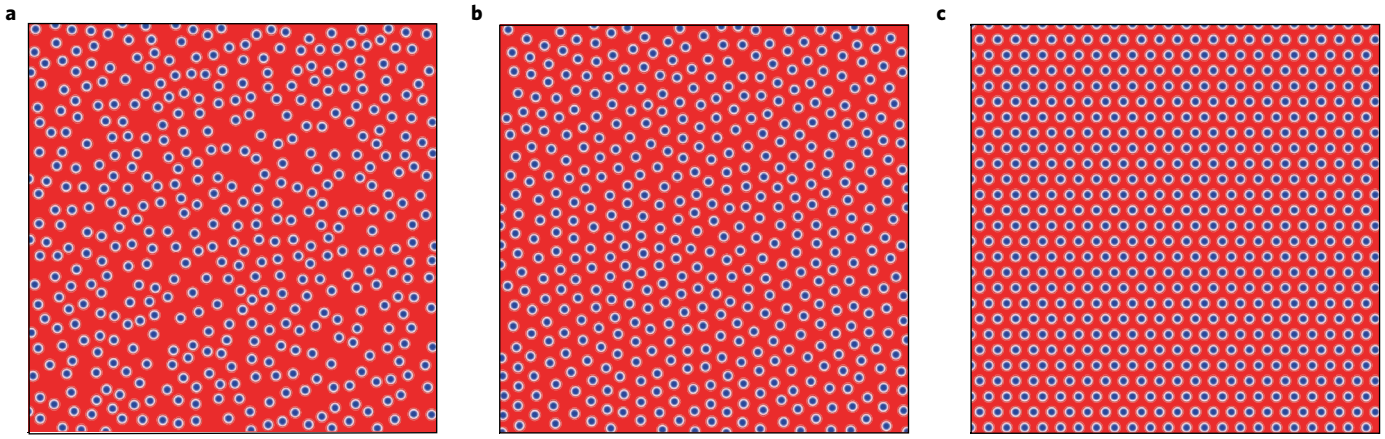

Fig. 2 | Skyrmion liquid to skyrmion lattice transition. a–c, Schematic images of skyrmions in the fully disordered liquid phase (**a**), in the hexatic phase with long range orientational order but without translational order (**b**) and in the solid phase with long range orientational and translational order (**c**). The blue–white–red colour code visualizes the out-of-plane component of the magnetization m_z. Illustrations by Florian Dittrich, Thomas Winkler, Peter Virnau and Mathias Kläui.

the melting process and can describe it in terms of topological-defect induced melting as predicted by the KTHNY theory.

The repercussions of these findings go beyond bulk materials. Recently, such 2D phase transitions have also been observed for skyrmions in thin films with interfacial chiral Dzyaloshinskii–Moriya interactions[11] showing that these 2D phases can occur in a wide range of systems hosting skyrmions.

The work by Huang, Schönenberger et al. demonstrates that one can now go beyond studying the intrinsic physics of skyrmions. It showcases that scientists can engineer such systems in ways that control the skyrmion properties precisely. Skyrmions become a tool to study more general physical principles such as 2D phases and phase transitions.

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

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

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2D MATERIALS

Excitons in a twisted world

Breaking the mirror symmetry in twisted bilayer $MoSe_2$ results in large scale exciton dipole oriented domains in a two-dimensional homostructure.

Paulina Plochocka

A moiré pattern arises from the interference produced by a superposition of two slightly different periodic templates resulting in a new, long range (slowly varying) pattern that is commonly referred to as moiré fringes. Perhaps the simplest example is the superposition of two rotated grids (see f or example Fig. 1a). Another well-known example is the beating of sound, the interference pattern between two sounds of slightly different frequencies, that is the

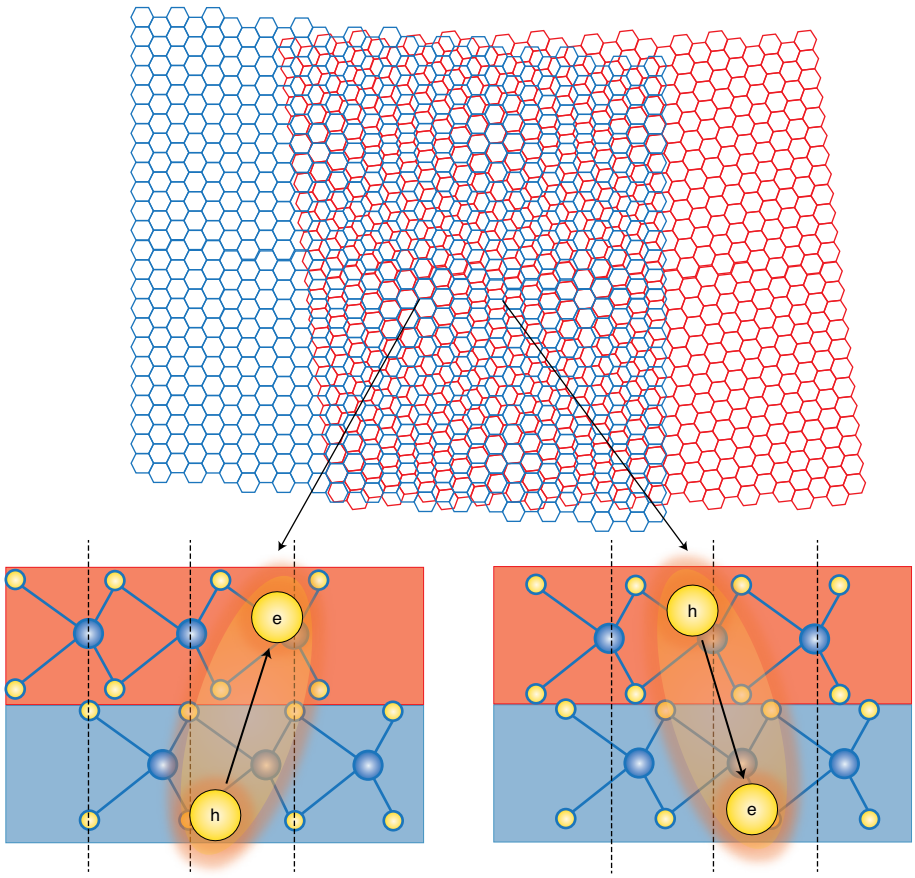

Fig. 1 | Schematics of moiré pattern formation. a, A moiré pattern formed by superposition of two hexagonal lattices. **b**, Opposite exciton dipole orientation in different part of moiré superlattice.

moiré pattern of two vibrations in the time domain. Moiré patterns are surprisingly common and we find them in our everyday lives. For instance, moiré fringes can be observed on television screens when pictures with particular patterns are displayed. Similarly, TV screens often exhibit moiré patterns when photographed using digital cameras. This is due to the periodic structure (pixelation) of TV displays and the digital sensor of the camera. This effect is also used in metrology for high precision shift or strain measurements and in marine navigation with the so called Inogon leading marks. Due to aesthetic reasons, moiré patterns can be found in art (for example, in the works of Andrea Minini) and architecture (see the Galleria Centercity Cheonan in Korea).

Over the past decade, moiré patterns have made a spectacular appearance in the field of fundamental solid states physics, with a plethora of new phenomena in assembled van der Waals structures[1]. The weak van der Waals forces between individual layers of graphene, transition metal dichalcogenides (TMDs) or hexagonal boron nitride (hBN) allows the vertical stacking of any combination of monolayers. In such a stack, each of the layers preserve their own lattice constant and can be rotated by any angle. This opens up a completely new playground for material engineering that is referred to as twist physics, an effect that is absent in regular crystals with covalent bonding. Since each of the monolayers is a crystal with periodic structure, any difference in the lattice constant or twist angle forms a moiré pattern. In this case the atoms' positions in one layer vary spatially with respect to the atoms in the consecutive layer, which has a non-trivial impact on the global electronic properties of homo- or heterostructures.

The rapid rise in interest in the moiré superlattice started with graphene–hBN heterostructures with the formation of Hofstadter butterfly states[2]. An even more spectacular example came later in 2018 when twisting two graphene monolayers by 1.1 degrees induced superconductivity in normally semiconducting bilayer graphene[3].

With the knowledge derived from the investigation of graphene it was natural to expect the formation of moiré patterns in TMD heterostructures, which was quickly confirmed with first principle calculations[4] and tunnelling electron microscopy[5]. In the past couple of years, we have realized that the consequences of the spatially varying atoms arrangement extend far beyond the long-range modulation of the potential landscape[6]. The interlayer excitons formed in TMD structures can preserve the spin-valley locking effect, characteristic for TMD monolayers, providing three degrees of freedom for carriers; the valley index, the layer index and the spin that can be controlled by optical excitations. Moreover, it has been shown that the moiré lattice can lead to spatially varying selection rules[6,7], the formation of Mott insulating states[8], or serve as a model for the two-dimensional (2D) Hubbard system[9] or Bose–Einstein condensates[10]. Thus the van der Waals stacks provide an enormously rich playground for the investigation of exciton physics and all of this for only the price of layer twist control.

In this issue of *Nature Nanotechnology*, J. Sung and colleagues report on another unique feature of the interlayer exciton in slightly twisted bilayer $MoSe_2$. Namely, they have shown that in such a bilayer the direction of the out of plane dipole moment of the interlayer exciton varies spatially as schematically presented in Fig. 1b. As they discussed, this is related to the broken mirror inversion symmetry due to the moiré pattern, which supports the formation of two types of rhombohedral domains. They have shown that the direction of the exciton dipole can be flipped by an external electric field providing control over domain-specific optical properties. Thanks to the use of a homostructure rather than a heterostructure, the period of the moiré pattern is not limited by lattice mismatch of constituting layers and for the first time they have shown spatially varying properties of interlayer transition in a far field optical investigation. Previously the optical response of TMD heterostructures was averaged over many domains since the period of moiré lattice was in the range of single or tens of nanometres. These results open the way for the realization of exotic exciton systems (antiferroelectric exciton droplets, exciton liquids and exciton condensates) with nontrivial topology or quantum emitter arrays whose properties can be precisely controlled by the twist angle.

Independently of the main result of this work authors report an intriguing multiple peak structure of an interlayer exciton PL spectrum, similar to the ones observed in

TMD heterostructures. However, despite similarities of the interlayer exciton spectrum in homo- and heterostructures, the moiré-quantum dot like origin[6] of it proposed in the case of the heterostructure cannot apply to the large scale well resolved domain formed in the homostructure, raising the question of its origin for both type of structures.

It is significant that many recent proof-of-concept demonstrations of moiré patterns in 2D systems answer some questions while simultaneously raising a series of new ones. Therefore, future progress in the field depends on the development of the repeatable and scalable synthesis techniques that will allow for extremely systematic studies in this new and fascinating 'twisted field' of science. ❐

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ENVIRONMENTAL NANOTECHNOLOGY

When plants and plastic interact

Overcoming the challenges of plastic detection in plants has made it possible to transfer many of the lessons learned from plant–metal nanoparticle interactions to plastic nanoparticles.

Fabienne Schwab, Barbara Rothen-Rutishauser and Alke Petri-Fink

Plants have always interacted with, and evolved in the presence of, nanoparticles from natural sources such as weathering processes in soils and surface waters or erupting volcanoes[1]. Human awareness of nanoparticle–plant interactions rose about a decade ago[2] with the increasing environmental exposure of anthropogenic incidental or engineered nanoparticles. Recent research on these interactions has led to exciting progress, most notably in the field of nanoagrochemicals[3,4]. With the emergence of plastic nanoparticles, or nanoplastics, in the environment due to human activities such as littering, use of plastic textiles and personal care products[5], and most recently, polymer-based nanoagrochemicals, the interactions of plastic nanoparticles with plants have caught the interest of scientists[6].

In contrast to animal cells, plant cells can accumulate only a small fraction of intact nanoparticles in their intracellular compartments known as symplast (Fig. 1). The limited uptake is mainly due to the fact that plants possess, in addition to the nanometre-thin phospholipid bilayer cell membrane, a strong cellulose cell wall and a coextensive pectin network that can be up to several micrometres thick (Fig. 1). Along and in between these cell walls, nanoparticles, especially those that are negatively charged, can move to some extent in microscopic extracellular channels and reach the vasculature responsible for water transport, which is called apoplastic transport. Once within the water transport system, nanoparticles can rapidly translocate into the stem, leaves and potentially also the fruits; albeit further barriers will hinder the accumulation of the nanoparticles in the latter reproductive organs[2]. Mucilage and exudates are less known but equally important barriers for nanoparticles, especially on root tips, root hairs and stomata (pores in leaves for gas exchange). For unicellular algae, excess mucilage production in response to nanoparticle exposure is a common phenomenon[2]. In higher plants, mucilage and exudates act as a negatively charged first layer of protection and have been reported to block positively charged metal nanoparticle uptake[7] on the outer edge of the cell wall (Fig. 1), for example in the root-growth medium interface (rhizosphere).

Our knowledge of nanoparticle movements in plants mostly originates from experiments on metal and metal oxide nanoparticle–plant interactions. Determining the fate of plastic nanoparticles in plants is much more challenging because plant tissue is essentially a complex mix of biopolymers and the detection of plastic in this environment is challenging. Now, Sun et al. use labelled particles with different surface charges to show that processes similar to those of relatively inert metal or metal oxide nanoparticles occur in the roots for polystyrene plastic nanoparticles. Negatively and positively charged plastic nanoparticles move similarly in roots of *Arabidopsis thaliana* (thale cress)[6] when compared to, for example, negatively charged gold nanoparticles investigated earlier[7]. By combining electron microscopy, confocal fluorescence microscopy and different plastic nanoparticles labelled by either metals or fluorescent dyes, Sun et al. demonstrate that both particle types accumulate to some extent on the root surface, but the negatively charged plastic nanoparticles can, in contrast to the positively charged particles, reach the plant vasculature. From there, they can travel widely within the plant as already shown earlier[2,6]. The positively charged plastic nanoparticles, likely due to electrostatic interactions, aggregate within plant exudates, or end up stuck in areas where a negatively charged protective mucilage layer is present such as the root border cells and root hairs, and thus mainly adsorb on the plant surface.

Sun et al. also examined the toxicological effects of the plastic nanoparticles on the plants at relatively high concentrations in the g kg^{-1} and mg l^{-1} range. The resulting moderate reduction in growth was less pronounced in soil than in culture medium, highlighting a mediating effect of soil on the toxicity or uptake. Exposure to the positively charged plastic nanoparticles triggered mild plant defence reactions; as reflected by an