Observation of a Lattice of Skyrmions in a Magnetic Metal

Featured papers:

1. "Skyrmion Lattice in a Chiral Magnet "
   Authors: S. Mhlbauer, B. Binz, F. Jonietz, C. Pfleiderer, A. Rosch, A. Neubauer, R. Georgii, P. Boni , arXiv:0902.1968. [Science 323, 915 (2009)]

2. "Topological Hall effect in the A-phase of MnSi"
   Authors: A. Neubauer, C. Pfleiderer, B. Binz, A. Rosch, R. Ritz, P. G. Niklowitz, P. Boni, arXiv:0902.1933.

3. "Unusual Hall Effect Anomaly in MnSi Under Pressure"
   Authors: Minhyea Lee, W. Kang, Y. Onose, Y. Tokura, N. P. Ong, arXiv:0811.3146.

Recommended with a commentary by Ashvin Vishwanath, UC Berkeley

In solid state systems, crystalline order is usually associated with the atomic positions. A notable exception is vortex matter in a superconductor, which leads to a host of new phenomena. The low energy scales associated with this crystalline order make it susceptible to disordering by thermal and quantum fluctuations and impurities. The resulting state of the vortex matter has a major impact on transport properties that continue to be actively studied and debated.

The featured references present evidence for an analogous crystalline order of spin spirals in the material MnSi, and their impact on transport properties. Over two decades of work has lead to a detailed characterization of MnSi, making it one of the best studied metallic magnets. To briefly summarize the earlier work: at ambient pressure, below 30K, magnetic order sets in. The order is nearly ferromagnetic, but the absence of inversion symmetry in the B20 structure of MnSi leads to Dzylosinskii-Moriya interactions that cause the order to spiral with a long pitch of 190Å. In this helical-order state, the magnetic moments are perpendicular to the spiral wave-vector, which is weakly pinned to a crystalline direction. A small magnetic field (0.1Tesla) is sufficient to unpin the spiral, and the wave-vector now aligns with the field direction, allowing the moments to cant and take advantage of the field. This conical phase is finally destroyed at high enough fields (0.6Tesla), where the spiral is ironed out, leading to a uniformly polarized ferromagnet. It is natural to ask if more complex magnetic orders can occur, with several spiral wavevectors simultaneously present, as in a crystal. If so what physical consequences would they lead to?

Article 1 reports a neutron scattering study of MnSi in a particularly interesting parameter regime. Earlier studies had identified a distinct magnetic phase ('A' phase) in a wedge shaped region at temperatures near the transition, and for a range of magnetic field values, as shown in the figure. However, the precise order in this phase was unknown until now.

As described in Article 1, Bragg peaks of six spiral wavevectors were observed in this phase, in a plane perpendicular to the applied field. Theoretical calculations show that such a hexagonal array of spirals is energetically favored in a magnetic field (for the same reason that the triangular lattice is chosen by two dimensional solids), and its stability is enhanced by thermal fluctuations. They also predict the field orientation property of this state. This was confirmed experimentally by rotating the field to different orientations, and verifying that the magnetic Bragg peaks followed. Multi-spiral structures are rare in metallic magnets, until now having been seen only in a few rare-earth materials. Field control of the magnetic structure appears to be unique to the A phase of MnSi.

The real space magnetic structure implied by this multi spiral state, is also shown in the figure. A triangular lattice of skyrmions appears, where the spin direction in each unit cell maps out all the points on a sphere. Like vortices, these skyrmions have a quantized charge Q associated with them - if $\hat{n}(r)$ is the direction of the spin field at point r, then

$$Q = \int_{\text{unitcell}} \frac{dxdy}{4\pi} \hat{n} \cdot (\partial_x \hat{n} \times \partial_y \hat{n}) \tag{1}$$

here $Q = -1$. Therefore, much like a field induced lattice of quantized vortices in a superconductor, here a two dimensional lattice of skyrmions appears perpendicular to the field direction. The lattice spacing however is field independent and controlled by the spiral wavelength ($\sim 190\mathring{A}$). A simple spiral of course shows none of this structure and has $Q = 0$. Historically, soliton solutions of this type were invoked by H.J. Skyrme to account for protons and neutrons within a pion field theory. In the condensed matter context, they are perhaps most familiar from the physics of the quantum Hall effect.

This skyrmion lattice real space structure is not simply a curiosity, for it has an interesting physical consequence. An electron moving in such a background will tend to align its spin along the local magnetic moment, and pick up an additional Berry's phase in the process. This can be interpreted as the Aharonov-Bohm phase of an additional magnetic field, which

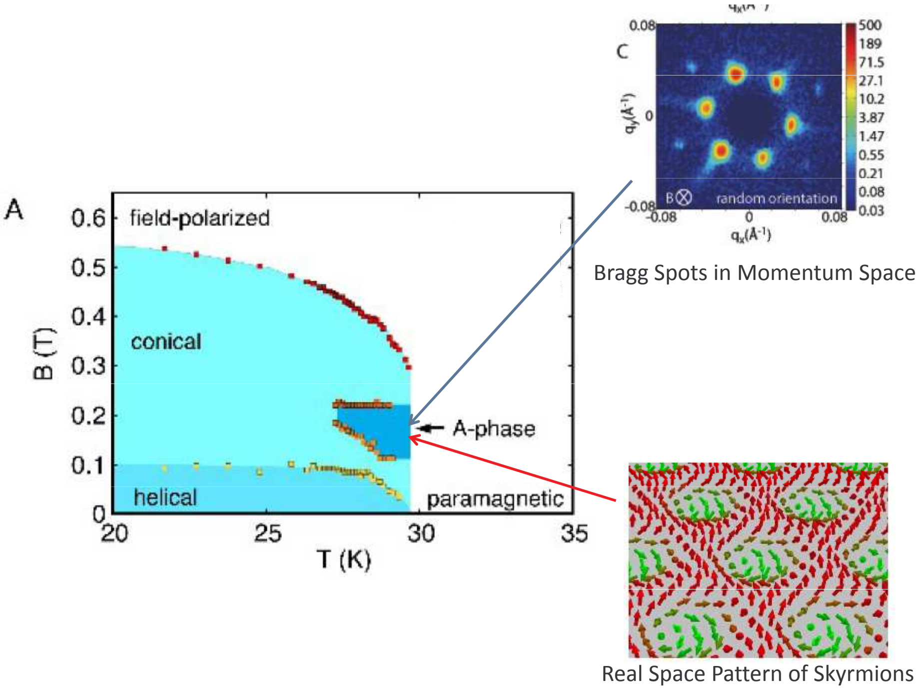

FIG. 1: Magnetic phase diagram of MnSi at ambient pressure. In the A-phase, Article 1 observes a multi-spiral magnetic structure, which forms a triangular lattice in the plane perpendicular to the field. The real space magnetization pattern corresponding to this is also shown - a lattice of skyrmions is present. In each unit cell, the central spin points down, and rotates on moving outwards till it point up along the unit cell boundary. Figure taken from Article 1.

will lead to a contribution to the Hall effect. Note, this occurs over and above the usual Hall effect as well as the anomalous Hall effect of ferromagnets with uniform polarization. Since this Hall effect is related to real space topological textures and the effective flux is in fact the topological density in (1), it is sometimes called the 'topological' Hall effect (in contrast, the anomalous Hall effect is related to similar topological textures in *momentum* space). Careful measurements of the Hall effect through the A phase is reported in Article 2, which detect this contribution. This part of the signal cannot be readily attributed to the anomalous Hall effect, and is argued to have the same sign and magnitude as theoretically expected for the topological Hall effect.

Article 3 had earlier observed a similar Hall effect signal, and attributed it to the topological Hall effect, but in an entirely different region of the MnSi phase diagram. The experiments were done at high pressure (6-12kbar), and also found an excess Hall effect contribution. However, in contrast to Ref 2, the contribution was larger by an order of magnitude, and present over a much wider range of temperature (from T_c to below $0.5T_c$) and field (0.1 to 0.4 Tesla), so this does not correspond to the 'A' phase, at these pressures. However, a different magnetic phase may well be present in this region, which needs to be studied in future neutron scattering experiments. At still higher pressures, exceeding 15kbar, MnSi is known to display a number of unusual properties. For example, a 'partial order' state was observed in neutron scattering, in which context the helical spin crystal was originally proposed. Even more interestingly, non-Fermi liquid signatures in the resistivity ($\rho \sim T^{3/2}$) are seen, which extends over a wide temperature range. Given the observation of a spin crystal in one part of the phase diagram, it is tempting to speculate that the high pressure anomalies are connected to these. For example, can a quantum fluctuating version of the crystalline state, or a disorder induced helical spin glass, explain these observations?