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A journey in the topologically protected world

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One day, the little prince landed on the topologically protected planet.

The king invited him for coffee and poured the hot beverage into a weird-looking mug.

"I am sorry my prince, our topologically protected mugs acquired bizarre shapes over the years". The little prince was baffled, so the king explained that on his planet, besides the usual forces, a special thing called topological protection prevented objects from undergoing certain types of deformations.

*Topology, he continued, is a branch of mathematics that studies the properties of space that are preserved under **continuous transformations**, such as stretching and bending. It focuses on the study of properties that do not depend on the exact geometrical shape, size, or orientation of objects. In other words, it captures the qualitative rather than quantitative aspects of geometry. For topology, a mug and a doughnut are the same objects because one can be transformed into the other continuously.*

"What do you mean by continuously?" asked the prince. "Well, I mean without creating new holes (singularities) in the material forming the object, nor filling holes that already exist. For example, a sphere and a torus are not topologically equivalent as they do not have the same number of holes, zero for the sphere and one for the torus."

The king explained to the little prince that topology has revised their entire vision of physics as this new way of classifying objects has revealed novel phenomena which cannot be described by conventional geometrical aspects.

"The protection that exists on this planet – he continued - has a topological nature and prevents objects from undergoing deformations that form or eliminate holes as creating or removing holes is energetically costly. For this reason, when we drop a mug on the floor, its handle does not break like it happens on other planets. Instead, all the energy of such a collision is used to create continuous deformations".

The king made a cartoon depicting the fate of a mug subjected to deforming forces, thermodynamic vibrations, collisions… on ordinary planets and on his own, to explain the prince why the mug he was drinking from had this special shape (Fig. 1).

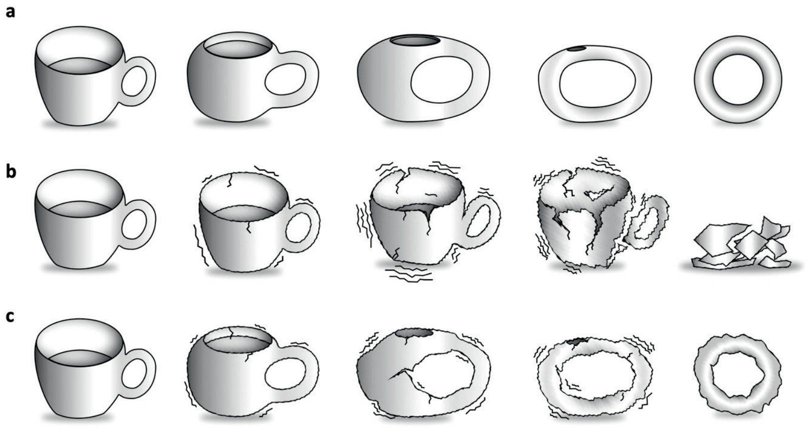

Figure 1. ***a****. Illustration of the topological equivalence between a mug and a doughnut through a continuous deformation. The handle of the cup expands as the bottom of the cup fills it.* ***b****. If the deforming forces are too strong it can lead to the destruction of the mug.* ***c****. In this case where topological protection is strong enough, the mug survived to the excess of energy by undergoing a continuous transformation keeping the same topology.*

The little prince also noticed a painting on the wall depicting three guys writing weird symbols on a blackboard. "Ah! - The king smiled - , those are Thouless, Haldane, and Kosterlitz, they understood the role of topology in materials and found a way to surround our planet with the topological field that protects our fragile objects. Sadly, all industries making glasses, mugs, windows, and fragile things like that went suddenly bankrupt. Those, and the drill industries in fact. Nobody has ever broken any of those objects since, nor has been able to make a hole easily on this planet after topological protection was activated".

Away from the weird topological protected planet, we wish to describe how manipulating topology in spatial distribution of spins can be achieved using out of equilibrium protocols. In our analogy, how to drill holes in mugs that are made of spins and that are topologically protected.

To understand this better, consider a simple example of a ferromagnetic material, such as iron, in which the spins of the individual atoms are aligned in the same direction, creating a uniform spin texture (see Fig. 2a). This spin distribution corresponds to the topological trivial case because it can be continuously deformed to a uniform spin texture in which spins align in any other direction without any topological change.

However, in certain materials the spin texture is not uniform, but rather contains defects such as skyrmions, which are whirlpool-like configurations of spins (see Fig. 2c), that are topological objects and have a nanometric size. Consequently, these defects have to be stable against conventional thermodynamic fluctuations (the equivalent of vibrations for the mug) and can be changed only by a topological transformation, which involves a change in the global topology of the spin texture.

These topologically non-trivial spin distributions have unique properties that make them interesting for various applications in electronics, spintronics, data storage, and quantum computing. For example, the topological defects in a spin texture could act as qubits, the basic units of quantum infor-

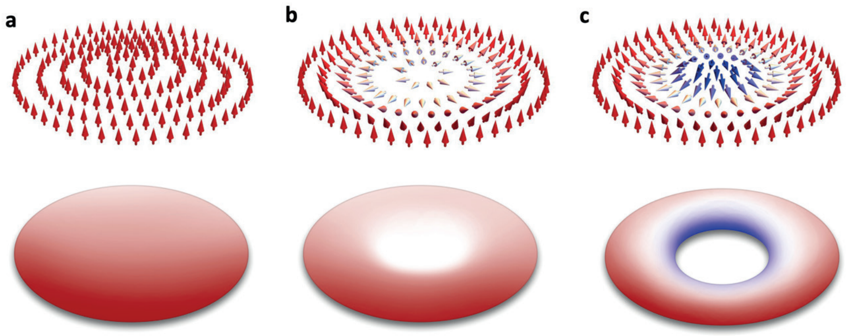

Figure 2. Illustration of the transformation between ***a.*** *a trivial magnetic arrangement going through* ***b.*** *a non-uniform intermediate state reaching* ***c.*** *a non-trivial topological spin configuration, named Skyrmion, with their associated topological representation, respectively.*

mation, and their stability and robustness make them promising candidates for building quantum computers at room temperature. However, to exploit the potential of such topological spin textures, one should find a way to manipulate them, create and erase topological defects, and even move them around at will.

Out of equilibrium protocols offer a unique opportunity in this respect because they allow to outrun thermodynamic fluctuations in a tunable fashion.

When a system is suddenly thrown out of equilibrium by an external perturbation, which can be a heat jump, a strong electric or magnetic field, or a light flash, its relaxation pathway can differ from those normally followed during a slow, adiabatic transformation. As an example, we can think of a ball falling down a stair bouncing off the steps (Fig. 3), where each step is a quasi-equilibrium thermodynamic intermediate state. In this scenario, it can even happen that an out-of-equilibrium protocol takes the system onto a different staircase, with different number of steps and height of the jumps which can even lead to a different equilibrium state that cannot be reached through the conventional quasi-equilibrium process. Some people call this kind of state “hidden state” which can be short or long-lived. The idea is to exploit such a possibility to circumvent the topological protection and drive a material strongly out of equilibrium and see if it will land in different states, maybe some having different topological properties.

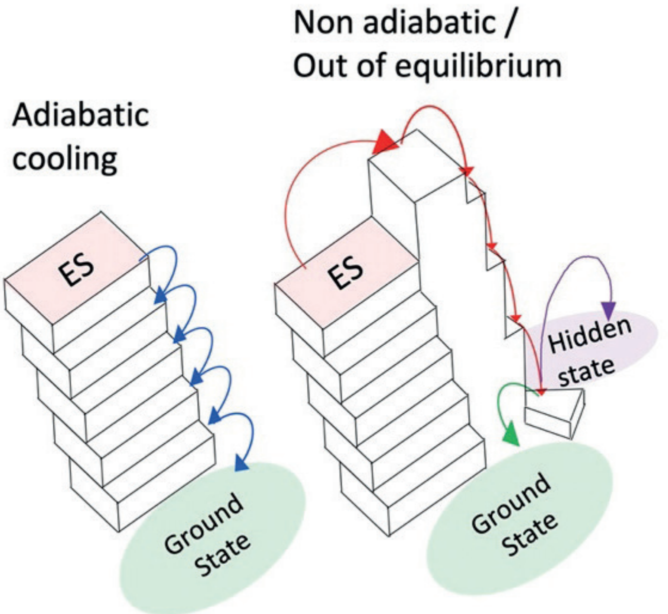

Figure 3. Left: Usual quasi-adiabatic relaxation pathway. Right: In the case that the excitation is faster than the system response timescale, the system can relax in an out-of-equilibrium fashion exploring other metastable states, and eventually reaching a hidden state.

Such experiments were carried out at the Laboratory for Ultrafast Microscopy and Electron Scattering, LUMES, at the EPFL. Here, a customized Transmission Electron Microscope (TEM) has been developed that allows varying magnetic field and temperature on materials (conventional adiabatic processes) but that also allows perturbing the specimen with ultrafast light pulses (out of equilibrium protocol) while imaging its magnetization response in real space with nm resolution using Lorentz microscopy. This is a technique that uses the deflection of electrons by the magnetic fields present in a sample to map the in-plane magnetization [1].

Conventional (adiabatic) perturbations are typically slow on the scale of electronic and spin re-arrangements, and make a system evolve through a set of quasi-equilibrium states. Changing the temperature of a material for example, applying pressure to it, or an external magnetic field are the typical handles that are used to control the properties of solids. Lasers instead can produce flashes of light that are as fast or even faster than the characteristic times of electronic and spin rearrangements. Therefore, they can be used to suddenly shake up things in a material faster than topological protection can even realize and counteract, and by tuning the properties of such laser pulses one can even dose the balance between topological protection and other fluctuations, such as thermal for example, to obtain different magnetic textures and manipulate them.

The topological magnet of choice for these studies was the Mott Insulator Cu_2OSeO_3, whose magnetic phase diagram is depicted in (Fig. 4a).

A 150 nm thick lamella of Cu_2OSeO_3 was inserted in the TEM and prepared in the low-temperature helical magnetic state. The ensuing magnetization was monitored with Lorentz TEM. By shining one single laser pulse at a time, varying its intensity, wavelength, and polarization it was found that above a certain fluence threshold skyrmions are generated (Fig. 4b).

Remarkably, laser pulses can generate skyrmions not only within the phase diagram regions where they are known to exist in equilibrium conditions, but also, they could be induced at very low magnetic fields where nobody ever observed skyrmions in Cu_2OSeO_3 (see [2]).

The explanation of this phenomenon is that indeed this material can host a variety of different topological phases, some of which however can only be reached through an out-of-equilibrium protocol that drives the system impulsively on a different relaxation path. LUMES researchers explained that light excitation was likely promoting the strong

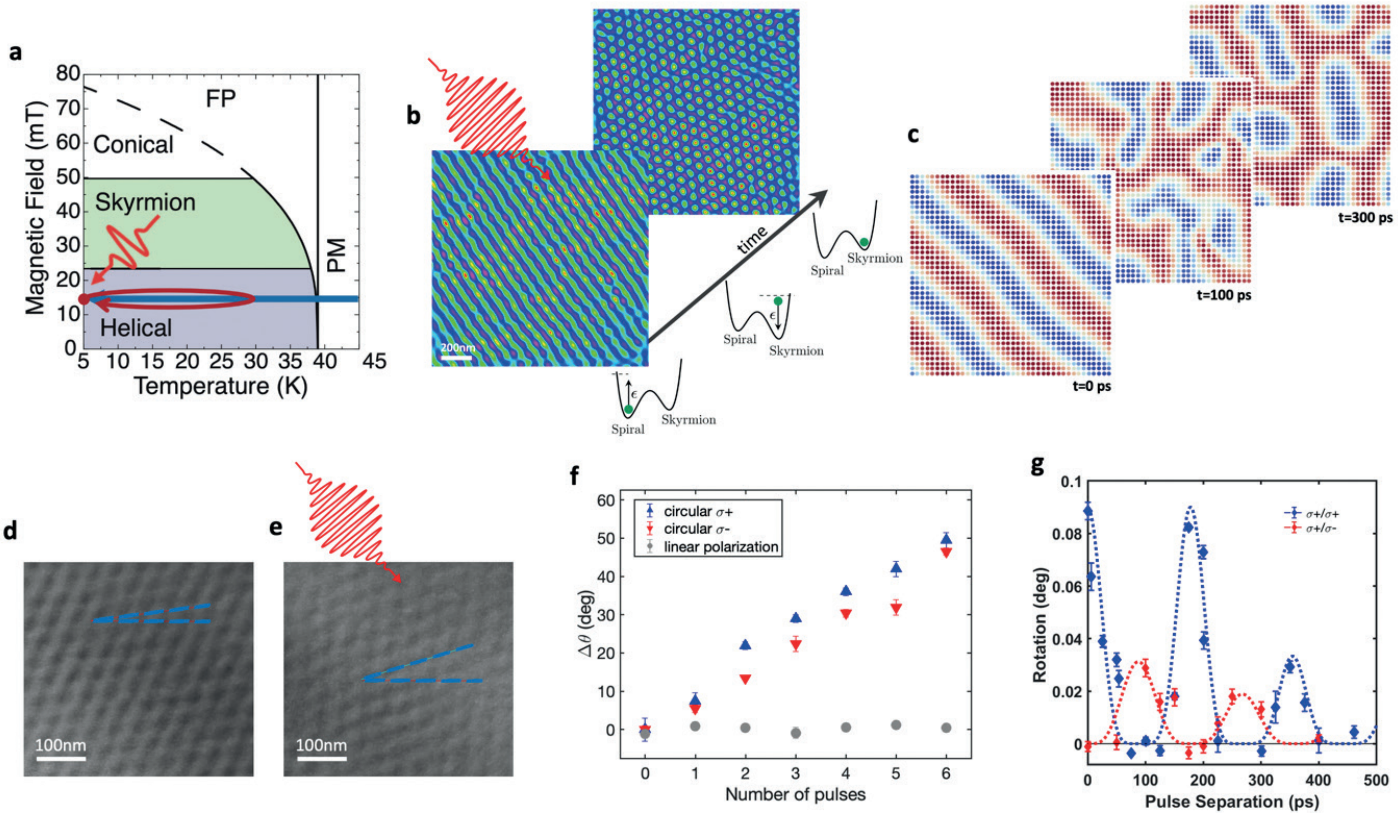

Figure 4. ***a.*** *Typical magnetic phase diagram of a Cu_2OSeO_3 lamella using the field-cooled-cooling protocol.* ***b.*** *Real space LTEM image showing the topological transition from the helical state to the skyrmion state after single shot illumination.* ***c.*** *Atomistic spin simulation of the magnetization dynamics invoking the presence of a strong phonon-magnon coupling. Images* ***d*** *and* ***e*** *show the magnetic state before and after photoexcitation with circularly polarized light, respectively. A clear skyrmion rotation is observed and is expressed in the graph* ***f.*** ***g.*** *Observation of oscillatory dynamics of the skyrmion rotation with a shift by half-period when the handedness of the second pulse is changed. Images a-c are adapted from [2] and d-g from [6].*

coupling between phonons (collective distortions of the atomic lattice) and spin fluctuations (collective distortions of the spin arrangements), such that the impulsive lattice distortions eventually allowed for the formation of topological spin patterns. A theoretical simulation (Fig. 4c) confirmed that this was indeed a plausible explanation. Interestingly, the skyrmions hidden phase discovered in this study [2] was found to be metastable, having a lifetime of at least 15 minutes, a time which is much longer (8 orders of magnitude) than any residual excitation possibly present in the sample after laser excitation.

The researchers also noticed that when the wavelength of the laser pulse was tuned below the optical absorption threshold of the material (i.e., in its transparency region) and circularly polarized, above a certain intensity, the photoexcitation was inducing a rigid rotation of the skyrmion crystal (Fig. 4d-e).

An intriguing observation was that such a rotation was not reversible, i.e., the system would not relax back in its initial angle position with time. Furthermore, the amount of rotation was found to be directly proportional to the intensity of the pulse and the number of pulses sent on the material (Fig. 4f). In other words, one pulse would rotate the skyrmions lattice by approximately 5 degrees, two pulses by 2 × 5 degrees, 3 by 3 × 5 degrees and so on. This is a very promising handle to control the magnetization in a deterministic way. An important question to reply was how fast such a rotation happens. Because the observed rotation is irreversible, ideally one would need an observation by single-shot Lorentz Transmission Electron Microscopy (LTEM) with a whopping temporal resolution of few hundreds of fs to a few ps to address its dynamics. To put things in perspective, LTEM provides the best spatial resolution (down to 1 nm) to observe magnetic textures, needed to look at skyrmions and their small rotation. However, because of the Coulomb repulsion that electrons suffer when they are close to one another, keeping many of them in a short bunch necessary to observe a ps / irreversible / nm effect in one single shot is even theoretically impossible [3].

To circumvent this problem, LUMES researchers had the idea to try to rotate the skyrmions using two laser pulses instead of one, leveraging the fluence threshold observed. The protocol consisted of sending two pulses each carrying half the intensity necessary to induce the rotation, i.e., below the fluence threshold. The logic was that when the two pulses were temporally overlapped, they would obviously induce the rotation while if the two pulses were placed far apart in time they would act as individual pulses keeping the skyrmion lattice unchanged. The question was then how close or far apart the two pulses must be to induce the skyrmion to rotate.

Surprisingly, the rotation angle turned out to be an oscillating function of the distance between the two pulses (Fig. 4g). Coherent spin dynamics in Cu_2OSeO_3 were observed by ultrafast magneto-optical Kerr effect experiments in [4]. Such oscillations were ascribed to the excitation of coherent magnons launched in the material by the inverse Faraday effect, which consists in the generation of a magnetic field pulse in a strong spin-orbit coupling solid when circularly polarized light impinges on it [5].

A possible explanation for the observed coherent control of the rotation angle of the skyrmion lattice was that a first pulse drives coherent motions of the spins which can result in an overall rotation of the lattice when they are large enough. In other terms, either when the individual pulse was strong enough, or when the second pulse participated constructively in the oscillation of the spins initiated by the first pulse, the skyrmions rotated. This explanation was further supported since when the pulse separation was tuned to exactly match half the period of this oscillation, no skyrmion rotation was observed.

While this explanation could be corroborated qualitatively by theoretical calculations (see [6]), a puzzling difference of a few orders of magnitude between the predicted rotation and the reported one was observed. In addition, the rotated skyrmion crystal had a new stable spacing of 70 nm, 5 nm more compared to the initial equilibrium state, opening further questions regarding the exact mechanism.

The protocol discovered to manipulate and visualize topological magnetic patterns allows to literally decide how much to tilt spins in the material with a precision of fractions of degrees in timeframes as short as a few tens of ps while visualizing this magnetic dance. To summarize, this work is the first to demonstrate a magnetic topological phase transition by directly shaping the relaxation pathway using an out-of-equilibrium protocol [2]. In addition, the coherent control of the skyrmion crystal angle has been achieved by tuning the polarization of the laser pulse [6]. Both works were performed using an photoexcitation energy below the optical bandgap of the compound, thus breaking ground for a novel approach to control topological magnetic state on demand at ultrafast timescales while drastically reducing heat dissipation.

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