Size-Specific Spin configurations in Fe Nanocubes probed by Magnetic Electron Holography and Micromagnetic Simulations: from flower to vortices

T. Blon[1], F.B. Bonilla[1], L.-M. Lacroix[1], A. Meffre[1], B. Chaudret[1], B. Warot-Fonrose[2], E. Snoeck[2], C. Gatel [2]

[1] Laboratoire de Physique et Chimie des Nano-objets (LPCNO), Université de Toulouse, France

[2] CEMES-CNRS, Toulouse, France

Iron nanocubes (NCs) elaborated by organo-metallic chemistry consist in ideal systems due to their single crystal structure, tunable sizes and bulk magnetic parameters. In such nano-objects, micromagnetic simulations predict that the magnetic configuration changes from single-domain (*i.e.* flower) to vortex states as the cube size increases (Fig. 3). By combining chemical synthesis, electron holography (EH) in a dedicated transmission electron microscope and micromagnetic simulations, here we focus on sufficiently small Fe NCs to reveal the single-domain/vortex transition.

Iron nanoparticles are synthesized by decomposition of a precursor under hydrogen atmosphere at 150°C in the presence of long-chain amines and acids. By tuning the amine/acid ratio we control the size and shape of our particles, ranging from 1.3 to 90 nm and evolving from spherical to cubic. All these particles are single-crystalline (Fig.1), and exhibit bulk magnetization, even the smallest ones.

The spin configuration phase diagram in size-controlled single Fe nanocubes is discussed. High sensitivity EH imaging explicitly reveals how three different spin configurations can be stabilized within a 3 nm window [1]. Magnetic maps of easy-axis flower, hard (<111>) and easy-axis (<001>) vortices states are analyzed in isolated Fe NCs of roughly 25, 26 and 27 nm size respectively (Fig. 2), and this in good accordance with dedicated calculations (Fig.2-3) [2]. It is the first time that a <001> flower state is observed in a so small magnetic element, and that a stable <111> vortex is measured. This gives a deeper understanding of the single-domain/vortex transition which is more complex than expected with the appearance of a <111> vortex intermediate state. Such measurements and simulations open the door to fine magnetic control of nano-objects which will find applications in fields as wild as spintronics devices, information storage or hyperthermia.

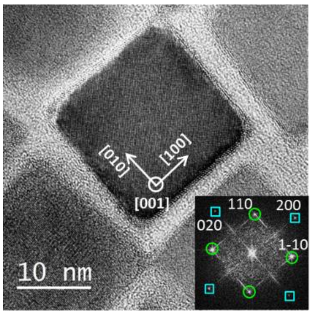

Figure 1. HRTEM picture of a Fe NC and resultant FFT.

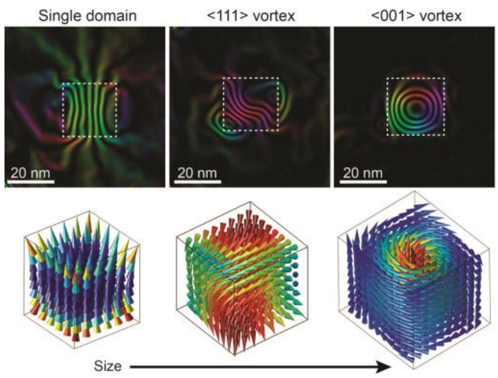

Figure 2. Measured EH phase images and corresponding simulated spin configurations.

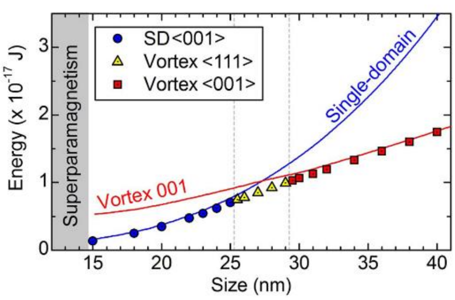

Figure 3. Calculated magnetic energy of an iron NC as a function of the nanocube size.

[1] C. Gatel, F.J. Bonilla, A. Meffre, E. Snoeck, B. Warot-Fonrose, B. Chaudret, L.-M. Lacroix, T. Blon, *Nano Lett.* 15 (2015) 6952-6957
[2] F.J. Bonilla, L-M. Lacroix, T. Blon, *J. Magn. Magn. Mat.*428 (2017) 394–400