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Unconventional magnetic states and defects

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Popular Summary

Over the last few centuries, our world has been experiencing rapid industrialization and urbanization, which will continue driving the global economic growth. However, it is crucial to recognize the challenges associated with this growth, particularly, the high energy consumption required for rapid development. This level of energy consumption is not sustainable in the long run due to the threats of global warming and the limitations of our natural resources. Therefore, finding ways to control and reduce global energy consumption is critical. Information is at the core of all major energy-consuming countries, as devices processing and storing data require significant energy. By searching for innovative and efficient data storage methods with low-energy demands, we work towards a more sustainable future for our planet.

Magnetic memory is an essential technology used in modern hard disk drives to store data. It utilizes large stripe domains of magnetization that are either up or down to represent the information bits. One proposed idea to improve this technology was to use cylindrical domains of flipped magnetization, called magnetic bubbles. Unfortunately, this approach was not as efficient as the semiconductor memory, so researchers continued to search for new ways to improve magnetic memory technology.

One promising approach is to use something called Magnetic Skyrmions. These tiny magnetic particles are very stable and can be moved by an electric current. These properties make Skyrmions ideal candidates for racetrack memory devices, wherein the Skyrmions move along a nanowire, akin to a train on a track. This technology can make magnetic memory devices much more efficient and powerful than they are currently.

Scientists also intensively study other unconventional magnetic states and defects in materials. They search for new emergent phases of matter, robust nanoscale quantum Skyrmions, and new types of topological defects in non-collinear antiferromagnets. By studying specific materials, we aim to understand better how these novel states can be stabilized and controlled. These insights are crucial for understanding how magnetic memory works at the microscopic level and how to improve it in the future.

In this thesis, we focused on realistic magnetic materials experimentally shown to host unique magnetic states, which conventional magnetic models cannot describe. We used state-of-the-art analytical and numerical methods, as explained in detail in **Chapter 1**. Chapter 1 also presents the main mechanisms in the magnetic energies of these materials that stabilize non-collinear magnetic textures, examining it from both microscopic and macroscopic perspectives.

In Chapter 2, we theoretically studied magnetism in thin films of $SrRuO_3$. This ferromagnetic material shows remarkable stability of the Skyrmion crystal subjected to temperature changes and tilted magnetic fields. We discovered an interesting interplay between the magnetostatic, second- and fourth-order anisotropic interactions. This combination ultimately gives rise to the robust Skyrmion crystal phase in this material.

In Chapter 3, we studied the non-collinear antiferromagnet, $Ba_3TaFe_3Si_2O_{14}$, called Fe-based langasite. Recent experiments showed that this complex material hosts unconventional magnetic structures due to multiple competing spin interactions. To understand these structures, we designed an effective model describing large-scale magnetic superstructures in this material and studied their behavior under applied magnetic fields. By using this model, we successfully reproduced experimental results. Our research led to the discovery of novel magnetic states, such as the three-dimensional Skyrmion and other two-dimensional vortices. Interestingly, similar particle-like states were predicted in other physical contexts, e.g., particle physics and superfluid ^{3}He. This work has significant implications, as it opens horizons to search for other materials hosting compact non-collinear structures in three dimensions. Such materials can be used in three-dimensional designs of memory devices and pave the way for exciting advancements in this field.

In Chapter 4, we derive an effective spin model of the ferromagnetic van der Waals material, CrI_3. CrI_3 is particularly interesting, because it was one of the first magnetic materials successfully exfoliated into a monolayer, making it a magnetic analog of graphene that allows studying magnetism in two dimensions. One unique feature of this material is its heavy iodine, which was predicted to give rise to the bond-dependent anisotropy of spin interactions. These anisotropic Kitaev interactions form the basis of one of the most intriguing ideas for obtaining non-volatile quantum computations. Our model calculations clarify the origin of spin-dependent interactions between magnetic ions and set the sound basis for the use and further study of these anisotropic two-dimensional magnets.

In Chapter 5, we numerically study the magnetization reversal process in the Zn-doped kamiokite $Fe_{2-x}Zn_xMo_3O_8$. This ferrimagnetic material exhibits a strong coupling between magnetic and ferroelectric orders. Our simulations explain the recently observed humps of electric polarization in the magnetic switching process of this material. Surprisingly, the electric polarization peaks originate from the metastable antiferromagnetic phase intervening between the magnetization up and down states. This discovery sheds light on the interplay between the magnetic and electric behavior of this material, contributing to a better understanding of its unique behavior.