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Magnetic vortices: into the third dimension

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Vortices are familiar phenomena in fluids and gases, apparent for example in tornadoes, hurricanes and whirlpools. Vortices also exist in ferromagnets, where they are characterized by a circulating in-plane magnetization structure. At their center, the magnetization lifts out of the circulation plane, forming a stable and narrow core, a few nanometers in radius (Figure 1a). The resulting pattern leads to flux closure, which reduces stray fields, thereby producing an energetically favorable state. Consequently, vortices form naturally and can exist as parts of larger structures, such as domain walls, or as isolated magnetic states.

Initially discovered within Bloch domain walls in bulk ferromagnets, vortex structures were called ‘Bloch lines’ [1]. Later, it was predicted that vortices should form the ground state of small magnetic cylinders [2] and possess a very narrow core [3]. The experimental study of isolated vortices in magnetic nanostructures became possible in the early 2000s thanks to advances in lithographic techniques and thin-film deposition, combined with the advent of high lateral resolution magnetic imaging techniques. The first observation of the vortex core was performed using magnetic force microscopy, by exploiting the dipolar interaction between the core and a sharp ferromagnetic tip [4] (Figure 1b). Later, the use of spin-polarized scanning tunneling microscopy, which measures the spin-dependent tunneling current between a magnetic tip and the sample through a vacuum gap, allowed the precise determination of the core structure on the nanoscale [5] (Figure 1c). Vortex formation, along with the size of the core, are defined by the competition between the exchange and magnetostatic interactions [6]. As a result,

when vortices form in magnetic nanostructures, they display remarkable stability down to very small nanostructure sizes.

The small size of the core, combined with the stability of vortices, naturally makes these promising candidates for technological applications. However, magnetic devices that range from nonvolatile memories to spintronic systems [7, 8], have long avoided vortices. Indeed, most applications of magnetism in reduced lateral dimensions involve the coherent reversal of the magnetization. This is because the magnetic switching in granular thin film media found in hard drives, or the reversal of the magnetization orientation in nanomagnets, which are part of various magnetoresistive random access memory (MRAM) architectures [9] or of proposed patterned storage media [10], require reliable and fast operation. In this context, the nucleation of vortices is undesirable given that it is not easily reproducible due to material defects and imperfections. This is known as Brown’s paradox [11]. Nanomagnets are thus generally engineered through their shape and size to exhibit single-domain behavior, thereby avoiding the vortex state that would otherwise naturally form. Only Arrott’s hysterion [12] used a vortex to drive the reversal of the magnetization in an MRAM cell at low switching fields.

The attitude towards vortices has, however, dramatically changed over the past decade and a half. While it was known since the 1970s that vortices possess rich dynamics derived from their topology [13, 14], experiments on vortex dynamics performed using scanning X-ray transmission microscopy, where the magnetic state is probed using circular-

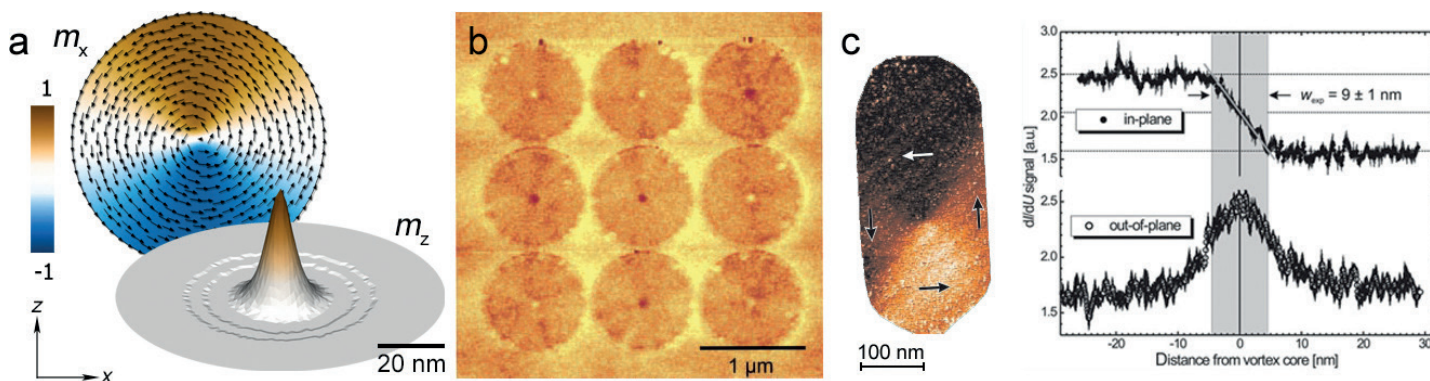


Figure 1. a) Simulated in-plane and out-of-plane magnetic structures of a thin film vortex in a disk-shaped sample 100 nm in radius. The arrows indicate the circulation of the in-plane magnetization. The colormap represents one of the in-plane components (m_x) of the magnetization. The topography of the out-of-plane component of the magnetization (m_z) reveals the structure of the core. b) Experimental observation of the vortex core in circular micron-sized Permalloy disks using magnetic force microscopy. The dark and

light spots at the center of the disks indicate the orientation of the core, where the dark spots are cores with magnetization oriented towards the viewer. From Ref. [4]. Reprinted with permission from AAAS. c) Left: measured vortex structure in a ca. 10 nm thick Fe nanoisland with spin-polarized scanning tunneling microscopy. Right: Line sections across the vortex core, showing the in-plane (top) and out-of-plane magnetization components (bottom). From Ref. [5]. Reprinted with permission from AAAS.

ly polarized photons [15], demonstrated that the orientation of the vortex core can easily be reversed using bursts of a low in-plane alternating field [16]. The strength of these bursts was of the order of only a thousandth of a Tesla – a remarkable result in view of the very high stability of the core, which is conferred by the exchange field. (In comparison, the magnitude of the exchange field is of the order of 100 Tesla). Shortly thereafter, it was also found that the vortex core orientation can be reversed using electric currents [17]. There were now means of easily switching between two stable core configurations, an essential requirement for technological applications. Moreover, it was demonstrated that the vortex core reversal unfolds within only a few tens of picoseconds [18, 19], representing one of the fastest known magnetization reversal mechanisms. Following these discoveries, it was clear that the stability and controllable dynamics of vortices makes them suitable for applications such as data storage [20, 21], processing [22, 23] and tunable radio frequency antenna technologies [24 - 26]. Recently, vortices have also been employed in novel approaches to neuromorphic computing [27, 28], based on their tunable resonant frequency, which can even be exploited to produce chaotic oscillations [29, 30], as well as based on the possibility of synchronizing multiple vortex oscillators [31, 32]. Going forward, it is possible that exploring vortices in curved geometries may lead to novel applications based on magnetochiral effects, which have recently been predicted [33 - 35].

The two-dimensional confinement of vortices in thin films has enabled their study in controlled geometries, where thickness plays very little role as far as the vortex profile is concerned. In contrast, in significantly thicker films and bulk samples, vortices evolve into more complex objects. For example, in films about 100 nm thick, the vortex core stretches, resulting in an asymmetric structure [36, 37]. In

bulk ferromagnets, it was long known that Bloch lines can assume complex configurations coupled to the three-dimensional structure of Bloch walls. These include twisting and narrowing where the Bloch lines intersect surfaces as well as the formation of micromagnetic singularities, or Bloch points, when the vortex circulation reverses [38]. However, this knowledge was derived from observing surface magnetic states that, combined with analytical models, allowed bulk domain structures in thin perfect crystals to be inferred. The direct observation of nanoscale magnetic features in the bulk of a magnet was not possible.

Recently, the development of X-ray based magnetic nanotomography with a spatial resolution of 100 nm [39] has enabled non-destructive imaging of bulk magnetic structures, opening the possibility to revisit old predictions and to make unexpected observations (see ‘X-ray magnetic tomography’ box). Among the first observed structures were a pair of magnetic singularities [39]. Bloch points were predicted over 60 years ago and their role in magnetization dynamics is generally well understood [40 - 42, 52, 53]. While the singularities cannot be directly observed, their existence is revealed by the surrounding magnetization state.

The bulk magnetic structure turned out to be very rich in features: upon further analysis of the data in Ref. [39] and based on subsequent measurements, we have established the presence of vortex loops, a few hundreds of nanometers in diameter [43] (Figure 2a). Cross-sections across these loops show that they are composed of bound vortex-antivortex pairs (see ‘Topology’ box). Moreover, these loops correspond to magnetic vorticity rings that are formally analogous to hydrodynamic vortex rings in fluids [44, 45]. The tomographic reconstruction of one such loop is given in Figure 2b. While the loops we observed have a ring-like structure, their similarity to hydrodynamic vortex rings has a

twist. Based on the magnetization distribution, the cross-section of a magnetic vortex ring contains a vortex and an antivortex, while the cross-section of the velocity field of a hydrodynamic vortex ring contains two vortices. This difference is due to the fact that the magnetization is not the magnetic counterpart of hydrodynamic velocity. The common ground for the description of the vortex rings is a different quantity – the vorticity vector. In hydrodynamics it is defined as the rotor of a velocity field. Its magnetic analog can be (albeit in a more complex form) expressed via the rotor of the analogous field obtained from the gradients of the magnetization [44]. Once constructed in this way, the magnetic vorticity vector circulates in a closed loop along the magnetic vortex ring (Figure 2c), just like hydrodynamic vorticity circulates in closed loop around the hydrodynamic vortex ring.

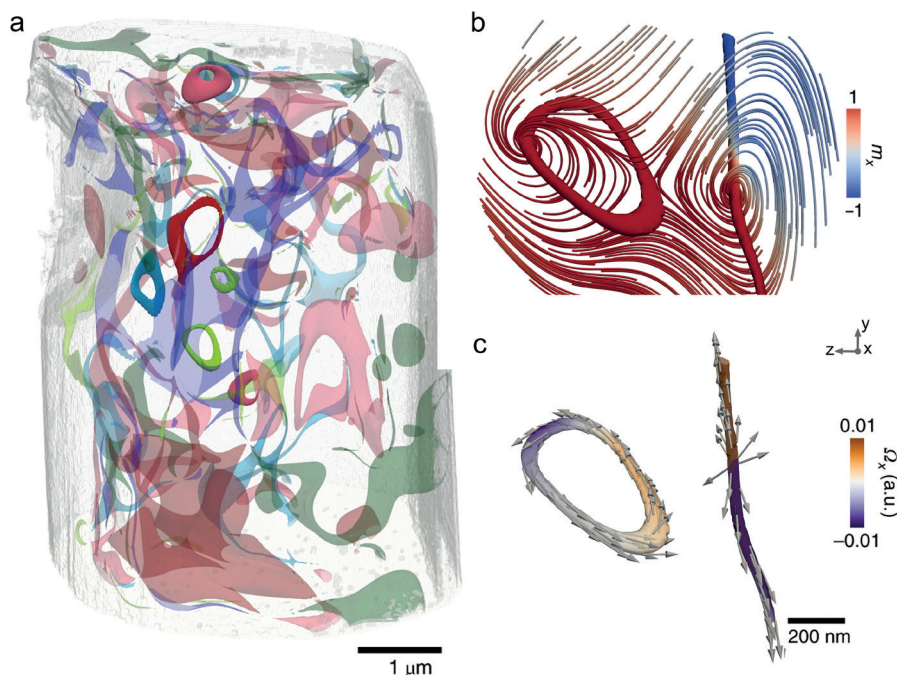


Figure 2. a) A large number of vortex rings are identified within a GdCo_2 micropillar. The rings are visualized by isosurfaces representing a defined magnetization direction. b) The cross-section of a ring is composed of a vortex-antivortex pair. The magnetization in the cross-section is represented by streamlines. A vortex structure is observed in the vicinity of the magnetic ring. c) The magnetic vorticity, Ω , represented by the plotted arrows circulates around the ring. Figure reproduced from Ref. [43].

While such magnetic vorticity loops had been predicted to exist in exchange ferromagnets [44], they were expected to be transient structures. In our measurements, we not only established their existence, but also discovered the surprising fact that

Topology

The magnetization vector has fixed magnitude within a given material and therefore has only two independent components, such that it can be mapped onto a sphere. The problem of finding equilibrium magnetization distributions then consists of continuously mapping one sphere onto another. From topology it is known that all such mappings can be classified by integers. In planar magnetism the topological class of a particular magnetization distribution is known as the skyrmion number or the topological charge. There is no continuous transformation be-

tween magnetization distributions with different skyrmion numbers. Such discontinuity implies that the formation of a singularity is required to access a state in which the skyrmion number is modified.

The vortex (Figure 3a) is an example of magnetization distribution with a topological charge of +1. Its counterpart, the antivortex (Figure 3b), has a topological charge of -1. These two objects are thus intimately related and always exist in pairs in infinitely-extended magnets (of which bulk micromagnets are good approximation).

In our measurements, we find a large number of Bloch points (Figure 3c), corresponding to locations where the magnetization reverses its direction within the vortex or the antivortex core. The singularities can equally be classified by their topological charge. The observed magnetic structures around a Bloch point and an anti-Bloch point are shown in Figures 3d,e.

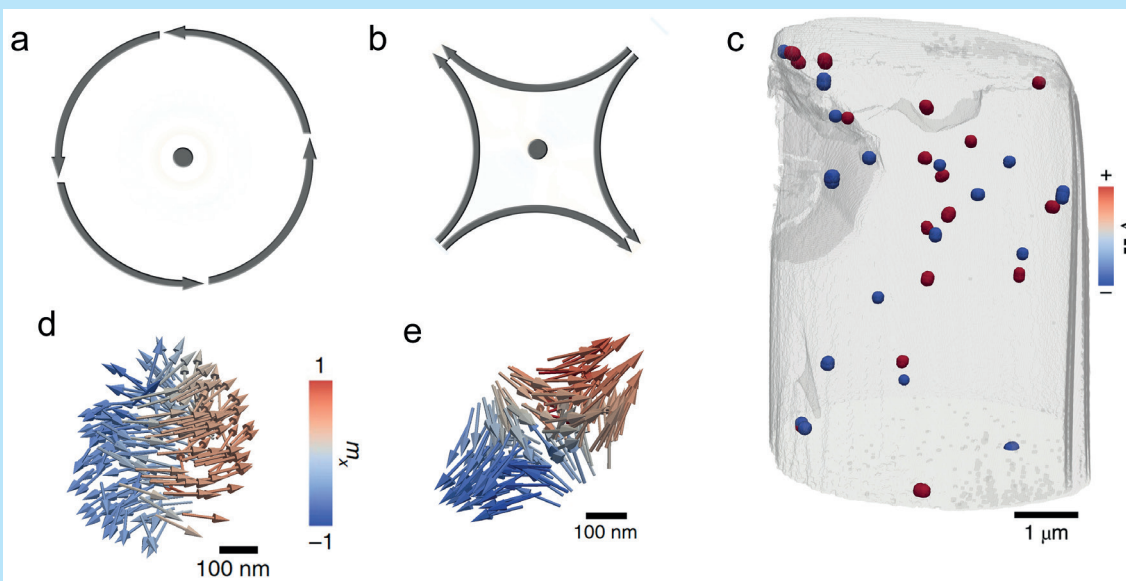


Figure 3. a) Schematic drawing of the in-plane magnetization of a vortex and b) of an antivortex. The central dot represents the core. c) Reconstructed Bloch point locations based on the divergence of the magnetic vorticity. d) Magnetic structure surrounding a Bloch point and e) an anti-Bloch point.

they can form stable, static configurations. Motivated by this finding, we were able to show that their stability is due to the magnetostatic interaction and provided an analytical estimate for the vortex ring size [43, 46]. In addition, we have observed stable vortex loops intersected by magnetic singularities at which the magnetization within the vortex and antivortex cores reverses. These structures have no counterparts in incompressible fluids given that there is no analogue of the local magnetization field in fluid dynamics.

These first observations of magnetic vortex rings represent an exciting step forward for the study of three-dimensional magnetic solitons. Even though the rings are topologically trivial (except when they contain singularities), with the new capabilities of magnetic tomography, it will be possible to unambiguously establish the structure of “knotted” solitons, such as hopfions [44, 47, 48]. Looking back at the history of magnetic vortices, we expect further discoveries, in particular concerning the dynamics of these structures, which may enable novel concepts and applications in information technologies. Recent simulations indicate that exotic structures – charge helices – exist within iron whiskers [49], which have been studied decades ago and were thought to be well understood. Hence, like dolphins who occasionally enjoy gazing at bubble rings, we admire the beauty of magnetic rings and look forward to being surprised for years to come.

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X-ray magnetic tomography

X-ray magnetic tomography involves measuring projections of the magnetic configuration in transmission for many different orientations of the sample with respect to the X-ray propagation direction (Figure 4). In contrast to usual tomography where a scalar quantity is reconstructed, the magnetization is a vector quantity with three components, which need to be determined for each voxel (three-dimensional pixel). The technique is based on the combination of three main aspects: 1) The measurement of high spatial resolution projections of the magnetisation probed with X-ray magnetic circular dichroism [50]; 2) The measurement of these projections for multiple sample orientations – each requiring separate tomographic measurements – in order to probe all components of the magnetisation; 3) The reconstruction of the magnetization with an iterative algorithm based on the angular dependence of the magnetic signal [51].

Once the reconstruction is performed, the next challenge consists of identifying the magnetization structures in three dimensions. To do this effect, the vorticity vector was calculated [43] which allowed determining the nature of topological objects such as vortices and singularities.

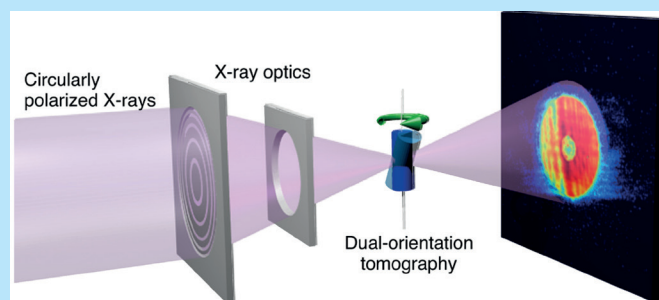


Figure 4. X-ray tomography of a magnetic micropillar. Magnetic projections are measured for two tomographic rotation axes to probe all components of the magnetisation. Figure reproduced from Ref. [43].