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Unconventional magnetic states and defects

Barts, Evgenii

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Summary and Outlook

Main aspects of our research can be unveiled within the concept of emergence, which refers to the phenomenon where a complex system exhibits behavior that is significantly different from its individual parts. P. W. Anderson describes emergence in his passage *More is Different* as “the whole becomes not only more than but very different from the sum of its part”. One example of emergence is the Skyrmion, the described above spatially extended collective state in magnets. Emergence challenges reductionism, which involves deconstructing a complex system into smaller comprehensible blocks. While reductionism is quite useful in science, it can limit our understanding because the questions we ask shape the answer we get. Thereby, recognizing these two opposite question lines is highly important. Due to advances in various scientific disciplines, including physics, biology, and computer science, in the latter half of the 20th century, the idea of emergence has become more popular among scientists.

In biology, the simple behavior of individual neurons eventually leads to the enormous complexity of the brain. Similarly, in computer science, neural networks exhibit intricate capabilities despite the simplicity of their individual components. In art, a single brushstroke may represent nothing, but the whole painting evokes lots of emotions. Social sciences also highlight the distinction, namely that the behavior of society is conceptually different from a person’s behavior. All these examples demonstrate a crucial property of a complex system – how its emergent properties strongly differ from the properties of its parts.

In condensed matter physics, Skyrmions in magnets have new properties that cannot be observed at the scale of a single magnetic ion. Emergent systems may not even involve individual particles as entities. For instance, the phenomenological Landau theory of magnetism does not imply any knowledge about the microscopic behavior of magnetic ions. Another example is superconductivity, where an electric current flows without dissipation, the property of large ensembles of electrons that cannot be found in a single electron system.

Through our study of emergent unconventional magnetic states, we contribute to understanding complex interactions in strongly-correlated electron systems, by exploring their rich and diverse behavior in realistic materials.

In this thesis, the first chapter explains the concept of non-collinear magnetism used throughout the work.

In Chapter 2, we studied a centrosymmetric ferromagnet $SrRuO_3$, which exhibits bizarre humps in Hall resistivity attributed to the presence of stable Skyrmion lattices. We used numerical analysis to obtain magnetic phases in thin films of this material. We showed that magnetic bubbles stabilized by magnetostatic interactions are stable in a much wider region than it was previously thought. The resilience of skyrmion lattices against oblique magnetic fields is attributed to the higher-order magnetocrystalline anisotropy of Ru ions with strong spin-orbit coupling.

In Chapter 3, we predicted a new type of 3D Skyrmion, a stable magnetic particle extended to three spatial dimensions, in a chiral frustrated antiferromagnet, the iron-based langasite $Ba_3TaFe_3Si_2O_{14}$. In zero magnetic field, this material shows the non-collinear 120° state of Fe spins, which is tuned into a short-range spiral by competing interlayer interactions. We proposed an effective model that describes large-scale magnetic superstructures recently observed in neutron diffraction experiments. We discuss two- and three-dimensional topological defects stabilized by Dzyaloshinskii-Mroiya interactions in this chiral magnet. We found that two-dimensional Skyrmions in this material behave as charged particles. We also discovered a new type of vortex, which does not have a singular core. We predict a new type of topological defect – a stable magnetic particle, which resembles Shankar monopole in superfluid ^{3}He-A and hedgehog in the Skyrme model of baryons. Mobile magnetic particles with unique properties in non-collinear antiferromagnets hold significant promise for advancements in antiferromagnetic spintronics.

In Chapter 4, we developed a microscopic model of strongly interacting electrons that describes magnetic properties of the van der Waals magnet, CrI_3. Harnessing and controlling magnetism in ultra-thin films, known as 2D materials, holds great promise for applications where magnetism is manipulated with electricity and light. Surprisingly, ferromagnetism was discovered in a single layer of CrI_3, which highlights the importance of anisotropic exchange interactions in 2D magnets. We calculated spin-spin interactions between neighboring atoms and argued how they affect the magnetic behavior of CrI_3. Our findings help explain the unusual properties of this material, such as the absence of certain interactions and a significant energy gap in the magnon spectrum. Our predictions are in good agreement with inelastic neutron scattering data. This study enhances our understanding of intricate magnetic properties of 2D van der Waals materials and paves the way for advancements in this rapidly evolving field.

In Chapter 5, we studied the process of magnetization reversal in a ferrimagnetic material $Fe_{2-x}Zn_xMo_3O_8$, called Zn-doped kamiokite. In this material, our colleagues have experimentally discovered a fascinating multiferroic behavior: a sudden increase in the electric polarization during the magnetization switching process. Through advanced Monte-Carlo simulations, we have discovered that this magnetization reversal involves a unique competition between two different magnetic phases. Namely, an antiferromagnetic phase with a higher electric polarization intervenes between the two ferromagnetic up and down magnetization states and facilitates the magnetization reversal process. This discovery suggests that the magnetization of kamiokite and similar materials can be controlled using carefully designed protocols favoring transitions between stable and metastable states. This breakthrough opens up exciting possibilities for the electric manipulation of magnetism, which could have significant implications for future technologies.

Overall, this work contributes to a deeper understanding of complex non-collinear magnetic structures, which can be potentially used in spintronics. Magnetic memory is a crucial technology that allows us to store and manipulate vast amounts of information. With continued research and innovation, we can make magnetic memory even more efficient and less-energy consuming, opening up new possibilities for technology in the future.