Topological spin structures for spintronics

Topological spin structures beyond skyrmions from first-principles

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In Short

- Topological spin structures beyond skyrmions exhibit favorable transport properties, most prominently absence of skyrmion Hall effect.
- Use of co-existing metastable topological spin structures allows to encode bits (0 and 1) for spintronic applications.
- We use density functional theory in combination with atomistic spin models to study the stabilization mechanisms and lifetime of topological spin structures beyond skyrmions.
- We will predict material systems which will allow the observation of such spin structures via spin-polarized scanning tunneling microscopy by our collaboration partners.

Magnetic skyrmions [1] stable, localized spin structures hold great promise for future spintronic applications such as magnetic data storage or logic devices, as well as for neuromorphic computing [2–4]. A skyrmion is characterized by its topological charge or skyrmion number Q defined by:

$$Q = \frac{1}{4\pi} \int \mathbf{m} \cdot \left(\frac{\partial \mathbf{m}}{\partial x} \times \frac{\partial \mathbf{m}}{\partial y} \right) dx\, dy \qquad (0.1)$$

where $\mathbf{m}(\mathbf{r})$ is the unit vector of the local magnetization and Q can take only integer values. For the skyrmion shown in Fig. 1(a) the integral results in an integer value of $Q = -1$ and for the antiskyrmion in Fig. 1(b) a value of $Q = +1$ is obtained. The ferromagnetic state is topologically trivial since $\mathbf{m}(\mathbf{r})$ is constant which leads to $Q = 0$. The topology of the skyrmion leads to a protection against continuous deformations e.g. due to external perturbations such as an applied magnetic field.

A key limitation of their potential application in spintronic devices is the skyrmion Hall effect which leads to a deflection of skyrmions from the direction of the electric current [2]. Therefore, skyrmions in a race-track like geometry [3] move towards the edge of the track resulting in their annihilation and thus the loss of information. In terms of using skyrmions as information carriers it is also hindering that the bit can only be stored by the presence $(= 1)$ or absence $(= 0)$ of the skyrmion. It is highly desirable to have another kind of metastable spin structure which can act as the zero bit value. Therefore, it is not only interesting from the fundamental point of view to study systems in which more than one type of metastable spin structure can co-exist.

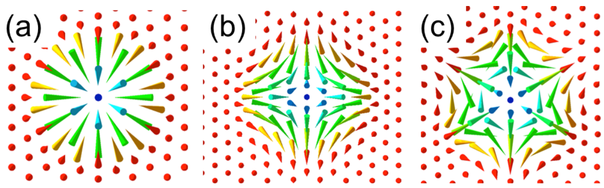

Figure 1: Spin structures of (a) a skyrmion ($Q = -1$), (b) an antiskyrmion ($Q = +1$) and (d) a higher-order antiskyrmion ($Q = +2$). Every cone denotes the magnetic moment direction $\mathbf{m}$ of a single atom in the hexagonal film. The color denotes the out-of-plane magnetization component with blue cones pointing downwards and red cones pointing upwards. Spin structures were obtained based on DFT parameters for Pd/Fe/Ir(111) using atomistic spin dynamics [7].

A zoo of topological spin structures beyond skyrmions, e.g. antiskyrmions, antiferromagnetic skyrmions, skyrmionium, higher-order skyrmions or bimerons, has been predicted [5–10] (see Fig. 1 for examples). These spin structures exhibit promising properties most prominently improved control due to the absence of the skyrmion Hall effect [11]. However, most of the theoretical studies are based on spin models with arbitrary magnetic interaction parameters and the stability of these spin structures remains largely unexplored. In particular, the collapse mechanisms are unknown and the energy barriers protecting them against annihilation have not been calculated.

Ultimately, the lifetime of such topological spin structures needs to be determined which is a very challenging task due to the complexity of possible transition paths and the need to calculate not only energy barriers but also the attempt frequency of the Arrhenius law. There is also a strong need for first-principles calculations in combination with atomistic spin simulations to explore the properties of topological spin structures beyond skyrmions and to predict promising material systems for their discovery and for potential applications.

In this project, we will develop and apply an atomistic spin simulations code built on first-principles electronic structure theory using density functional theory (DFT) to predict novel magnetic interfaces exhibiting topological spin structures beyond skyrmions. Using cutting-edge atomistic spin simulations [12–16] – which are further developed within this project such that they can be applied to topological spin structures beyond skyrmions – we will explore their properties such as collapse and creation mechanisms, their stability and their lifetime at finite temperature based on DFT parameters for all magnetic interactions. The choice of systems is such that they are experimentally feasible which may allow to discover topological spin structures beyond skyrmions and to investigate their properties. This will be an important step towards using such spin structures in spintronic devices.

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More Information

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Project Partners

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