Mesoscale Priority Research Direction

Magnetization Dynamics: The Inherently Mesoscale Problem

Opportunity

Magnetization dynamics are key ingredients to many magnetic phenomena and at the same time offer a rich variety of complex behavior. Even though the underlying equations of motion are well established the connection of magnetization dynamics to other degrees of freedom (charge and heat flow, mechanical motion) is still wide open for exploration.

Approach

This research requires to synthesize magnetic materials and heterostructures with tailored properties, which take advantage of magnetic interactions spanning many lengthscales. Advanced spectroscopy and microscopy together with multi-scale modeling will allow to unravel the underlying physics.

Meso Challenge

Magnetization dynamics are governed both by competing short-range exchange interactions (THz and nm) and long-range dipolar interactions (GHz and >µm), which generate a surprising amount of complexity.

Impact

A better understanding of magnetization dynamics is crucial for many basic and applied research fields ranging from information technologies over magnetism based energy conversion to biomedical applications.

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B. Lenk, H. Ulrichs, F. Garbs, and M. Münzenberg, Phys. Rep. **507**, 107 (2011)
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Mesoscale Magnetic Interactions For Efficient Technologies

Magnetic interactions span across a wide variety of length and time-scales – from ultrafast (fsec) exchange between neighboring atoms to long-range dipolar interactions, which enable probing and manipulating magnetism at a distance and at moderate speed. Concurrently, the electron spin can be coupled to charge transport and lattice vibrations through spin-orbit coupling, which generates complex pathways for controlling spin behavior. For these reasons magnetism is key to many modern applications, ranging from information technologies to energy conversion. The grand challenge for progressing towards the thermodynamic Landauer limit of information processing is the conundrum of combining data retention, requiring high thermal stability, with low-power computation, requiring small energy differences. Towards this end, modern magnetic materials and devices contribute significantly to improvements of computational performance and energy efficiency of both data storage and logic. For energy applications the important issues are the inherent energy stored in the magnetization and the interaction with charge and heat currents. New surprising solutions for many of these applied problems come from recent basic science developments, such as spin currents, spin torques, electric field or photonic effects. Similarly, the ability to synthesize emerging magnetic materials and heterostructures with tailored properties, which take advantage of the magnetic interactions across various fundamental length- and time-scales, will enable to harness the full potential of these new physical phenomena. At the same time cutting-edge analytical tools, such as X-ray, neutron, electron, and probe-based spectroscopy and microscopy combined with multi-scale computational techniques allow unraveling the underlying physics across all length and time scales.

The main focus of current magnetism research revolves around fundamental science issues involving competing interactions. This encompasses static and dynamic magnetization textures, which balance short-range exchange with long-range dipolar interactions and give rise to critical phenomena, such as magnetic phase transitions. Similarly, interactions at materials interfaces and surfaces can result in completely new spin phenomena, such as emergent magnetism at complex oxide interfaces, hard/soft core shell structures or the quantum spin Hall effect, when Rashba spin-orbit coupling can overcome the bulk bandgap in topological insulators. This enables fundamentally new energy efficient ways of coupling spin transport to other degrees of freedom, including electric fields or charge and heat transport. Recent examples include novel pathways to multiferroic behavior from rotational degrees of freedom, unexpected coupling between spin and heat currents in ferromagnetic insulators, and the switching of magnetization via direct charge currents and spin-orbit coupling. The latter has direct applied impact, since it eliminates the need for a magnetic reference layer for spin torque effects, which in turn enables novel schemes of magnetic information technologies with the ultimate goal of controlling spin properties down to the single-spin level. This research requires the combined effort of cutting edge **synthesis**, such as deposition and self-assembly methods, **analytical tools** such as X-ray, neutron, electron, and probe-based based spectroscopies and microscopies, ultrafast X-ray and optical techniques as well as transport and magnetometry measurements; and **theoretical efforts** in the computation of electronic structures of these materials and in modeling magnetic distributions, domain distributions and dynamics and transport properties.

Examples of open mesoscale research topics:

- Manipulating spins via spin currents and spin torque
  - Charge currents generate spin accumulations on nm scales, while heat currents results in spin currents over mm scales; why is there such a big difference in scale? Do magnons matter for heat conduction?
  - Beyond the Macrospin approximations: How do non-local effects due to spatial magnetization inhomogeneities influence magnetization dynamics?
  - Can thermal spin currents give rise to novel thermoelectric effects?
  - How do we harness the mechanical angular moment flow associated with spin currents?
  - Can electric field effects replace charge current based magnetization manipulation?
- Magnetization dynamics from competing interactions
  - How do spatial and temporal varying magnetic textures connect to charge dynamics?
  - Is it possible to harness the increase of non-linear magnetization dynamics in confined systems?
  - Can we use spin or magnetization dynamics for computation, i.e., magnetic quantum cellular automata?
- Coupled order parameters
  - Does phonon-magnon coupling matter?
  - Can we have quantum coherent systems based on photon and magnon interactions?
  - What are the design principles for high-performance multiferroic materials?
- New materials and devices
  - What is the transition from quantum to classical magnetic behavior?
  - Can proximity in mesoscale structures dramatically increase magnetic anisotropies?
  - Does far from equilibrium matter for magnetic systems?
  - Are magnetic systems useful as high-power, high-bandwidth, and high frequency oscillators?