TOPS - Metrology for topological spin structures

Joint Research Project
Newsletter November 2020

Metrology for topological spin structures

Introduction

We are pleased to welcome you to the second newsletter for the "TOPS" Joint Research Project. The project started in June 2018 and will end in November 2021. The underlying goal of TOPS is to develop and establish metrological and scientific tools for the characterization of topological spin structures. This work is expected to contribute to the development of new magnetic storage, spin-logic, and microwave devices in the future well as new quantum standards.

The project is divided into four technical work packages: (i) Towards reliable measurements of key parameters in topological spin structures, (ii) Distinct detection and manipulation of multiple and individual topological spin structures, (iii) Novel dynamical and quantization effects in topological spin structures, and (iv) Materials and simulations.

The aim of this newsletter is to summarize selected work that has been performed across this project over the previous year. More details will be available through further newsletters and on our webpage.

Contact & further information

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(1) Thermoelectrical signature of individual skyrmions

Skyrmions are nano-scale topologically non-trivial spin structures which are inherently robust due to their particular topology and can be driven efficiently by electrical currents. Their electrical characterization and manipulation have been investigated intensely over recent years. However, only very few studies have addressed their thermoelectrical properties.

In our work we study the thermoelectrical signature of individual skyrmions in a Pt/Co/Ru multilayer microdevice using an all-electrical single-shot technique. We achieve this by employing a highly controlled nucleation process using nanosecond current pulses to nucleate skyrmions in single digit numbers confirmed by magnetic force microscopy (MFM) imaging. Subsequently, we controllably annihilate them using a novel approach employing a highly localized stray magnetic field provided by the MFM probe. We attribute the observed thermoelectric signature, unambiguously, to the resulting thermoelectric response to the anomalous Nernst effect (ANE) originating from the spin structure of the skyrmions. For the experimental conditions used in this work, we define a thermoelectric signature of 4.6 nV per skyrmion.

Our findings enable the unique non-invasive characterization, detection and counting of skyrmions in magnetic microdevices adding to the plethora of techniques available and present a route for spin caloritronic devices based on skyrmions. Furthermore, our work provides fundamental insight into the thermo-electrical properties of topological spin structures.

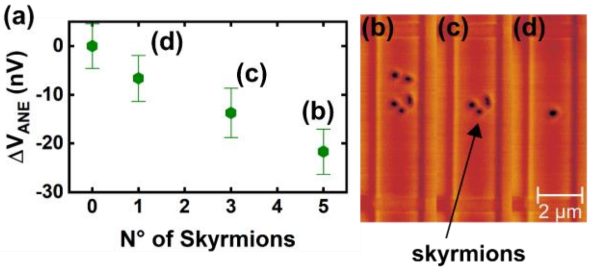

Fig. 1: (a) ANE voltage, ΔV_{ANE}, as a function of the skyrmions present in the microdevice. (b)-(d) MFM measurements sequences showing the skyrmion annihilation process. The green dots in (a) correspond to the skyrmion configuration in (b)-(d).

Reference

[1] A. Fernández Scarioni, C. Barton, H. Corte-León, S. Sievers, X. Hu, F. Ajejas, W. Legrand, N. Reyren, V. Cros, O. Kazakova, and H.W. Schumacher, "Thermo-electric signature of individual skyrmions", Phys. Rev. Lett. [to be published], https://arxiv.org/abs/2001.10251

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(2) Reciprocal space detection of skyrmion eigenmodes: REXS-FMR

The hexagonal skyrmion lattice (SKL) phase of bulk chiral magnets exists in a small pocket in magnetic field and temperature phase space close to the Curie temperature of the material. For Cu_2OSeO_3, one of the prototypical skyrmion hosting materials, not only the static lattice has been investigated in recent years, but, mostly by using broadband ferromagnetic resonance techniques, also the lowest lying dynamic modes of the SKL. These low lying modes comprise the so-called breathing mode of the lattice where the diameter of the skyrmion tubes periodically grows and shrinks at GHz

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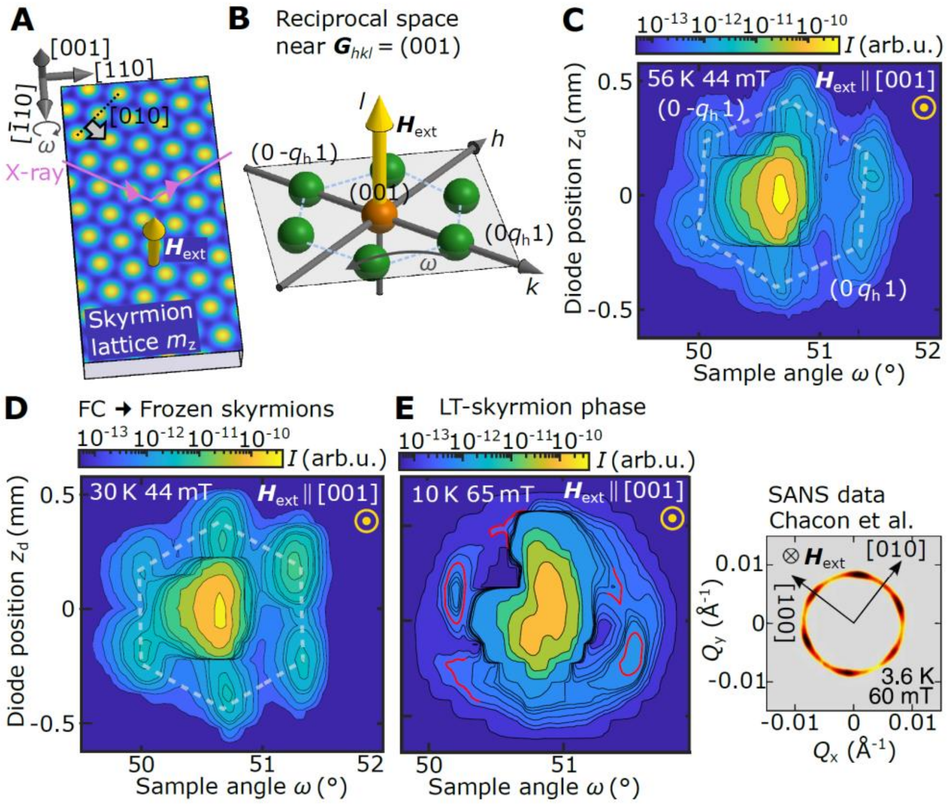

Fig. 2: Reciprocal space maps of skyrmion and LT-skyrmion phase. **(A)** Sample geometry and indicated skyrmion lattice. **(B)** Reciprocal space near (001) with imposed skyrmion $\boldsymbol{q}_\mathrm{h}$-vectors. **(C)** Experimental reciprocal space map obtained by REXS for skyrmion phase and **(D)** field-cooled skyrmion phase. **(E)** Experimental reciprocal space map of LT-skyrmion phase and SANS data for comparison. The SANS data in (E) is taken from A. Chacon et al. *Nat. Phys.* **14,** 936 (2018).

frequencies, and the two gyrating modes, the counter-clockwise and clockwise modes, where the tubes rotate around the tube centre. For typical field values in the SKL pocket, the frequencies lie between 1 and 5 GHz. In the same frequency range, the modes of the helical and conical phases can be found. However, in broadband FMR experiments an unambiguous assignment of the modes is only possible with the help of micromagnetic simulations.

In recent experiments we could show that it is possible to identify the modes in the various phases in reciprocal space [1]. We used magnetic resonant elastic X-ray scattering at the VEKMAG end station at the Bessy II synchrotron, Berlin, to map out the various phases in reciprocal space. Some example reciprocal space maps in the SKL phases are shown in the Fig. 2. We then recorded the intensity of the Bragg peak and of peaks corresponding to the various non-collinear phases of Cu$_2$OSeO$_3$ as a function of magnetic field at a fixed excitation frequency and were able to unambiguously resolve the excitations of this chiral magnet.

Reference

S. Pöllath, A. Aqeel, A. Bauer, C. Luo, H. Ryll, F. Radu, C. Pfleiderer, G. Woltersdorf, and C.H. Back, Ferromagnetic Resonance with Magnetic Phase Selectivity by Means of Resonant Elastic X-Ray Scattering on a Chiral Magnet, Phys. Rev. Lett. 123, 167201 (2019), https://arxiv.org/abs/1909.08293

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(3) Diameter-independent skyrmion Hall angle observed in chiral magnetic multilayers

The topology of magnetic skyrmions, which originates in their chiral domain wall winding, governs their unique response to a motion-inducing force. When subjected to an electrical current that applies such a force by means of a spin-orbit torque, the chiral winding of the spin texture leads to a deflection of the skyrmion trajectory.

The deflection can be characterised by an angle with respect to the applied force direction, known as the skyrmion Hall angle. This skyrmion Hall angle is predicted to be skyrmion diameter-dependent within a Thiele model that treats the skyrmion as a rigid particle-like object moving in a flat energy landscape.

We studied skyrmions in Pt/CoB/Ir multilayers by means of scanning transmission x-ray microscopy at the PolLux

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beamline at the Swiss Light Source at the Paul Scherrer Institute. A 2 µm wide magnetic wire was heated by means of a current pulse to nucleate skyrmions within it. Application of a field in the opposite direction to the magnetisation in the skyrmion core compresses the skyrmions, allowing the diameter to be varied. We then took snapshots of the magnetic textures within the wire after pairs of spin-orbit torque-inducing current pulses and tracked the changes in the position of each individual skyrmion after each pair. Examples of such tracks are given as series of coloured points in the figure. By this means we could determine the average velocity and skyrmion Hall angle for each skyrmion of a known diameter.

In contrast to the Thiele model, our experimental study finds that the skyrmion Hall angle is diameter-independent for skyrmions with diameters ranging from 35 to 825 nm. At an average velocity of 6 ± 1 ms^{-1}, the average skyrmion Hall angle was measured to be 9° ± 2°. In fact, the skyrmion dynamics is dominated by the local energy landscape such as materials defects and the local magnetic configuration.

Reference

Katharina Zeissler, Simone Finizio, Craig Barton, Alexandra J. Huxtable, Jamie Massey, Jörg Raabe, Alexandr V. Sadovnikov, Sergey A. Nikitov, Richard Brearton, Thorsten Hesjedal, Gerrit van der Laan, Mark C. Rosamond, Edmund H. Linfield, Gavin Burnell & Christopher H. Marrows, “Diameter-independent skyrmion Hall angle observed in chiral magnetic multilayers”, Nature Communications **11**, 428 (2020), https://doi.org/10.1038/s41467-019-14232-9

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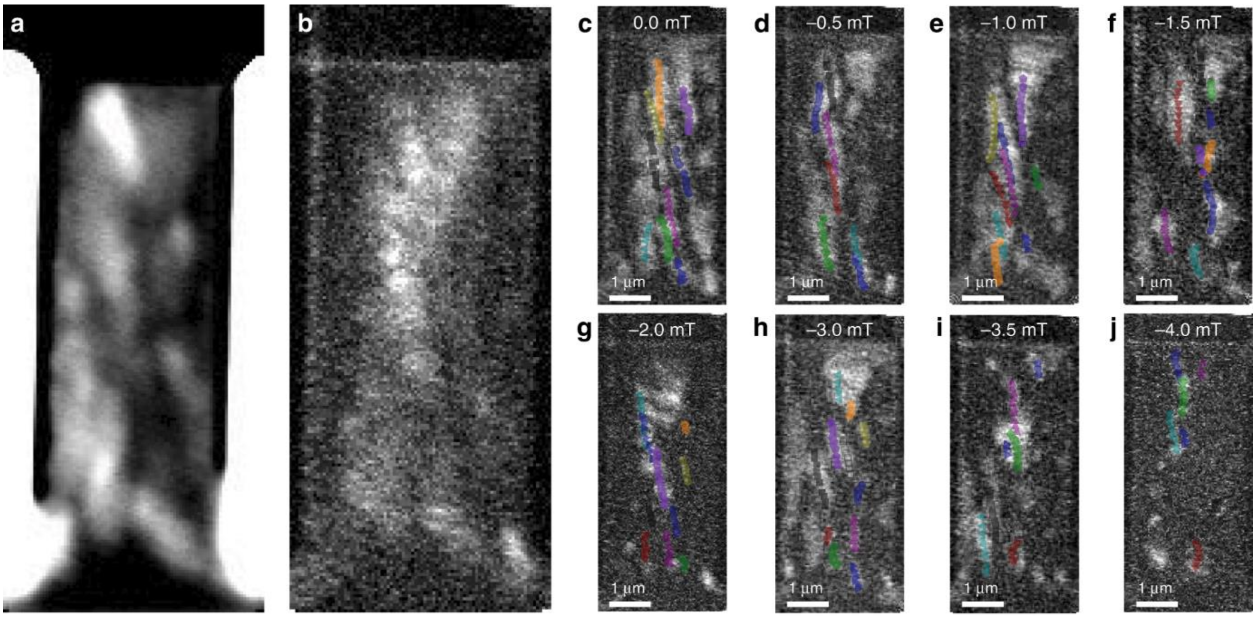

Fig. 3: a Average intensity map of all STXM images. Bright regions represent areas with high probability of containing a reversed magnetic domain or skyrmion. b Average intensity map of the absolute difference between consecutive images. Bright regions show high probability of an expanding magnetic domain or a moving skyrmion. c–j Average intensity map of the absolute difference between consecutive images obtained at each applied field, superimposed are the skyrmion centre positions (coloured symbols) throughout all the pulse series measured in this experiment.