Publishable Summary for 17FUN08 TOPS
Metrology for topological spin structures

Overview

In recent years, topology (the study of the properties of geometric configurations which are unaltered by certain elastic transformations such as a stretching, bending or twisting) has emerged as a fascinating phenomenon in solid state research from both fundamental and applied perspectives. This is particularly the case for certain magnetisation configurations, where the topology protects the spatial magnetisation or spin arrangement. Due to their unique properties, such topologically-protected spin structures (TSS) have the potential to revolutionise the Information and Communications Technology sector. The goal of this project is to underpin fundamental research in this active field by developing metrological tools and methods for the characterisation of TSS and, thus, support future applications. In addition, the feasibility studies towards new topological quantum standards will be explored.

Need

Fundamental research in the field of spintronics has led both to the recognition of scientific merits at the highest level and to extremely fast development of a huge market sector dealing with mass production of consumer and industrial electronics, such as hard disk storage devices and sensors for mobile phones and cars. The search for new materials featuring room temperature operation, ultralow power consumption, full electrical control, and scalability continues apace. Recently, the study of spin structures with a certain topologically-protected spin arrangement, has moved into worldwide focus. Despite intensive ongoing research on TSS (such as *chiral domain walls* which are boundaries between regions of uniform magnetisation with a certain gradual rotation of the magnetisation or *skyrmions,* which are vortex-like spin arrangements with diameters typically ranging between several nm to several 100 nm), there are several high-level requirements in this field connecting basic research, metrology, and ability to exploit these structures in novel devices that need to be addressed:

- The quest for new materials and systems with stable TSS requires a precise understanding and knowledge of relevant material parameters such as the Dzyaloshinskii-Moriya interaction (DMI) constant. However, validated metrology tools for these parameters do not currently exist.

- Due to their nanoscale size, it is difficult to experimentally probe some types of TSS. Therefore, validated measurement methods are needed enabling the identification and manipulation of multiple and individual TSS.

- Reliable concepts for the investigation of current- and field-induced dynamics of TSS at GHz and THz frequencies still have to be developed. In addition, experimental high-risk-high-gain research is required to verify whether TSS enable the realisation of novel quantum standards.

- Future research on TSS requires the fabrication of TSS with reproducible topological characteristics. Micromagnetic simulations and analytical tools are required to validate experimental results and to reliably predict novel material properties.

Objectives

The overall objective of this project is to develop and establish metrological and scientific tools for the characterisation of TSS. This work is expected to significantly contribute to the development of new magnetic storage, spin-logic, and microwave devices in the future well as new quantum standards.

The specific objectives of this project are:

1. To develop and validate metrology tools and methods for reliable determination of key material parameters of TSS, i.e., the Dzyaloshinskii-Moriya interaction (DMI) constant.

2. To develop, compare and validate measurement techniques capable of unambiguously identifying and manipulating specific nanometre-scale TSS, such as domain walls, bubbles, and skyrmions in different magnetic materials. These methods will be applicable to both multiple and individual TSS.

3. To develop methods for the investigation and analysis of novel dynamical and quantisation effects in TSS. This work will capture the dynamics of TSS at GHz and THz frequencies and explore whether TSS might serve as quantum standards at room temperature and low magnetic fields.

4. To provide protocols for the reproducible growth of materials for experiments on TSS and reliable micromagnetic simulations and analytical tools for the modelling of TSS. The simulations will allow for a comparison with and an interpretation of experimental results.

5. To implement a research network on TSS in Europe with complementary infrastructure. To develop guidelines for accurate characterisation of TSS and to implement new measurement services on the DMI constant.

Progress beyond the state of the art

The accuracy of the determination of the DMI constant is crucial for designing materials with TSS and modelling TSS. To date, different strategies for DMI measurement have been attempted leading in part to contradictive results. It is therefore not yet clear how DMI depends on material properties such as composition, interface quality, or layer thicknesses. The project will undertake, for the first time, a systematic comparison of different methods for the determination of the DMI constant and develop a measurement setup suitable for establishing a measurement service for the DMI constant.

TSS such as skyrmions can have a diameter ranging from several nm to several 100 nm. Skyrmions have already been identified using several high-resolution measurement techniques. However, especially with regard to thin films the exact phase transitions of skyrmions are still under deep discussion. The project will develop quantitative measurement techniques and techniques capable of unambiguously identifying multiple and individual TSS. Moreover, novel emergent thermoelectric and electrodynamic phenomena, e.g., spin-charge coupling, will be studied with the aim of obtaining new insight into the electrical manipulation of TSS.

So far, characteristic dynamical modes, which typically occur at several GHz have been identified in TSS by comparing experiments with simulations. Yet, little is known about ultrafast dynamics of topological spin structures at THz frequencies. This project will investigate high-frequency properties of TSS by direct imaging of the characteristic modes at GHz frequencies and by performing THz spectroscopy on TSS. Moreover, feasibility studies towards novel quantum resistance standards operating at room temperature and low magnetic fields will be explored. To this end, TSS will be combined with a low-dimensional semiconductor to seek quantised voltage-current dependencies in transport measurements.

Several bulk crystals have been identified as prototypical materials for TSS and different thin films allow for the existence of TSS. Modelling of TSS has already been used to predict novel properties, however, some topics still lack a general theory. This project will develop protocols for the reproducible growth of materials for TSS with the aim of obtaining stable high-quality and large-size materials. Moreover, the experiments in this project will be supported with micromagnetic simulations, and this combined experimental and theoretical approach will be essential for the success of the project.

Results

Reliable determination of key material parameters of TSS (objective 1)

The DMI constant will be precisely and systematically investigated for the most common material stacks. This will be accomplished through comparisons between different experimental techniques applied to the same sample. Moreover, given that the observation of asymmetric bubble expansion through magneto-optical Kerr effect (MOKE) microscopy is the most widely used method to measure the DMI, this technique will be tested for reproducibility across different laboratories. Additionally, a recently developed technique for measurement of the DMI constant within the project and known as all electric spin wave spectroscopy, will be investigated with respect to its advantages and limits in terms of sample requirements (design, materials), DMI range, reproducibility and accuracy. If feasible, a measurement service for the DMI constant will be established.

Several samples for the DMI comparison were grown and distributed to all partners who take part in the comparison. A protocol including measurement methods, samples, and schedule of the comparison was defined and shared with all partners. Five partners finished the measurements using different techniques, i.e., Brillouin Light Scattering (BLS) and MOKE. An analysis of the results was presented at the M27 meeting and at an international conference. So far, the different measurements are not fully consistent with each other and the differences are currently analysed.

The partners also prepared a software package for the determination of the DMI constant using MOKE and the asymmetric bubble expansion measurement. The software package is intended to enable automatised evaluation of the domain wall velocity from bubbles with rough circumferences. First tests of the software package were made and applied to MOKE measurements obtained from different partners.

Unambiguous identification and manipulation of specific nanometre-scale TSS (objective 2)

A comparison of quantitative magnetic force microscopy measurements on TSS will be conducted. This will, for the first time, deliver reliable quantitative information about the stray field of TSS and, thus, provide a pathway for classification and standardised measurements of such structures. Additionally, spatially resolved measurements on TSS in real and reciprocal space will be compared with transport (anomalous Hall) and thermoelectric (anomalous Nernst) measurements for unambiguous identification of single and multiple skyrmions. These combined and complementary techniques are expected to yield new information about skyrmion characteristics in different bulk materials and thin films. Finally, transport measurements will be used to determine the possibility of observing quantised Hall resistances from single skyrmions.

Different spatially resolved measurement routines have been performed on different TSS (such as multilayers and thin film membrane samples). The magnetic force microscopy setups have been calibrated to allow for quantitative stray field measurements. All measurements for the MFM comparison are finished. Data analysis has been completed on these measurements which resulted in the stray field from different sized skyrmions at a range of different lift heights of the MFM tip. Additionally, error propagation algorithms have been implemented in order to estimate the uncertainties of the skyrmion stray field data, being fully in-line with the targets.

A skyrmion count technique as function of temperature and magnetic field has been developed and will be compared to MFM measurements. Moreover, a paper detailing a recipe on how to measure skyrmion diameters with a certain microscopy technique has been published in Ultramicroscopy, being in good agreement with the targets.

A large variety of thermoelectric and transport measurements have already been undertaken. From this work a paper on individual skyrmion manipulation by local magnetic field gradients has been published in Communication Physics. An additional paper on the thermoelectric signature of individual skyrmions has been accepted in Phsical Review Letters. Moreover, a manuscript on deterministic field-free skyrmion nucleation has been published in Nano Letters. These publications are in good agreement with the targets.

Analysis of novel dynamical and quantisation effects in TSS (objective 3)

Dynamic magnetoelectric modes in TSS will be studied using ferromagnetic-resonance-(FMR)-based techniques and resonant x-ray scattering experiments with the aim of identifying experimentally these modes without invoking theoretical modes. Time-resolved measurements of dynamic properties of TSS will be attempted using spectroscopy based on free-space THz radiation and ultrashort voltage pulses. Moreover, experiments will focus on the possible observation of quantisation effects in TSS. An experimental observation of quantised topological Hall effects will have tremendous implications on electrical quantum metrology by opening a path to long sought room-temperature quantum resistance standards.

FMR measurements have been performed on bulk skyrmion hosting materials in both high temperature skyrmion phase and low temperature phase. Certain dynamic modes have been identified unambiguously using FMR and x-ray scattering experiments and published in Physical Review Letters. Additionally, new low-temperature skyrmion and tilted conical states have been detected in a bulk crystal and published in Physical Review Letters. These dynamical measurements are in very good agreement with our targets.

Different setups for laser-based time-resolved THz measurements on TSS have been built, i.e., setups for time-resolved measurements of the magneto-optical Kerr effect (TR-MOKE) and time-resolved THz spectroscopy. The TR-MOKE measurements were performed in a large parameter range of temperature and magnetic field to study the dynamics in different magnetic phases and identify the contribution of the magnetic order. For both, B20 magnets FeCoSi and MnSi, the helical, conical, and field-aligned phase show characteristic magnetic dynamics. Furthermore, the characteristic eigenmodes of skyrmions in FeCoSi have been detected with TR-MOKE for the first time. Thereby the metastable skyrmion phase at low temperatures, as well as, the skyrmion pocket just below the critical temperature were investigated and compared to each other. The obtained experimental data will now be compared to simulations. This is in good agreement with the targets.

Protocols for reproducible growth of materials and reliable micromagnetic simulations and analytical tools (objective 4)

Protocols for reproducible growth of TSS will be developed. Different growth parameters will be optimised with the aim of obtaining stable high-quality thin-film materials and large-size high-quality bulk materials. The size aspect is especially important for future applications since at present the bulk material size is restricted a few millimetres. Moreover, despite previous theoretical work, the development of new models will be an essential prerequisite to validate the experimental results obtained in this project. Several phenomena such as the anomalous Hall effect, magnetoelectric modes, and spin-charge coupling can only be reliably interpreted and assigned to TSS characteristics if accurate simulations are available.

A variety of multilayer and bulk samples have been grown and characterised. Samples have been shipped to partners for further experiments. All necessary bulk materials and thin films have been prepared and their growth recipes have been optimised. This is in good agreement with the targets.

Simulations will be performed using the software package mumax 3. To this end, different partners have already performed characterisation measurements to obtain accurate input parameters for the simulations, such as anisotropy constants and saturation magnetisation. This is in line with the expected targets of performing simulations and providing magnetic parameters of nanoscale spin structures for the simulations. Different simulations such as stray field calculations, dynamical responses of TSS, and calculations of TSS under high temperatures are currently ongoing.

Impact

This project will create impact for the scientific, metrological, industrial and end user communities through fundamental investigations on spintronics of magnetic nanolayers and nanosystems with the first steps towards traceable measurements on such devices, initial research towards future metrological applications, availability of guidelines for accurate characterisation of topological spin structures and the development of a measurement service in Europe.

Key dissemination activities to date are (i) 47 presentations at international conferences such as MMM-Intermag, CLEO, CPEM, JEMS, or SPIE Photonics West; (ii) 9 published articles in peer-reviewed journals such as Nano Letters, Communication Physics, Physical Review Letters, Physical Review B, Applied Physical Letters; and (iii) an interactive training course/tool for PhD student at INRIM. Additionally, 5 papers have been submitted to peer-reviewed journals. These achievements are in very good agreement with the targets, despite institute closures due to COVID-19.

Impact on industrial and other user communities

ICT is an important sector for economic development in Europe and affects economic growth across the economy. The research in this project will enable a fundamental understanding of novel spintronic effects, enabling promising new device concepts. Such new concepts have already been proven to be important in the past for the foundation of technological companies. Making use of intellectual property protection, new devices and concepts developed in the project will also be offered for exploitation to European stakeholders to increase the competitiveness of the European ICT industry and, thus, consolidate the current excellence of European industry and research institutes.

Close cooperation between NMIs and leading research institutes will provide unique expertise to support the existing research networks on topological spin structures in Europe. Such cooperation might also lead to a follow-on collaboration after the project lifetime and, thus, strengthen the research in Europe. European researchers pioneered this field and are at present among the leading experts. Moreover, several national programmes on topological spin structures are running or planned. Interaction with different national programmes will be an important dissemination activity and collaborations previously established in other programmes will be helpful for the dissemination activities. The DMI already has an influence on today’s magnetic nanoscale devices. With an ongoing decrease of the size of such devices, the influence will even become more important. The successful implementation of the project will create new measurement capabilities for the DMI constant at NMI level from which industry will profit in the short- and long term, respectively.

The project will yield information about charge-spin coupling in TSS, single skyrmion detection, and dynamics of TSS. Such information will be essential for future applications of TSS, e.g., for racetrack memory devices, high density storage devices, or logic devices.

Impact on the metrology and scientific communities

The creation of new electrical quantum standards, which do not rely on ultracold temperatures and high magnetic fields, as needed for present quantum Hall resistance standards, could revolutionise the metrological landscape. TSS are possible candidates for such devices. Investigations in this project will provide information about the possibility of using TSS for quantum resistance standards.

The accuracy of the determination of the DMI strength is crucial for the design of future applications employing TSS, e.g., novel types of magnetic memories. Only if the DMI strength is uniquely defined and measured a clear relation with intrinsic or extrinsic material properties can be established. This project will take a major step to resolve this key scientific controversy by organising a round robin (RR) comparison measurement involving the world-leading groups in the field. For the first time it will thus allow the effects of different measurement setups on the determination of the DMI constant to be pinpointed. If economically feasible, a measurement service for the DMI constant will be established.

Two researchers of the TOPS consortium (Brian Hickey, ULE, and Massimo Pasquale, INRIM) lead a session at the Joint European Magnetic Symposia (JEMS) entitled "Magnetic based metrology tools and techniques".

Impact on relevant standards

So far, no relevant standards exist related to the measurement of the DMI constant. After finishing the round robin measurements of the DMI constant and analysed, and guidelines for DMI measurements will be written afterwards. The consortium is in regularly contact with IEC TC 113 and IEC TC 68 to explore the possibility of implementing an IEC standard on DMI measurements.

Longer-term economic, social and environmental impacts

Several possible industrial products for TSS devices are currently envisaged in the scientific community. First, TSS allow for discrete magnetic states being of smaller size and energetically more stable than their single-domain counterparts. For this reason, it is envisaged that TSS may be used as bits to store information in future memory and logic devices, where the state of the bit is encoded by the existence or non-existence of the TSS. This will have significant economic impact, since the global digital storage device market is anticipated to reach $ 6.27 billion by 2022. Second, the position of TSS within a nanostructure may be manipulated using low current densities. Thus, TSS also provides promising candidates for future racetrack-type storage or logic devices. Third, TSS exhibit strong gyrotropic and breathing modes at GHz frequencies, which might open the avenue for TSS-based microwave applications.

A major goal of the EU is a 20 % increase of energy efficiency and a corresponding reduction of CO_2 gas emissions by 2020. The use of low power magnetic logic and storage devices based on TSS could lead to more energy efficient ICT and CE devices enabling a significant reduction of global energy consumption.

Society needs technologies based on innovative and disruptive products and concepts. TSS offers the potential to create novel spin-based electronic devices with improved speed, reliability and significantly decreased power consumption.

List of publications

[1] S. Saha, M. Zelent, S. Finizio et al., "Formation of Néel-type skyrmions in an antidot lattice with perpendicular magnetic anisotropy", Phys. Rev. B 100, 144435 (2019), https://arxiv.org/abs/1910.04515

[2] A. Casiraghi, H. Corte-León, M. Vafaee et al., "Individual skyrmion manipulation by local magnetic field gradients", Commun Phys 2, 145 (2019), https://arxiv.org/abs/1903.00367

[3] S. Pöllath, A. Aqeel, A. Bauer et al., "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

[4] K. Zeissler, S. Finizio, C. Barton et al., "Diameter-independent skyrmion Hall angle observed in chiral magnetic multilayers", Nat Commun 11, 428 (2020), https://doi.org/10.1038/s41467-019-14232-9

[5] G. Carlotti, “Pushing down the lateral dimension of single and coupled magnetic dots to the nanometric scale: Characteristics and evolution of the spin-wave eigenmodes”, Applied Physics Review 6, 031304 (2019), https://arxiv.org/abs/1908.11098

[6] Weinan Lin, Baishun Yang, Andy Paul Chen et al. “Perpendicular Magnetic Anisotropy and Dzyaloshinskii-Moriya Interaction at an Oxide/Ferromagnetic Metal Interface”, Phys. Rev. Lett. 124, 217202 (2020), https://arxiv.org/abs/2006.14268

[7] C. Back, G. Carlotti, A. Casiraghi e al., “Measuring Interfacial Dzyaloshinskii-Moriya Interaction: A Review”, Proceedings 26, 41 (2019), https://doi.org/10.3390/proceedings2019026041

[8] S. Finizio, K. Zeissler, S. Wintz et al., “Deterministic Field-Free Skyrmion Nucleation at a Nanoengineered Injector Device”, Nano Lett. 19, 7246-7255 (2019), https://arxiv.org/abs/1902.10435

[9] S. Pöllath, T. Lin, N. Lei et al., “Spin structure relation to phase contrast imaging of isolated magnetic Bloch and Néel skyrmions”, Ultramicroscopy 212, 112973 (2020), https://arxiv.org/abs/2002.12469

This list is also available here: https://www.euramet.org/repository/research-publications-repository-link/

Project start date and duration:	01 June 2018, 42 months	
Coordinator: Mark Bieler, PTB Tel: +49-531-592-2540 E-mail: mark.bieler@ptb.de Project website address: https://www.ptb.de/empir2018/tops		
Internal Funded Partners: 1 PTB, Germany 2 INRIM, Italy 3 NPL, United Kingdom	External Funded Partners: 4 Singulus, Germany 5 TUM, Germany 6 ULE, United Kingdom 7 UNIPG, Italy	Unfunded Partners: -
RMG1: INRIM, Italy (Employing organisation); PTB, Germany (Guestworking organisation)		