Skyrmions in Chiral Metals

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Introduction

This talk continues the discussion of skyrmions as a topological excitation. In contrast to the last talk, skyrmions appear here in a small region in the phase diagram of a certain class of *chiral* structures, for which manganese silicide ($MnSi$) serves as an example.

The Impact of Chirality

In chiral materials inversion symmetry is broken, i.e., after mapping every point $\vec{x}$ to -$\vec{x}$ there exists no sequence of rotation and translation, such that the system is in the same state as before.

The lack of inversion symmetry gives rise to some additional, chiral terms in the free energy like the Dzyaloshinskii-Moriya term S_{DM} (1) which leads to a small displacement of adjacent magnetic moments with respect to each other.

$$S_{DM} = \int d^3x \; 2D \, \hat{\mathbf{M}} \cdot \left(\nabla \times \hat{\mathbf{M}} \right) \tag{1}$$

The wavelength λ of the resulting helical structures depends on the coupling constant and is usually very long compared to the lattice constant a. The coupling of these spin structures to the underlying lattice is therefore very weak, which allowes the skymion lattice to be set into motion quite easily.

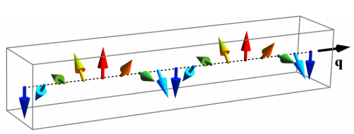

Figure 1: *Spins align in a helical structure. [1]*

Skyrmionic Phase

In a small temperature region ($26K - 28K$ for $MnSi$) and at a finite external magnetic field ($0.1T - 0.2T$ for $MnSi$) the state which lowers the free energy most[1] consists of not only one, but three helices[2] which together form a magnetic whirl structure resembling the skyrmions of last talk.

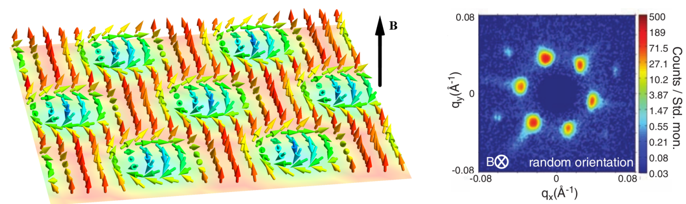

Figure 2: *Left: Skyrmion in real space. Right: actual data from neutron scattering. [1]*

Emergent Electrodynamics

As seen in the last talk, a test electron moving through the skyrmion structure picks up a Berry phase, which can be written as an effective Aharonov–Bohm phase caused by an emergent magnetic field $\mathbf{B}^e$ and electric field $\mathbf{E}^e$. These fields read

$$B_i^e = \epsilon_{ijk} \frac{\hbar}{2} \, \hat{\mathbf{M}} \cdot \left(\partial_j \hat{\mathbf{M}} \times \partial_k \hat{\mathbf{M}} \right) \tag{2}$$

$$E_i^e = \hbar \, \hat{\mathbf{M}} \cdot \left(\partial_i \hat{\mathbf{M}} \times \partial_t \hat{\mathbf{M}} \right) \tag{3}$$

And with $\partial_t \hat{\mathbf{M}} = \frac{\partial x_i}{\partial t} \cdot \partial_{x_i} \hat{\mathbf{M}}$ the emergent electric field can be written as $\mathbf{E}^e = -\mathbf{v}_d \times \mathbf{B}^e$, with the drift velocity $\mathbf{v}_d$.[3]

In Hall measurements (see [2]) these emergent fields contribute to the Hall resistivity and thus can be experimentally observed. Most interestingly, experimental data show that even a small current density is sufficient to induce motion in the skyrmion lattice.[4]

References

[1] K. Everschor: *Current-Induced Dynamics of Chiral Magnetic Structures*, PhD Thesis

[2] A. Rosch et al.: *Emergent electrodynamics of skyrmions in a chiral magnet*, Nat. Phys. 8, 301-305 (2012)

[3] S. Buhrandt, L. Fritz: *Skyrmion lattice phase in three-dimensional chiral magnets from Monte Carlo simulations*, Phys. Rev. B 88, 195137 (2013)

[1] In a mean field analysis the Skyrmion solution only corresponds to a local minimum, the global minimum still consists of only one helix. Only when taking fluctuations into account, the skyrmionic phase becomes stable. This effect is called "*order by disorder*".

[2] As can be seen in the right part of Fig. 2, the three helices are just a first approximation to the actual solution. There exist higher order modes with half the wavelength (double wave vector $\mathbf{q}$). The wights of these modes however decay rapidly.

[3] Note that the emergent electric field is only nonzero for a moving skyrmion, whereas the magnetic field is present even in the static case.

[4] The critical current density was $\sim 10^6 A/m^2$ which is much lower than $10^{11} A/m^2$ needed to move magnetic domain walls in todays HDD's.