Gliga, S., Seniutinas, G., Weber, A. and David, C. (2019) Architectural structures open new dimensions in magnetism: Magnetic buckyballs. *Materials Today*, 26, pp. 100-101. (doi: 10.1016/j.mattod.2019.05.001).

Architectural structures open new dimensions in magnetism

Sebastian Gliga[a,b], Gediminas Seniutinas[b*], Anja Weber[b,c], Christian David[b]

[a] School of Physics and Astronomy, University of Glasgow, Glasgow, G12 8QQ, United Kingdom.
[b] Paul Scherrer Institut, 5232 Villigen-PSI, Switzerland
[c] Laboratory for Mesoscopic Systems, Department of Materials, ETH Zurich, 8093 Zurich, Switzerland

*Corresponding author: gediminas.seniutinas@psi.ch

Over 60 years ago Buckminster Fuller, a visionary engineer and architect, introduced a concept that revolutionized structural engineering: the geodesic dome. It was the result of years of experimentation and search for a general shape that would exhibit high structural integrity, and at the same time be light and affordable to build. The domes were used in large-scale projects, such as the American pavilion at Expo 67 in Montreal. These structures defined principles for structural integrity that can be applied on a large range of scales. Remarkably, with a radius below one nanometer, the structure of the C_{60} molecule is reminiscent of that of a geodesic dome and it was therefore named 'buckminsterfullerene'.

Today, the advent of modern nanofabrication tools has opened exciting new possibilities for defining structures on scales ranging from hundreds of nanometers to micrometers. However, it is only since relatively recently that such small structures can be fabricated in three dimensions – and Buckminster Fuller's principles are again essential. Indeed, his ideas find direct applications in structures that allow to create mechanical metamaterials. These structures combine ideas of large-scale mechanical properties with bio-inspired architectures to create materials with unprecedented strength, and properties including a negative Poisson's ratio [1].

Now, we add an additional degree of freedom to such materials: magnetism. In ferromagnetic nanostructures, the relationship between geometry and magnetic configuration is well understood. The main driver is the magnetostatic interaction, for example in the form of shape anisotropy, which can lead to the formation of specific and often complex domain patterns. These are characterized by particular dynamics that emerge due to the constitutive elements of the patterns, such as uniformly magnetized regions, domain walls or vortex structures.

More recently, the study of three dimensional nanostructures, mostly cylinders and nanotubes, has demonstrated that curvature could give rise to novel magnetic behavior, in particular chiral effects in the presence of magnetic fields [2]. Such magnetochiral effects have so far been predicted by theory and simulations and are promising for applications, in particular for data storage concepts, which rely on magnetic domain walls to store bits of information. Experimentally, such structures are only starting to be studied [3] and novel measurement techniques are currently being developed [4-7].

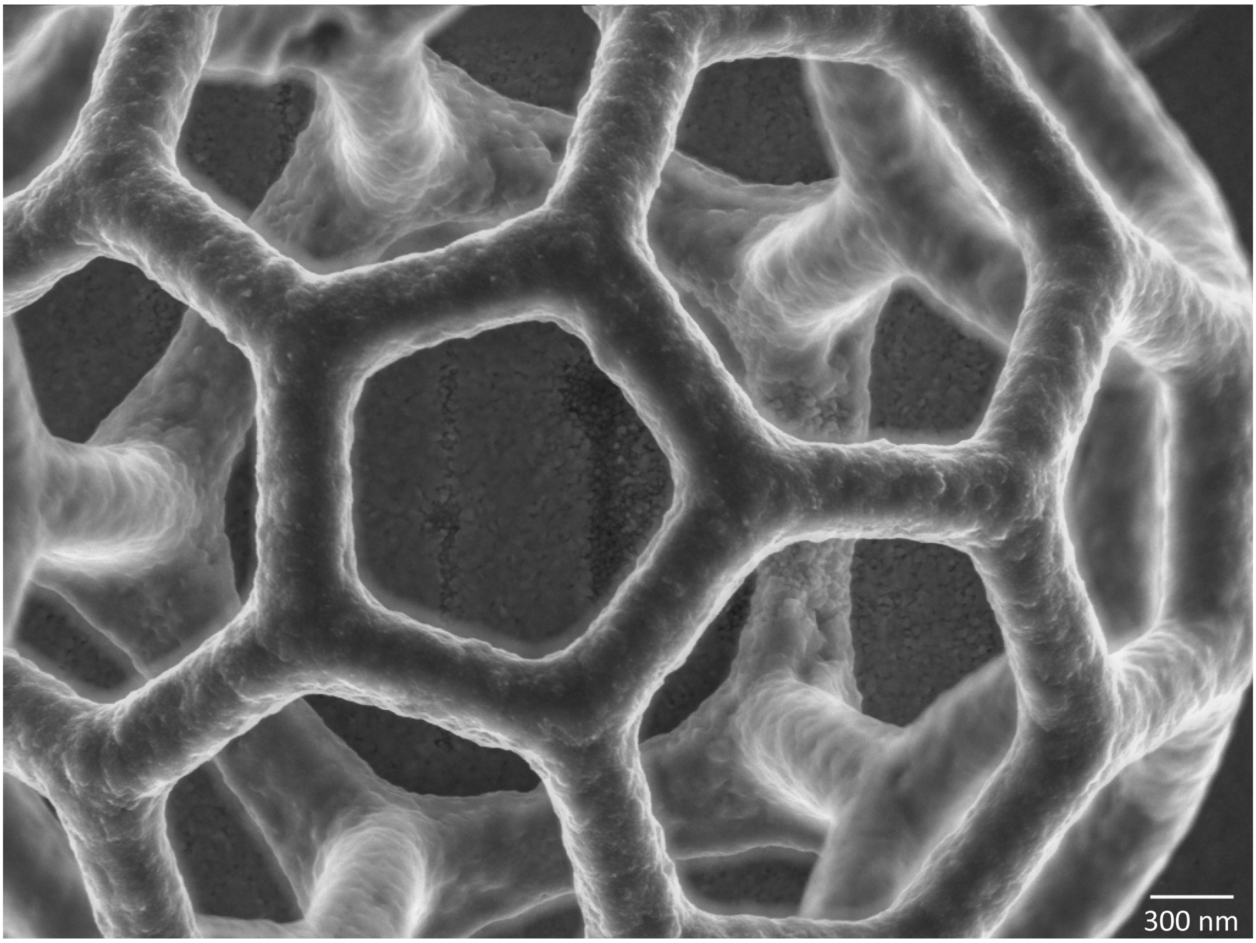
Using patterned ferromagnets, it is also possible to exploit the magnetostatic interaction to create so-called artificial spin systems. These are a novel class of magnetic materials, which consist in lithographically defined nanomagnets displaying collective behavior. Such materials have been studied in two dimensions and it has recently been shown that their properties could be tailored to create topological states [8], metamaterials for spin waves [9], and even thermal ratchets [10].

A logical extension of this work is the realization of such materials in three dimensions: the use of the third dimension indeed allows to fully achieve the potential of artificial spin structures, by offering maximal configurability and the possibility to optimize the magnetostatic interaction between the different elements of the system. It also allows to tailor novel dynamics characterized by the propagation of domain walls along curved structures in connected artificial spin systems, i.e. systems that are not only magnetostatically, but also exchange coupled. Of course such systems require specific fabrication as well as measurement techniques, which are still being actively developed.

As a proof of concept for the fabrication and the observation of the collective magnetic properties of such systems, we have chosen a mesoscopic buckyball. In this structure, the vertices correspond to the location of the carbon atoms in the C_{60} molecule and the solid bars connecting the vertices correspond to the molecular bonds. The structure demonstrates specific collective magnetic excitations due to its shape and magnetic structure and defines paths for domain wall propagation that could conceivably be used to perform logical operations [11]. However, the fabrication of such magnetic architectures with nanoscale features remains challenging.

Over the last years, multi-photon laser polymerization has emerged as a high resolution free-form three dimensional structuring technique. The technique provides great flexibility in envisioning and designing structures for various applications and so far has been widely used to produce metamaterials, photonic crystals and scaffolds for tissue engineering [12]. Commercially available three dimensional lithography systems reach sub-micron resolution in the plane perpendicular to the optical axis of the writing beam. However, the resolution along the axis is typically two to three times lower due to a weaker confinement of light along this direction and, as a result, elongated voxels are produced. In three dimensional laser lithography, high resolution buckyball structures are typically produced by properly combining single voxel lines. However, in this case, oval rather than round bar cross-sections are obtained, resulting in difficulties to disentangle various magnetic phenomena occurring in the structure. One solution to mitigate the initial voxel elongation is composing the bars of a few overlapping lines, but this increases dimensions of the structure. A way around it is to scale down polymerized 3D structures by pyrolysis and plasma etching [13].

We implement three dimensional laser lithography and resist post-processing to develop three dimensional magnetic structures at the mesoscale. Polymerized scaffolds, where voxel asymmetry is compensated by writing larger structures, are pyrolyzed and treated in oxygen plasma to scale them down to sizes relevant for magnetic investigations. However, resists used are typically nonmagnetic and post-processed scaffolds need to be further altered to endow them with magnetic properties. We have achieved this by depositing a uniform conductive film of iridium using atomic layer deposition and subsequent electroplating of a magnetic material – in this case, nickel. The result is a mesoscale 3D structure composed of magnetic nanotubes. One of these magnetic buckyballs is featured on the cover of this issue of *Materials Today*. The image shows scanning electron micrograph of a 5 µm diameter Buckyball composed of nickel tubes of around 300 nm in diameter and having sidewall thickness of ca. 30 nm. Further studies of these architectures should give insights into three dimensional nanomagnetism and provide a basis for the design of novel magnetic micro-devices.



Acknowledgments

GS and CD acknowledge funding from the EU-H2020 Research and Innovation program under Grant Agreement No. 654360 NFFA-Europe. SG acknowledges funding by the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No. 708674. SG is grateful to Claire Donnelly, Laura J. Heyderman and Riccardo Hertel for fruitful collaborations and discussions.

References

[1] L.R. Meza, et al., Proc. Natl. Acad Sci. USA 112 (2015) 11502-11507
[2] R. Hertel, SPIN 3 (2013) 1340009
[3] A. Fernández-Pacheco, Nat. Commun. (2017) 15756
[4] C. Phatak, et al., Nano Lett. 14 (2014) 759–764

[5] C. Donnelly, et al., Phys. Rev. Lett. 114 (2015) 115501
[6] R. Streubel, et al., Nat. Commun. 6 (2015) 7612
[7] C. Donnelly, et al., Nature 547 (2017) 328-331
[8] C. Nisoli, *in* The Role of Topology in Materials, p. 85-112, Springer (2018)
[9] E. Iacocca, et al., Phys. Rev. B 93, 134420 (2016)
[10] S. Gliga, et al., Nature Materials 16, 1106 (2017)
[11] A. Pushp, et al., Nature Physics 9, 505 (2013)
[12] M. Malinauskas et al., Light Sci. Appl. 5 (2016) 16133.
[13] G. Seniutinas et al., Microelectron. Eng. 191 (2018) 25-31.