

1 2D phase transition

2 Freezing and Melting Skyrmions in 2D

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4 **Lattices of magnetic whirls are a promising model system to study phases and phase transitions in** 5 **2D.**

6 Phase transitions govern many processes in nature, in quantum condensates as well as in biological
7 systems; the melting and freezing of water are probably the most familiar examples. Freezing, the
8 crystallization of water, is a complex process [1], and many different phases and phase transitions
9 occur in various temperature and pressure regimes. Furthermore, phase transitions often exhibit
10 universal behaviour that does not depend on the details of the physical system but only on the
11 dimensionality and the interaction range. In particular, the dimensionality plays a key role. In 2D
12 systems, for instance, phases and phase transitions exist that do not occur in the more frequently
13 studied 3D systems. These include for instance topological phase transitions, such as the Kosterlitz –
14 Thouless transition, which gained fame when its description was recognized with the Nobel Prize in
15 2016 [2].

16 Experimentally, the phases and phase transitions in novel magnetic 2D systems have been explored
17 in the work by Huang et al. [3]. In this work, reported in Nature Nanotechnology, magnetic (quasi-
18)particles (Fig. 1) were studied that can form arrangements in 2D akin to the formation of ordered
19 solids by a crystallization phase transition.

20 The nature of 2D phase transitions of particle systems, such as hard and soft disks has been a grand
21 challenge in statistical physics. A recent numerical approach [4] analysed, in addition to the liquid
22 (Fig. 1 a) and the solid phase (Fig. 1 c), a hexatic phase, which is unique to 2D systems. Roughly
23 speaking the hexatic phase possesses little, only short-range translational order, but significant
24 longer range six fold orientational order (Fig. 2 b)). It is thus distinct from the solid phase with both
25 quasi-long range translational and long-range orientational order as well as from the (isotropic) liquid
26 phase where both translational and orientational order decay on short length scales. Depending on
27 the particle interaction potential, two scenarios occur: either the transition from the liquid to the
28 hexatic phase is of first order and a continuous transition to the solid phase follows, or the transition
29 from the liquid to the hexatic phase becomes continuous and of the Kosterlitz-Thouless-Halperin-
30 Nelson-Young (KTHNY) type [5].

31 Earlier work focused on 2D phase transition for instances in colloidal systems confined at liquid-gas
32 interfaces in complex experiments [6, 7].

33 In thin magnetic specimens under certain boundary conditions, localized whirl magnetic textures
34 exist [8] (Fig. 1). These skyrmions are spin structures with a non-trivial real-space topology that
35 include a fixed chirality of the whirling spin structure. The chirality is set by an anti-symmetric chiral
36 exchange interaction, the Dzyaloshinskii-Moriya interaction. This interaction results from symmetry
37 breaking either in the bulk due to the asymmetric crystal structure or due to symmetry breaking at
38 interfaces. The resulting skyrmions exhibit quasi-particle properties which, combined with their
39 observed arrangements into hexagonal lattices [9], present a promising platform to study statistical
40 phase behaviour in 2D. Theoretically, the expected phase transitions were recently analyzed [10].
41 Now, writing in Nature Nanotechnology [3], Huang, Schönenberger et al. demonstrate the 2D phases
42 of skyrmions experimentally in a Cu_2OSeO_3 thin film. This compound possesses bulk inversion
43 asymmetry leading to a chiral bulk exchange interaction that stabilizes chiral skyrmions. By applying
44 magnetic fields, the authors showed how their system undergoes a transition from a solid to a liquid

45 phase via the hexatic phase. This observation confirms the 2D nature of their system. They analyse
46 the melting process and can describe it in terms of topological-defect induced melting as predicted
47 by the KTHNY theory. The repercussions of these findings go beyond bulk materials. Recently such 2D
48 phase transitions have also been observed for skyrmions in thin films with interfacial chiral
49 interactions [11] showing that these 2D phases can occur in a wide range of systems hosting
50 skyrmions.

51 The work by Huang, Schönenberger et al. demonstrates that one can now go beyond studying the
52 intrinsic physics of skyrmions. It showcases that such systems can be engineered in a way that
53 control the skyrmion properties precisely. Now, skyrmions become a tool to study more general
54 physical principles such as 2D phases and phase transitions.

55 The use of skyrmions for such studies can have major advantages compared to the previously used
56 systems, such as colloids: skyrmions as quasi-particles can be modified during the experiment on-the-
57 fly. For instance, compared to colloids with a fixed diameter, one can easily change the skyrmion
58 diameter on short timescales by changing an applied magnetic field. This can lead for instance to
59 non-adiabatic changes to the system allowing one to probe out-of-equilibrium 2D systems. As a next
60 step, one could study the dynamics of phases and phase transitions in 2D. These were not easily
61 accessible in the previously studied systems where key properties of the particles could not be
62 changed during the experiment.

63 Skyrmions are promising new model systems to study 2D phases and phase transitions and we are
64 looking forward to seeing real-time movies of the freezing and melting processes of skyrmions in 2D.

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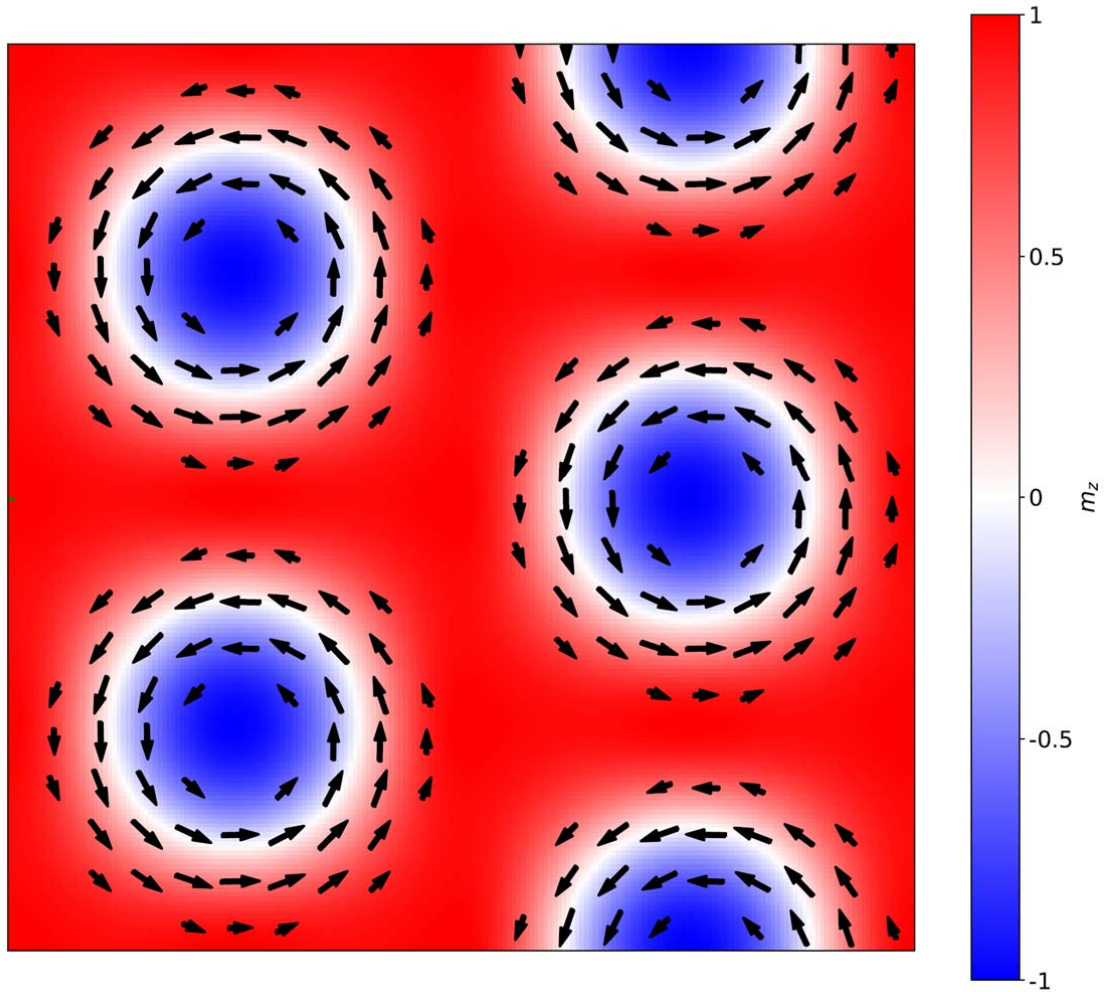
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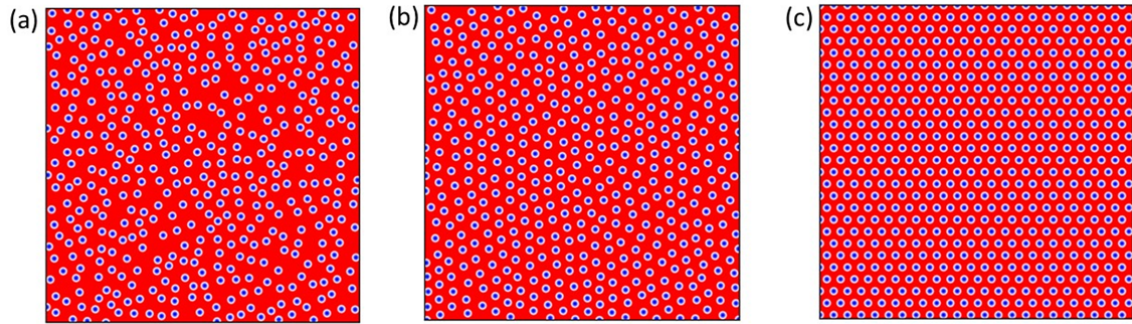


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81 Figure 1: **Schematic spin structure of skyrmions.** The colour code indicates the out-of-plane
82 magnetization m_z (blue pointing out of the plane and red pointing into the plane), while the arrows
83 show the whirling in-plane magnetization with a fixed chirality.

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87 Figure 2: **Skyrmion liquid to skyrmion lattice transition.** Schematic images corresponding to
88 skyrmions in the fully disordered liquid phase (a), the hexatic phase with long range orientational
89 order but not with translational order (b) and the solid phase with long range orientational and
90 translational order (c). The blue-white-red colour code visualizes the out-of-plane component of the
91 magnetization m_z . Illustrations by Florian Dittrich, Thomas Winkler, Peter Virnau and Mathias Kläui.

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