# Unified Helicity of the Magnetic Skyrmion Lattices in EuPtSi and $EuNiGe_3$

**The magnetic skyrmion lattice is a periodic array of spin-swirling structures formed by multiple helimagnetic waves with identical helicity. Although this striking structure has been widely observed, direct evidence for unified helicity had remained elusive. Using circularly polarized resonant X-ray diffraction, we confirmed that the helicity is indeed unified in EuPtSi, likely due to its chiral crystal structure and single-oriented Dzyaloshinskii–Moriya interaction (DMI). Surprisingly, $EuNiGe_3$ – despite hosting opposing DMI due to its mirror symmetry – also showed unified helicity across all three helimagnetic components. One component even reversed its helicity from the zero-field state. These results suggest that the energy gain from helicity unification can overcome competing antisymmetric interactions.**

In certain magnetic materials, the spins of magnetic atoms collectively form swirling, particle-like textures that arrange periodically into lattices. These spectacular structures, known as magnetic skyrmion lattices (SkLs), often form two-dimensional, close-packed triangular arrays. SkLs were first discovered in 2009 in the chiral cubic magnet MnSi. They can be described as a superposition of three helical magnetic modulations propagating at 120° angles relative to one another. As noted in the seminal work by Mühlbauer *et al*., “All three helices have the same chirality” [1]. In other words, the three magnetic Fourier components forming the SkL must share the same helicity. However, until now, this unification of helicity had not been experimentally verified.

To address this issue, we focused on the SkL phase discovered in the chiral f-electron magnet EuPtSi and investigated the magnetic helicity using circularly polarized resonant X-ray diffraction. Circularly polarized X-rays are readily available at BL-3A using a diamond phase retarder system and are highly sensitive to spiral magnetic orderings. By combining with the normal linear polarization analysis of the scattered X-rays – which detects the linear polarization state after scattering – we determined the magnetic Fourier components, including their chirality. As shown in Fig. 1, our measurements clearly demonstrated that all three helical components forming the SkL possess the same helicity [2].

Since a single-handed (either right- or left-handed) helical spin structure constitutes the fundamental element of the SkL, it has long been believed that the Dzyaloshinskii–Moriya-type antisymmetric interaction (DMI), which selects a specific helicity, is essential for SkL formation. Indeed, many SkLs have been observed in chiral magnets lacking both inversion and mirror symmetry – such as MnSi among transition metals and EuPtSi among rare-earth compounds.

However, as research on magnetic skyrmions has progressed, SkLs have also been discovered in centrosymmetric materials such as $Gd_2PdSi_3$, $Gd_3Ru_4Al_{12}$, $GdRu_2Si_2$, and $EuAl_4$ [3]. In such systems, where DMI is absent, it is believed that higher-order symmetric exchange interactions mediated by conduction electrons stabilize the SkL by coupling multiple helical waves propagating in different directions. This raises an intriguing question for magnetic systems that lack inversion symmetry but retain mirror planes: what kind of SkL can form when opposing DMI contributions coexist?

Motivated by this question, we investigated the field-induced magnetic phase in the tetragonal compound $EuNiGe_3$, hypothesizing that it might host a skyrmion lattice. We searched for three coupled magnetic propagation vectors and examined their helicities using circularly polarized resonant X-ray diffraction. Remarkably, we found that all three helical magnetic components forming the SkL share the same helicity [4].

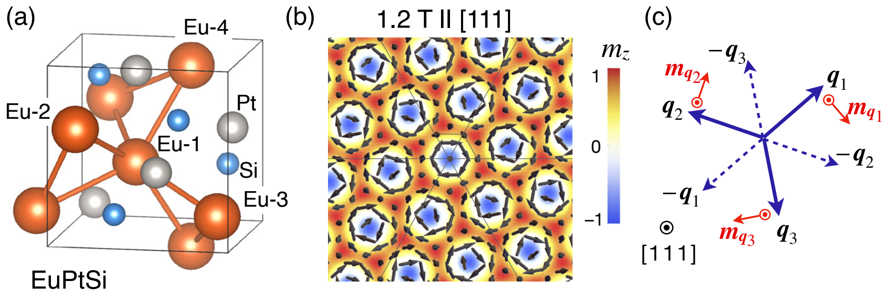


**Figure 1: (a)** Crystal structure of EuPtSi. **(b)** Triangular magnetic skyrmion lattice realized at 1.2 T || [111]. Only the spins of Eu-1 atoms are shown. **(c)** Three magnetic propagation vectors and the experimentally determined Fourier components of the triangular skyrmion lattice.



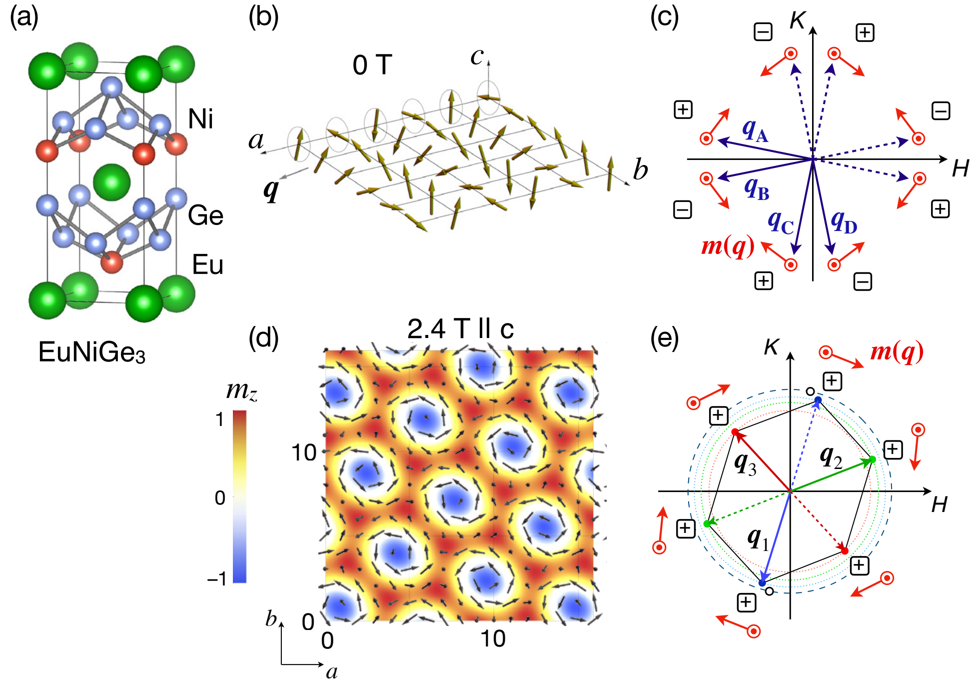


**Figure 2: (a)** Crystal structure of $EuNiGe_3$. **(b)** Helical magnetic structure at zero magnetic field. **(c)** Magnetic propagation vectors and Fourier components corresponding to the four magnetic domains A, B, C, and D at zero field. **(d)** Triangular magnetic skyrmion lattice (domain C) realized at 2.4 T || c. **(e)** Three magnetic propagation vectors and the experimentally determined Fourier components of the triangular skyrmion lattice.

In a chiral magnet like EuPtSi, DMI inherently selects a single helicity, naturally unifying the components. In contrast, $EuNiGe_3$ is not chiral – it has mirror planes including the fourfold c-axis, although it lacks inversion symmetry and thus permits DMI. In the zero-field helical state, two of the four magnetic domains exhibit positive helicity and the other two negative as shown in Fig. 2(c), reflecting the crystal’s fourfold rotational and mirror symmetries.

When the SkL forms under a magnetic field, the three helical components couple together (Fig. 2(e)). Surprisingly, one component reverses its helicity from the zero-field state. Another, which would normally adopt a longitudinal cycloidal structure, instead forms a helical structure that matches the helicity of the others. These findings suggest that a unifying interaction overcomes the intrinsic DMI constraints, enforcing a single helicity across all components and enabling the formation of a triangular SkL.

This experimental evidence challenges the conventional understanding of SkL formation and has drawn significant attention in the field. Moreover, the realization of a triangular lattice within a tetragonal crystal system – achieved through symmetry reduction and the formation of a distorted triangle – adds to its significance. These results underscore the diversity of SkL formation mechanisms and open new directions for future research.

## REFERENCES

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