Stability and Transformation of Skyrmion Lattices in Anisotropic Heisenberg Antiferromagnets: From Isotropic Order to Helical Fragmentation

Chu Ye[1], Milan Žukovič

[1]Pavol Jozef Šafárik University, Košice, Slovakia

The stabilization and manipulation of topological spin textures, such as skyrmions, remain a focal point of condensed matter physics and statistical mechanics due to their potential in spintronics and the fundamental interest in their topological properties [1]. This study investigates the influence of exchange anisotropy on the stability and topological properties of skyrmion textures within a Heisenberg antiferromagnetic model on a triangular lattice. Specifically, we explore systems where the exchange coupling J' in one direction is smaller than the couplings J in the other two directions ($J'/J < 1$), introducing a unique competition between topological winding and spatial anisotropy. Using Monte Carlo simulations, we analyze a system incorporating Dzyaloshinskii-Moriya Interaction (DMI) and an external magnetic field, focusing on the evolution of the system as it deviates from the perfectly isotropic case ($J' = J$) toward a directionally dependent anisotropy ($J' < J$).

Starting from the ideal isotropic limit, the system stabilizes a regular lattice of circular skyrmions at low temperatures [2,3]. As the ratio J'/J is slightly decreased to 0.9 and 0.8, we observe an unexpected increase in the skyrmion number compared to the isotropic baseline. We attribute this phenomenon to the stabilizing effect of slight anisotropy, which lifts the degeneracy of competing orientational modes and reduces the impact of thermal fluctuations by "locking" the skyrmions into preferred, slightly elliptical configurations. This structural constraint enhances the coherence of the topological winding, resulting in a higher measured topological charge density on the discrete lattice.

However, as anisotropy is further increased ($J' = 0.7$), a fundamental qualitative shift occurs. At low temperatures, the skyrmion phase becomes energetically unfavorable, and the system collapses into a helical ground state characterized by long magnetic stripes. A key finding of our research is the existence of a thermally induced crossover in this regime: as the temperature is raised to intermediate values, the skyrmion number peaks once again. In this context, thermal energy acts as a decoupling agent that fragments the rigid helical stripes, allowing the DMI to locally stabilize skyrmion excitations that are otherwise suppressed at low temperatures.

Thermodynamic analysis reveals that while the global transition to a disordered paramagnetic state at high temperatures is marked by a distinct peak in specific heat, the emergence of skyrmions from the helical phase at intermediate temperatures lacks a singular signature. This suggests a continuous topological crossover driven by fluctuations rather than a formal symmetry-breaking transition. Our results shed light into understanding of how the competition between topological protection, geometric anisotropy, and entropic contributions dictates the phase stability of complex spin textures in frustrated magnets.

References:

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