

M2 Internship Proposal

Subject: Ferromagnetism and skyrmions in the Hofstadter-Hubbard model
Laboratory: Laboratoire de Physique et Modélisation des Milieux Condensés (LPMMC UGA/CNRS)
Supervisor: Cécile Repellin, Felix Palm
Contact: cecile.repellin@lpmmc.cnrs.fr, felix.palm@lpmmc.cnrs.fr

Context:

The quantum Hall effect is a fundamental phenomenon in solid-state systems, whereby a two-dimensional electron gas in a perpendicular magnetic field acquires a quantized Hall response. In this setting, flat single-particle bands (*Landau levels*) suppress the kinetic energy and enhance the role of interactions. Including the spin degree of freedom can give rise to interaction-driven magnetism. For example, for a filled Landau level (filling factor $\nu = 1$), interactions can favor a *quantum Hall ferromagnet* [1]. This state supports exotic excitations known as *skyrmions* [2]: spatially extended spin textures in which the local spin orientation winds non-trivially across the system [Fig. 1].

Quantum simulators based on ultracold atoms are a promising platform to investigate these phenomena. They realize lattice models in artificial magnetic fields, like the *Hofstadter-Hubbard model* [3], and provide access to spatially resolved measurements not directly accessible in solid-state experiments, potentially permitting the direct observation of skyrmions. Skyrmions have long been investigated in continuum models in the context of the quantum Hall effect in solids. Moreover, previous numerical studies of the Hofstadter-Hubbard model on square [4] and triangular [5] lattices have found signatures of quantum Hall ferromagnetism and skyrmion formation. However, fundamental questions regarding how the lattice affects the skyrmions' structure have not been addressed.

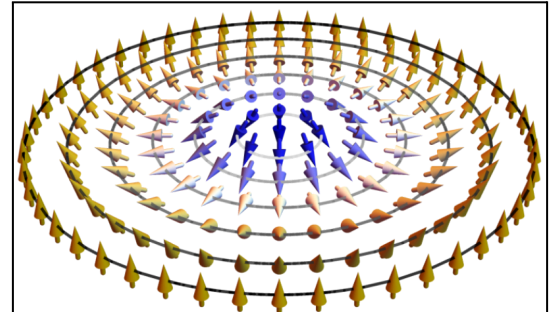


Fig. 1. Skyrmions are characterized by a (topological) winding of the local spin. In particular, while locally the spin is aligned, at large distances the spin is anti-aligned.

The project:

The goal of this project is to investigate skyrmion formation in the Hofstadter-Hubbard model on a square lattice with open boundaries (box geometry), as typically realized in quantum simulators. Starting from the quantum Hall ferromagnetic regime, the project will explore the spin textures emerging in this geometry and investigate their structure. We will estimate the spatial extent of the skyrmions and study the influence of an additional Zeeman term on their stability and size.

The student will learn and use tensor-network methods, in particular the density matrix renormalization group (DMRG) method, building on existing Julia code and the MPSKit/QuantumKit software ecosystem [6]. The project will provide experience with state-of-the-art tensor-network methods in quantum many-body physics. It addresses a question of direct relevance to the microscopic observation of topological excitations in quantum simulators. Possible outlooks for a PhD project include the investigation of skyrmions in the fractional quantum Hall regime in the Hofstadter-Hubbard model, and in moiré multilayer materials.

Candidate: The internship is well-suited to a student with an interest in theoretical condensed-matter physics. Hands-on experience with numerical methods and programming is an advantage.

References:

- [1] Z. F. Ezawa and G. Tsitsishvili, Rep. Prog. Phys. **72**, 086502 (2009)
- [2] S. L. Sondhi, A. Karlhede, S. A. Kivelson, and E. H. Rezayi, Phys. Rev. B **47**, 16419 (1993)
- [3] M. Aidelsburger, S. Nascimbene, and N. Goldman, C. R. Physique **19**, 394 (2018)
- [4] F. A. Palm, M. Kurttutan, A. Bohrdt, U. Schollwöck, and F. Grusdt, New J. Phys. **25**, 023021 (2023)
- [5] J. K. Ding et al., Phys. Rev. X **14**, 041025 (2024)
- [6] QuantumKitHub: <https://github.com/QuantumKitHub>