Topological Spin Structures - from individual ultrafast motion to diffusion and collective crystallization of 2D lattices

M. Kläui[1,2]

[1] *Institut für Physik and Graduate School of Excellence Materials Science in Mainz, Johannes Gutenberg-Universität Mainz, Mainz, Germany*
[2] *Centre for Quantum Spintronics, NTNU, Trondheim, Norway*

Novel spintronic devices can play a role in the quest for GreenIT if they are stable and can transport and manipulate spin with low power. Devices have been proposed, where switching by energy-efficient approaches, such as spin-polarized currents is used to manipulate topological spin structures [2].

Firstly, to obtain ultimate stability of states, topological spin structures that emerge due to the Dzyaloshinskii-Moriya interaction (DMI) at structurally asymmetric interfaces, such as chiral domain walls and skyrmions with enhanced topological protection can be used [3-5]. Here we will introduce these spin structures ad we have investigated in detail their dynamics and find that it is governed by the topology of the spin structure [3]. By designing the materials, we can even obtain a skyrmion lattice phase as the ground state [4]. Beyond 2D structures, we recently developed also systems with chiral interlayer exchange interactions that lend themselves to the formation of chiral 3D structures [6].

Secondly, for ultimately efficient spin manipulation, we use spin-orbit torques, that can transfer more than $1\hbar$ per electron by transferring not only spin but also orbital angular momentum. We combine ultimately stable skyrmions with spin orbit torques into a skyrmion racetrack device [4], where the real time imaging of the trajectories allows us to quantify the novel skyrmion Hall effect [5]. Recently, we determined the possible mechanisms that lead to a dependence of the skyrmion Hall effect on skyrmion velocity [7]. We furthermore use spin-orbit torque induced skyrmion dynamics for non-conventional stochastic computing applications, where we have developed a skyrmion reshuffler device [8] based on skyrmion diffusion [8]. Such diffusion can furthermore be controlled by symmetry – breaking in-plane magnetic fields [9] and this is useful for token – based Brownian computing.

Finally, we take the next step beyond studying the properties of topological skyrmions and use them as model systems to study phases and phase transitions in two dimensions. We determine the transition of skyrmions from a disordered "liquid" phase to a "hexatic" phase, which is a particular phase that only exists in 2D [10]. This demonstrates that skyrmion lattices are perfectly 2D systems, opening up an avenue to using skyrmions as model systems to study statistical mechanics, phases and phase transitions [10]. In particular in confined structures, thermal skyrmion dynamics can be used to study the skyrmion-skyrmion and skyrmion-wall interaction [11] and details of the pinning energy landscape can be ascertained.

[1] K. Everschor-Sitte et al., J. Appl. Phys., vol. 124, no. 24, 240901, 2018.
[2] G. Finocchio et al., J. Phys. D: Appl. Phys., vol. 49, no. 42, 423001, 2016;
[3] F. Büttner et al., Nature Phys., vol. 11, no. 3, pp. 225–228, 2015.
[4] S. Woo et al., Nature Mater., vol. 15, no. 5, pp. 501–506, 2016.
[5] K. Litzius et al., Nature Phys., vol. 13, no. 2, pp. 170–175, 2017.
[6] D. Han et al., Nature Mater., vol. 18, no. 7, pp. 703–708, 2019.
[7] K. Litzius et al., Nature Electron., vol. 3, no. 1, pp. 30–36, 2020.
[8] J. Zázvorka et al., Nature Nanotechnol., vol. 14, no. 7, pp. 658–661, 2019.

[9] N. Kerber et al., Phys. Rev. Appl. **15**, 044029 (2021).
[10] J. Zazvorka et al., Adv. Funct. Mater. **30**, 2004037 (2020); M. Kläui, Nature Nano. **15**, 726 (2020);
[11] C. Song et al., Adv. Funct. Mater. **31**, 2010739 (2021)

Acknowledgements: The authors acknowledge funding from TopDyn, SFB TRR 146, SFB TRR 173 Spin+X (project A01 #268565370), Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) Project No. 403502522 (SPP 2137 Skyrmionics). We acknowledge financial support from the Horizon 2020 Framework Programme of the European Commission under FET-Open Grant No. 863155 (s-Nebula) and Grant No. 856538 (ERC-SyG 3D MAGIC).