipolar interactions that lead to an ordered ground state at absolute zero. However, many systems, whatever the fabrication technique, dynamically freeze before magnetic ordering arises and ground state or low-energy configurations remain out of reach experimentally. Here, Vojtěch shows that the dynamical freezing can be by-passed in his artificial kagome ice with notches. He explains the magnetostatic effect of a notch (notch-rule), how the notch size and the duration of the demagnetisation protocol tune the system's effective temperature. The effect of the notch is obtained by MC simulations and enabled to figure out how the notches had to be placed to get the spin liquid 2 phase. Alltogether, he obtains the *a priori* dynamically inaccessible ordered ground state and fragmented spin liquid configurations (long range order and spin liquid 2). He could experimentally image them in real space at room temperature. From the MC simulations of the notch impact, it's clear that the notch breaks the vertex symmetry and two coupling constants and modified models are required as discussed at the end of the chapter. The later ends with the effect of notches on domain wall propagation, mainly with simulations. It also refers to results of an additional publication (Advanced Materials) of which Vojtěch is co-author. They exploit the propagation of domain wall in kagome artificial networks that leads to a tunable stochastic response, depending on the applied magnetic field and the local defect creation. It seems to me that this research direction (calculation, logic gates …) may provide very interesting perspectives to this work.

Chapter 4 is focused on artificial two-dimensional square arrays. When natural 3D pyrochlore crystals are projected along the edge into the plane, the strengths of the interactions between the first and second neighbours are different. To restore the coupling interactions, previous solutions in literature proposed to change the system's geometry by elevating one sub-lattice above the other to lessen the strength of the first neighbours or to add interaction modifiers (a microdisc at the vertex's center). Here, again, the nanomagnets are connected so that the dipolar driven many body interactions is not the driving force. A hole of different diameter is used to tune the energy of the domain wall and vertex types (antivortex; homogeneous domain wall; Néel transverse domain wall - less than 1% and vortex domain wall - high energy, not considered). With only 2 types of vertex, a emulator of the 6 vertex model can be done. By changing the hole diameter, an equivalent temperature is evaluated and acts again as a temperature knob. Vojtěch explains how it allows to probe the thermodynamics of both Slater KDP and Rys F models as they reach their high-energy ice-like disordered phase. In principle, the six vertex model considers only the existence of the configurations that follow the ice rule (with a unique coupling constant). However, since the symmetry is often not equivalent, there are different realisations of the model namely the Slater-KDP and the Rys-F models, with reversed relative couplings strength and Vertex types. The combined role of the demagnetization procedure and hole diameter was investigated. The combination of the ability to reach all realisations of the six vertex model and a negligible number of Type III defects allowed him to probe the system using Faraday lines. He reminds their definitions: type II excitations separate patches of type I vertices. Only the type II vertices carry magnetic moments, which can be joined into the Faraday lines. The chapter ends with an experimental description of the probe and of the control the topological properties of the F model as the systems undergo the phase transition from the low-energy antiferromagnetic ground state into the high energy ice-like phase. It includes a complex analysis of the Faraday lines (parity and chirality) in the vicinity of the phase transition and a discussion of the role of the type III vertex (even if small).

Importance for practice or development of the discipline: Attested by the publications

It would have been more comfortable to get a list of the publications made in the two supervising teams on frustrated systems in the previous years. Even if I could built my own idea from the references list, a small paragraph with the “internal” state of the art would have been welcome. Importantly, at different places in the manuscript, Vojtěch SCHÁNILEC is fully honest and distinguish his own contribution (in the simulations, fabrication or data analysis software for example) from that of his colleagues.

Formal adjustment of the thesis and language level:

The thesis is well written; it is made of 4 distinct chapters (background and state of the art, methodology and results in the two kinds of systems investigated). Figures and illustrations are didactic and well chosen. Some of them are very aesthetic. The choice of putting some detailed points in Appendix is great.

(4) The study is duly completed by a state doctoral examination and the defense of a dissertation, which proves the ability and readiness for independent activity in research or development or for independent theoretical and creative artistic activity. The dissertation must include original and published results or results accepted for publication.)

Questions and comments:

Concerning the context, I may have missed an explanation about the co-supervision. It was not clear to me which part of the work was done where (Institut Néel and BRNO University of Technology). I did not understand neither if Vojtěch SCHÁNILEC spent half of his Ph-D time in each lab or not.

Conclusion:

As a non expert of spin ice and frustrated spin models, the PhD work presented appearead to me as a nanomagnetism approach of the physics of frustated systems. I may have missed the main goal or interest of the realization of artificial spin arrays. Is it a pure check of the variuos existing modelsAre those especially important for statiscal physics or because they provide an improved understanding of the existing natural crystals? Can we learn more than from simulations? I may get the anwer to those questions during the defense that is for sure allowed. Indeed, apart of that point, the manuscript of Vojtech Schanilec is well written. It describes its experimental work (sample design, fabrication and measurements), meangfull data analysis and includes significant new results in two kinds of artificial spin systems. To acheive that, notches and holes are used as tuning parmaters of the micromagnetic energies in the fabricated systems. This allowed Vojtech Schanilec to capture the spin configuration of low-energy phases of the kagome spin arrays with connected magnets with notches avoiding the dynamical freezing and the long range dipolar interactions imprint. He also could approach the physics of the F model in a two-dimensional sqaure artificial magnetic system in which he restored the symmetry and degeneracy. He could reveal the proliferation of Faraday lines as the square system is brought from low- to high-energy magnetic configurations.

In my opinion, the reviewed **thesis fulfill** all requirements posed on theses aimed for obtaining PhD degree. This thesis **is ready** to be defended orally, in front of respective committee.

In Orsay, France , date…………2023 April 17th

……Alexandra MOUGIN……………………………

Name of the reviewer