Review Report on PhD Thesis

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

Student: **Ing. Vojtěch Schanilec**

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

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

Supervisors:**prof. RNDr. Tomas Sikola, CSc.** **Nicolas Rougemaille, Institut Néel**

Reviewer**:** **Prof. Julian CARREY**

PhD thesis title: Artificial arrays of magnetic nanostructures

Topicality of doctoral thesis:

Understanding the collective properties emerging from spin networks coupled by magnetic interactions is an old theme in magnetism, but it is constantly renewed by new characterization methods, new theoretical models, or by the development of new systems. The context of this work is the building and analyzing of two-dimensional magnetic equivalents to the ice. In this work, Vojtěch Schanilec focused his research on two types of artificial spin systems: kagomé and square dipolar spin ice systems. Both systems are designed to directly measure the individual spin degree of freedom in a real space with imaging techniques such as magnetic force microscopy. The magnetic network can be also simulated using micromagnetic simulations and frustrated spin Hamiltonians. It is tricky to build experimentally artificial networks that are able to reach the ground state predicted by simulations or by simple energy minimization considerations. Because of dynamic issues, artificial frustrated spin systems are generally frozen in a high-energy configuration after the demagnetization process (equivalent to “cooling” the network), and a fairly large density of high-energy magnetic “defects“ – the so-called magnetic monopoles in spin ices – remained trapped in the network. Several ways to better approach, and eventually reach, the ground state manifold of the artificial kagomé and square dipolar spin ices have been pursued, and are well described in the manuscript. Although a perfect artificial equivalent to the kagomé and square ice has so far never been elaborated, this work brings significant advances toward this objective and is therefore of high relevance in the community of nanomagnetism.

Meeting the goals set:

To reach his objective, Vojtěch followed a very original way: instead of using nanomagnets to mimic Ising pseudo-spins and to tune pairwise spin coupling strengths through their mutual dipolar interaction, he uses the energy of domain walls in a magnetic array made of connected nanomagnets. Formally, this approach consists in studying vertex models instead of spin models. The interaction between vertices can be finely tuned by inserting notches or holes into the array.

This novel approach has permitted him to reduce drastically the number of unwanted high-energy states and to better approach, and sometimes even reach, the ground state manifold. Playing on the size of the notches and holes permits to adjust interaction strengths and/or to get a magnetic equivalent of the temperature. A temperature-like effect can also be obtained by varying the duration of the demagnetisation process. This novel approach has permitted Vojtěch to elaborate and observe configurations the low-energy physics of the kagomé and square ices, including ice regimes and monopole-like excitations. He successfully obtained well-analyzed data, with convincing explanations of the observations, which have been published in two articles.

Problem solving and dissertation results:

The manuscript is composed of 106 pages plus 8 pages of annexes. Chapter 1 provides to the reader the theoretical basis to understand the general subject of the PhD : the basics of magnetism as well as the physics of ice, spin ice and artificial spin systems are briefly presented. This chapter is rather short since the various experimental ways which have been followed to build artificial spin ice as well as more focused results from the literature are presented all along subsequent chapters. Chapter 2 presents the various tools used during the PhD : i) e-beam lithography to build the network; ii) micromagnetic simulations to study the influence of notches and holes on the energy of vertices iii) Monte-Carlo simulations to study theoretically the thermodynamic properties of the arrays iv) magnetic force microscopy to image magnetic configurations; v) lab-made softwares permitting to perform image treatment, extract more rapidly the spin, vertex and charges configurations from magnetic images, and calculate pairwise spin correlations. With regard to the latter point, Vojtěch has contributed to the development of the lab software package by writing two toolkits. Chapter 3 is devoted to the presentation of the results obtained on kagomé spin ice systems. Vojtěch has shown that using adequate notch size, it is possible to imprint into the array any desired micro state, including the ground state and spin-fragmented configurations, and to drive the vertex networks into these imprinted low-energy configurations after a demagnetization process. This gives access to previously inaccessible spin and magnetic charge configurations. Chapter 4 is devoted to the study of artificial square lattices with holes. In a standard system composed of square-ordered isolated nanomagnets, the interaction strength between the first and second neighbors is intrinsically different, which precludes to observe an ice state, the latter requiring to have a similar interaction strength between first and second neighbors. Here a system composed of an array of horizontal and vertical magnetic lines in which a hole is created at the cross between the lines is fabricated and studied. The size of the hole permits to tune the energy of the domain wall so that, for an adequate hole size, a six-vertex model is build. Interestingly, a spin-liquid like state and Faraday lines are observed and fully analyzed.

Importance for practice or development of the discipline:

The way opened by Vojtěch is large and further developments of the work can be envisaged. The possibility to tune the interactions using the notches or holes could be applied to any currently studied lattices with in-plane magnetization such as Santa Fe, Tetris, Brickwall or Shakti lattices.

Formal adjustment of the thesis and language level:

The manuscript is extremely clear, with a good level of English. A few typos are still present, which will be communicated to the candidate before final printing. The manuscript contains original data, which have been published in two Phys. Rev. Lett. articles, with Vojtěch as first author.

Questions and comments:

A first strength of the manuscript is its extremely high level of teaching skills and references to the literature. All the results obtained by Vojtěch are presented after a comprehensive review of the theoretical aspects and results, permitting easily to the non-specialist to enter into the subject. This gives the feeling to the reader to read a book on the subject, and I encourage Vojtěch to publish as a review his PhD after changing the structure, if such a comprehensive review does not exist yet. A second strength is that the obtained results are first plan ones and are presented in a clear yet concise manner.

The other side of this quality is that it is hard for the reader to discover the difficulties which have been met and overcome, the failures, the exotic samples, the unexplained behavior and so on: it is like all the results obtained during this PhD have been obtained first attempt and all been understood, which is quite rare in real life. The main exception is the discrepancy – related in chapter 4 – between the micromagnetic simulations and the experimental results with respect to the hole size permitting to get the ice model.

A second comment is that the one-page summary of the PhD is unfortunately of very low quality compared to the manuscript and does not pay tribute to the exceptional work conducted by Vojtěch. I thus recommend to write it again completely before the final publication of the PhD.

Conclusion:

Given all the elements presented above, I consider that this manuscript is of extremely high level. In my opinion, the reviewed thesis **fulfill/~~doesn´t fulfill~~** all requirements posed on theses aimed for obtaining PhD degree. This thesis is/~~isn´t~~ ready to be defended orally, in front of respective committee.

In Toulouse, March 9th, 2023

Julian Carrey