Annual Report 2022/2023

Ph.D. student: Luca Maranzana *Supervisor:* Sergey Artyukhin

1 Research activity

Multiferroic materials combine multiple coexisting orders and potentially enable cross-controls, e.g. the electric control of magnetization, a functionality of pressing interest in spintronic and information storage technology. My research activity concerns a particular type of multiferroics, the spiral magnets [1]. In the spiral phase, the magnetization rotates in space with a fixed wavevector and rotation axis (Fig. 1). Since a spatial inversion changes the rotation sense, the spiral order breaks this symmetry and induces a ferroelectric polarization [2]. If the Hamiltonian is invariant under inversion and contains an easy-plane anisotropy, the spiral magnet has two degenerate groundstates, a clockwise and a counterclockwise spiral with opposite polarization (Fig. 1). Thus, it can be thought of as a magnetoelectric bit. The electric field-driven switching of such a bit is a subject of practical importance and fundamental interest.

Switching between two magnetic states proceeds through the creation, propagation, and annihilation of a domain wall (DW). The DW between two spiral domains with opposite rotation sense consists of a periodic array of vortices or merons, except for a few symmetry-determined orientations that are topologically trivial [3]. The existing literature focuses on vortex DWs or topologically trivial DWs. The meron DWs, arising when the anisotropy is weak, are still widely unexplored. In the last year, we studied the structure and the electric field-driven dynamics of such meron DWs by combining the Ginzburg-Landau approach and the collective coordinates method [4]. We corroborated the results with atomistic spin dynamics simulations [5].

A meron is a vortex-like configuration where the magnetization goes out-of-plane in the core. Thus, the magnetization covers either the upper hemisphere (i.e. positive topological charge) or the lower hemisphere (i.e. negative topological charge). We found that the lowest energy meron DW consists of a periodic array of merons with alternating topological charges (Fig. 2). At low electric fields, the dynamics can be described by two collective coordinates: the position of the DW $\bar{y}$ and the dimerization parameter of the meron array d. The equations of motion for $\bar{y}$ and d are reminiscent of a classical particle in 1D (i.e. $m\ddot{\bar{y}} = qE_y - \beta\dot{\bar{y}}$ and $d = m\dot{\bar{y}}$, where m, q and β are determined in terms of the parameters of our model).

While DW motion in ferro- and antiferromagnets is facilitated by the rotation of spins within the wall, in meron DWs with non-alternating topological charges, the spins outside the wall, in the whole system, must rotate for the wall to move. In fact, the DW position is coupled with the phases of the two spiral domains [6]. Hence, the velocity of the DW depends on the distance from the surfaces. Moreover, such bulk rotations may dramatically enhance the dissipation and pinning of the meron DW.

The helicity of the merons φ (Fig. 2) can be controlled via an out-of-plane electric field. In particular, it is possible to switch between $\varphi = 0$ and $\varphi = \pi$ by inverting the field. The switching time is strongly influenced by fluctuations (e.g. thermal fluctuations) because the initial and final states are local extrema of the driving potential and, thus, the electric field exerts no force for $\varphi = 0$ and $\varphi = \pi$. Nevertheless, this effect offers another interesting form of electric control.

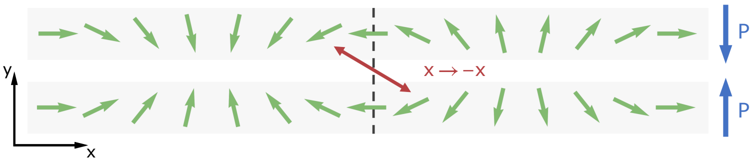

Figure 1. Spirals with wavevector $\pm Q\hat{x}$ and rotation axis $\hat{z}$. These configurations are related by spatial inversion and have opposite ferroelectric polarization $P \parallel \hat{y}$.

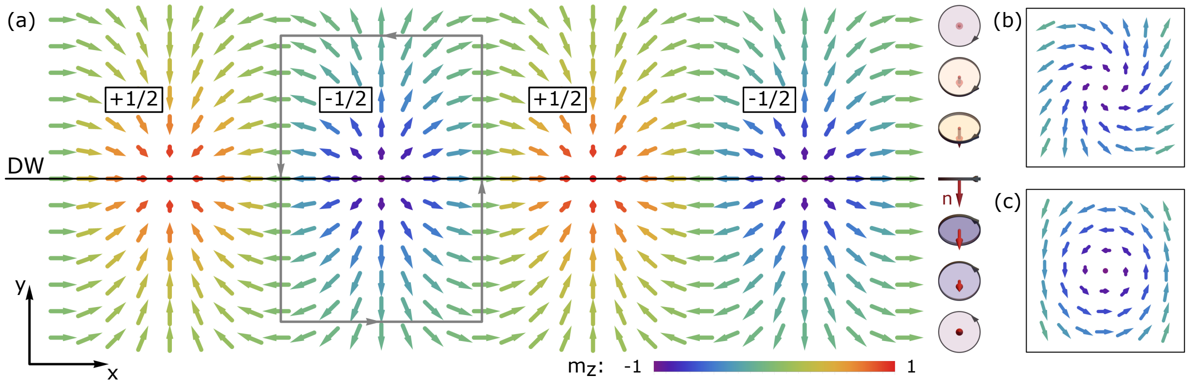

Figure 2. (a) Meron DW with helicity $\varphi = 0$ plotted in the xy-plane. The colors encode the out-of-plane component of the magnetization. Such a DW separates a clockwise spiral (upper domain) and a counterclockwise spiral (lower domain). The gray contour encircles a meron with topological charge $-1/2$. There are two merons per spiral period and they have opposite topological charges. The right panel shows the spin rotation axis $\hat{n}$ at different y. Inside the DW, $\hat{n}$ rotates by π around $\hat{x}$. Meron DWs with different helicity can be obtained by a rigid rotation of the magnetization in the xy-plane. Panel (b) and (c) show a meron with $\varphi = \pi/4$ and $\varphi = \pi/2$, respectively.

References

[1] T. Kimura *et al.*, Nature **426**, 55 (2003).

[2] M. Mostovoy, Phys. Rev. Lett. **96**, 067601 (2006).

[3] F. Li, T. Nattermann and V.L. Pokrovsky, Phys. Rev. Lett. **108**, 107203 (2012).

[4] O.A. Tretiakov *et al.*, Phys. Rev. Lett. **100**, 127204 (2008).

[5] B. Skubic *et al.*, J. Phys.: Condens. Matter **20**, 315203 (2008).

[6] F. Foggetti and S. Artyukhin, arXiv:2204.09027.

2 Courses

- *Fasi topologiche della materia condensata* (Master's Degree course)
  Exam passed on January 27$^{\text{th}}$, 2023
- *Crystalline solids: electronic correlations, instabilities and order* (Ph.D. course)
  Exam passed on August 2$^{\text{nd}}$, 2023
- *School on quantum many-body phenomena out of equilibrium: from chaos to criticality* (Ph.D. training school, ICTP)
- *Crash course on theoretical condensed matter physics* (Ph.D. course)

3 Publications

- L. Maranzana and S. Artyukhin, *Electric field-driven dynamics of meron domain walls in spiral magnets*, in preparation.

4 Presentations

- CMT@Brixen – Poster presentation (*Electric field-driven dynamics of meron domain walls in spiral magnets*) June 5th, 2023
- School on quantum many-body phenomena out of equilibrium: from chaos to criticality – Poster presentation (*Electric field-driven dynamics of meron domain walls in spiral magnets*) August 29th, 2023