# Magnetic Induction Mapping of Nanostructured Materials using Electron Holography

R.E. Dunin-Borkowski [1], T. Kasama [2,1], A. Wei [3], S.L. Tripp [3] and M.J. Hÿtch[4]

1. Department of Materials Science and Metallurgy, Pembroke Street, Cambridge CB2 3QZ, UK
2. RIKEN, 2-1 Hirosawa, Wako, Saitama 351-0198, Japan
3. Department of Chemistry, Purdue University, West Lafayette, IN 47907, USA
4. CECM - CNRS, 15 rue G. Urbain, 94407 Vitry-sur-Seine, France

*rafal.db@msm.cam.ac.uk*

The off-axis mode of electron holography is ideally suited to the characterization of magnetic fields in nanostructured materials in the transmission electron microscope. The technique involves applying a voltage to an electron biprism in order to overlap a coherent electron wave that has passed through the sample with a part of the same electron wave that has passed only through vacuum. Analysis of the resulting interference pattern allows the phase shift of the electron wave to be recovered quantitatively and non-invasively at a spatial resolution close to the nm scale [1]. Here, we illustrate the application of the technique to the characterization of magnetic remanent states in rings and chains of magnetic nanocrystals. The magnetic properties of such particles are of considerable interest, both fundamentally and for the design of ultra-high-density magnetic devices.

Figure 1a shows a low magnification bright-field image of self-assembled rings and chains of 20-nm-diameter Co nanoparticles, which are each encapsulated in a 3-4 nm oxide shell. Figures 1b-e show magnetic flux lines in four nanoparticle rings [2], recorded at 300 kV using electron holography in a Philips CM300ST field emission transmission electron microscope. The images, which show flux closure states, were recorded in field-free conditions. The flux lines are formed from the cosine of 128 times the magnetic contribution to the measured phase shift, and reveal the in-plane induction in each ring integrated in the electron beam direction. The spatial resolution of the magnetic information is estimated to be approximately 10 nm. The unwanted mean inner potential contribution to the phase shift has been subtracted from the images using an approach that is described elsewhere [1]. It was established that the chirality of the states shown in Fig. 1b could be switched *in situ* in the electron microscope using an out-of-plane magnetic field.

Figures 2a and b show magnetic flux lines in two chains of $Fe_{55}Ni_{45}$ particles [3]. The remanent state of a 75 nm particle sandwiched between two smaller particles is shown in Fig. 2a. Closely-spaced contours run through all three particles in a channel of width 22 nm. Comparisons with simulations suggest that the largest particle contains a vortex, as shown schematically in Fig. 2c. In Fig. 2b, a vortex can be seen end-on in a 71 nm particle at the end of a chain. The positions of the particle's neighbors determine the chirality of the vortex (Fig. 2d), whose core is only 9 nm in diameter. The larger value in Fig. 2a results from dipole-dipole interactions along the chain. A similar induction map recorded from a chain of $Fe_{10}Ni_{90}$ particles is shown in Fig. 2e. The magnetic microstructure in this sample, which has a higher Ni concentration, is closer to that expected for a chain of single-domain spheres. Flux channels, which are 70 nm in diameter, now form only when the particles are above ~100 nm in size [4].

1. R.E. Dunin-Borkowski and M. R. McCartney, in *Magnetic Nanostructures*, edited by H. S. Nalwa (American Scientific Publishers, 2002), pp. 299-325.
2. S.L. Tripp, R.E. Dunin-Borkowski and A. Wei, Angew. Chemie **42** (2003), p. 5591.
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4. We thank the Royal Society, the EPSRC and the European Research Group "Quantification and measurement in transmission electron microscopy" for support.

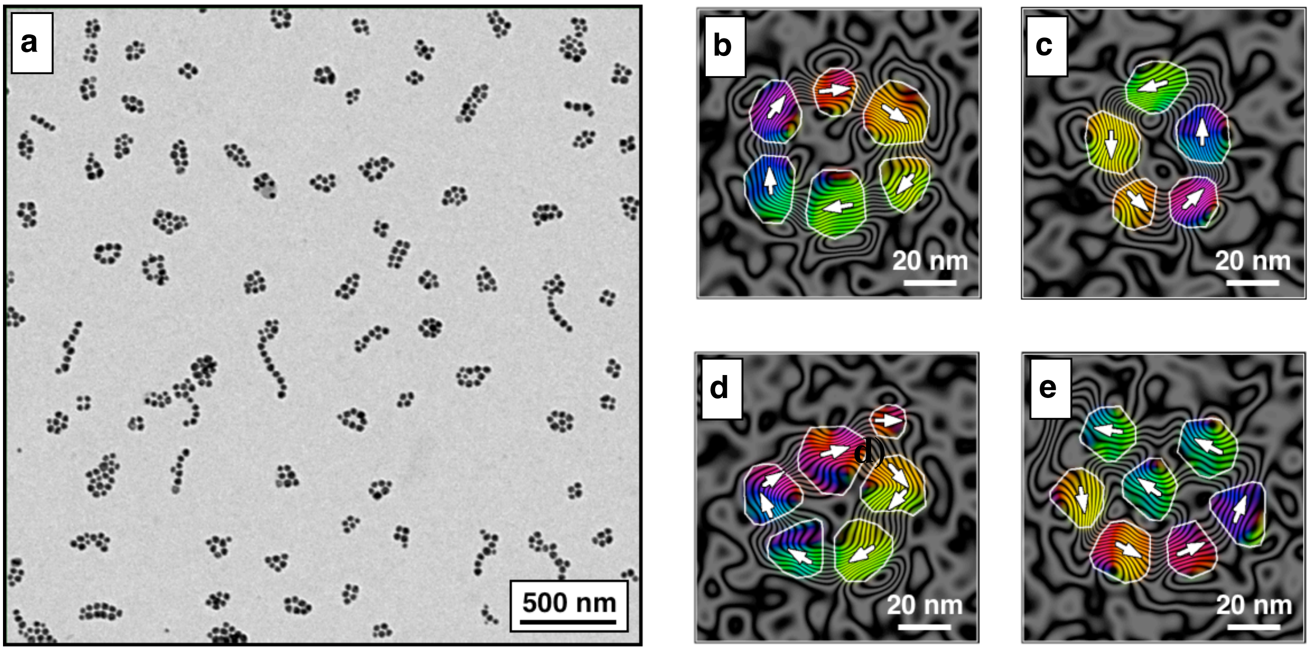


**Figure 1.** a) Low magnification bright-field image of self-assembled Co nanoparticles deposited onto an amorphous carbon film. Each Co particle has a diameter of between 20 and 30 nm. b) - e) Magnetic phase contours in four different nanoparticle rings (128 × amplification; 0.049 radian spacing), formed from the magnetic contribution to the measured phase shift. The outlines of the nanoparticles are marked in white, while the direction of the measured magnetic induction is indicated using arrows.

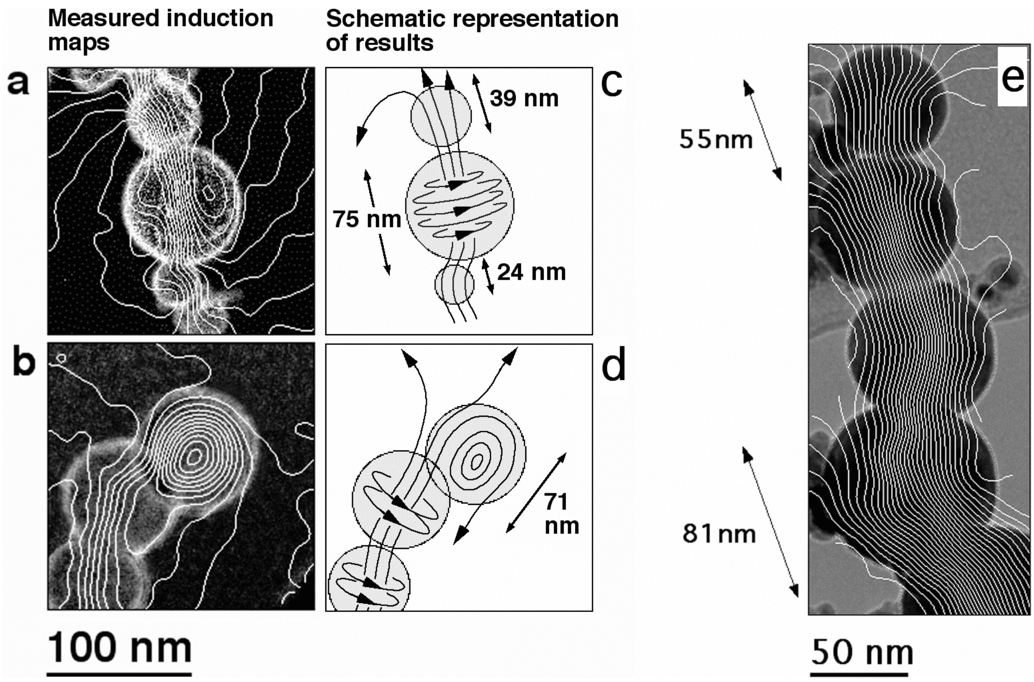


**Figure 2** a) - b) Phase contours in two chains of $Fe_{55}Ni_{45}$ particles, overlaid onto O elemental maps, showing the in-plane induction integrated in the electron beam direction, recorded with the microscope objective lens switched off. The contour spacings are 0.083 and 0.2 radians for a) and b), respectively. c) and d) show schematic diagrams of the magnetic microstructure in the chains, in which vortices spin around each chain axis. A vortex perpendicular to the chain is also visible in d). e) shows similar phase contours recorded from a chain of $Fe_{10}Ni_{90}$ particles (spacing 0.125 radians, overlaid onto a bright-field image).