Magnetic States in Fe Nanoparticles Imaged by Off-axis Electron Holography

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Magnetic nanoparticles that fall within a certain size range show single domain magnetic properties. In an intermediate size regime between single and multi domain behaviour, such particles may exhibit flux closure, i.e. their magnetic configurations may be vortex-like. The critical size for this transition from single domain to vortex behaviour is crucial for determining the net magnetic moments carried by magnetic nanoparticles, i.e. for applications. Since the magnetic anisotropy of a particle is influenced strongly by its surface properties, it is difficult to predict this critical size. Here, we present images of such vortex states measured directly using off-axis electron holography [1].

FIGS. 1 (a), (b) and (c) show slightly defocused bright field images of single crystalline Fe nanoparticles with diameters of 20-40 nm, which were deposited onto an amorphous C film. Each particle is passivated by a 3-nm-thick ferrimagnetic Fe_3O_4-γ-Fe_2O_3 shell. The fabrication, and the structural and magnetic characterisation, of the particles have been described elsewhere [2-4]. Off-axis electron holograms were acquired in Lorentz mode using a Philips CM300 microscope equipped with a 1024 pixel CCD camera located at the end of a Gatan Imaging Filter. The biprism voltage was 200 V, corresponding to a holographic interference fringe spacing of 2.9nm. All measurements were performed at room temperature. A magnetic field (2 T) was applied to the sample parallel to the direction of the electron beam by using the objective lens, with the sample tilted by ± 30 degrees. The field was then reduced to zero, the sample tilted back to zero degrees, and holograms were recorded with the particles at remanence. The holograms were analysed using the Semper image-processing package [5].

FIGS. 1 (d), (e) and (f) show the corresponding magnetic induction maps recorded from (d) a chain of magnetostatically-interacting particles; (e) an isolated single domain particle; (f) a single domain (upper) and a vortex state (lower) particle. The mean inner potential contribution to the phase shift has been removed using a procedure that is described elsewhere [1]. In FIG. 1 (d), a magnetic vortex surrounds a flux tube that runs along the chain, while in FIG. 1 (f) the vortex core in the larger particle is imaged end-on. Quantitative information about the magnetic induction and the magnetic radius of each particle can be deduced by fitting measured phase profiles (FIG. 1 (g)) to simulations [1]. The phase profiles in FIG. 1 (g) are consistent with the magnetic induction of Fe to within experimental error.

[1] Dunin-Borkowski R.E. et al. Encyclopedia of Nanoscience and Nanotechnology, Nalwa H.S., ed., American Scientific Publishers, vol. 3 (2003) 41-99
[2] Theil Kuhn L., Geim A.K., Lok J.G.S., Hedegård P., Ylanen K., Jensen J.B., Johnson E. and Lindelof P.E. *European Physical Journal D* **10** (2000) 259-263
[3] Theil Kuhn L., Bojesen A., Timmermann L., Meedom Nielsen M. and Mørup S. *Journal of Physics: Condensed Matter* **14** (2002) 13551-13567
[4] Fauth K., Goering E., Schütz G. and Theil Kuhn L. *Journal of Applied Physics* **96** (2004) 399-403
[5] Saxton W.O., Pitt T.J. and Horner M. *Ultramicroscopy* **4** (1979) 343-353
[6] LTK kindly acknowledges financial support from the Allan Mackintosh Fund. RDB thanks the Royal Society for support.

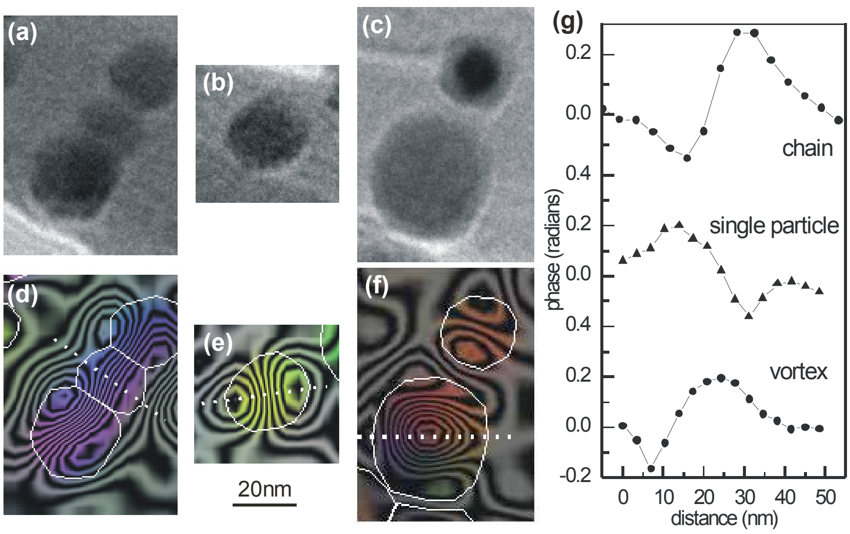

FIG. 1. Bright field images of (a) an interacting chain of Fe particles, (b) an isolated particle and (c) two particles on an amorphous C film. (d), (e) and (f) show the corresponding magnetic induction maps (128 times phase amplified). The white lines show the edges of the particles, the contours represent magnetic lines of force, and the dotted lines show phase profiles, which are plotted in (g).