From Biological Magnetism to Nanotechnology:
How Electron Holography Provides the Eyes to See the Invisible in Nanoscience

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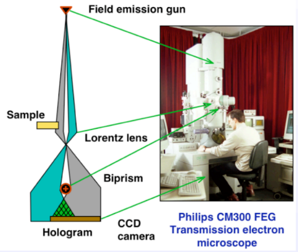
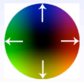


Philips CM300 FEG Transmission electron microscope

Electron Holography

Electron Holography is a transmission electron microscopy (TEM) technique that allows the phase shift of an electron wave to be recorded. The phase shift is sensitive to electric and magnetic fields in a sample, and can be used to obtain information about these fields at the nanometre scale[1].

A schematic ray diagram for electron holography is shown on the left, together with a photograph of a Philips CM300 TEM. The magnetic induction maps shown on this poster contain contours, which represent magnetic field lines, and colours, which show the direction of the field according to the colour wheel shown below.



As well as mapping the magnetic induction, holography is also a fully quantitative technique, revealing the magnitude of fields examined.

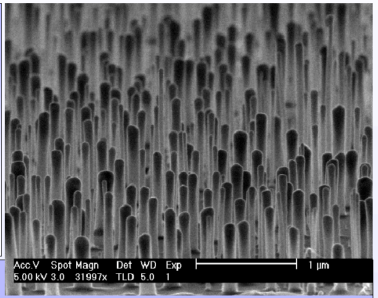
Magnetic Particles in Carbon Nanotubes

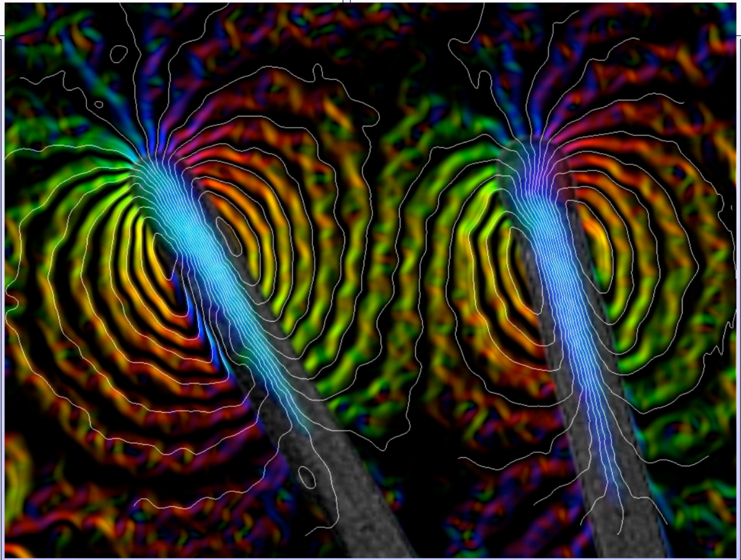
The catalysts which are used to grow some carbon nanotubes, can often remain in the end of the nanotube as it growth proceeds. This small crystal, encapsulated within the nanotube can alter the properties of the resultant nanocomposite, depending on the material used.

The SEM image on the right shows a 'forest' of these nanotubes grown from a cobalt-palladium alloy. There are nanotubes of various heights and widths, but all contain a catalyst crystal, which exhibits a stable magnetic moment for this particular alloy. Electron holography can reveal the nature of the magnetic properties of these crystals, and map the magnetic induction and deduce quantitative information about the field.

The induction map shown below shows two of these nanotubes containing a Co-Pa alloy, overlayed with the field the crystals produce. The close proximity of the two elements means the fields interact.

As before, the colours represent the intensity and direction of the field, shown here with field lines created by contours of equal magnetic phase.



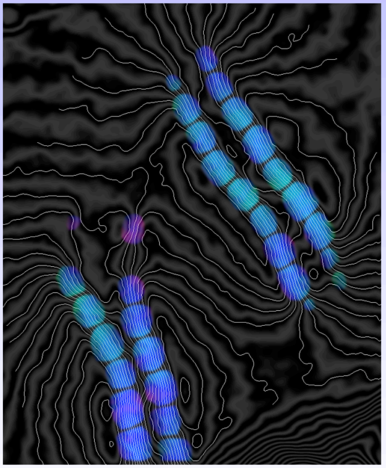


Magnetotactic Bacteria

There are certain strains of bacteria which contain chains of magnetite nanocrystals within the cell. These are grown for the purpose of orientation with the geomagnetic field, so the bacterium can swim up or down in a water column to find the oxic-anoxic transition zone in sediment, where it then feeds [2].

The arrangements of crystals in these chains provide a model system for studying nanomagnetic interactions, and for looking at the properties of single domain, closely spaced magnets.

The image below shows a magnetic induction map of the field produced by two double chains of magnetite crystals, from a wild magnetotactic bacterium collected in Hungary. Interactions between the chains can be seen, and the magnetic moment calculated from phase map.

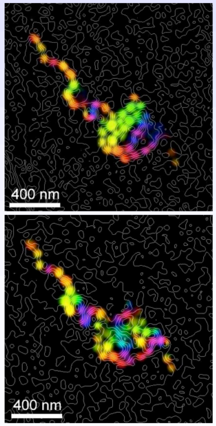


Depending on the strain of bacteria, there is variation among the morphologies of chains observed, with different crystal sizes, spacings and shapes. However, the one thing they all have in common is that they provide a single magnetic moment for orientation in the geomagnetic field. This means that there is little deviation from the 'bar magnet' configuration you see on the left, in natural samples.

Genetic Modification of Bacterial Chains

To move away from the single magnetic moment configuration, in order to explore magnetic interaction beyond this, we need to modify the way the bacteria build these chains. The two images on the right show the crystals and field from a bacterium with the mamJ gene deleted - this is the gene that controls the building of the chain.

The resulting 2D arrangment of magnetosomes produces a more complex magnetic field, with flux vortices that change configuration even within the same cell, over time. The top image has a single vortex, the bottom, three interlinked.

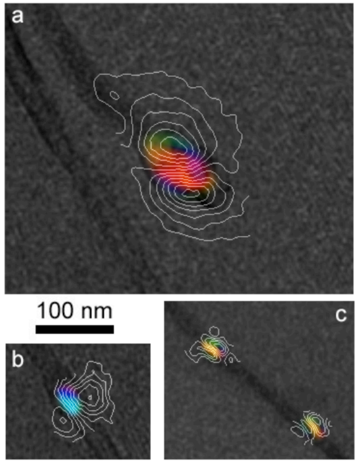


Periodic Magnetic Particles

Insertion of magnetic particles into nanotubes is not just limited to the ends, as described above. Magnetic alloys can be periodically inserted into these nanostructures to modify the properties in different ways [3].

Here, metal phosphides have been inserted into CNTs, with a periodicity of approximately 150nm. These crystals are much smaller than those encapsulated at the ends of nanotubes, some being very close to the superparamagnetic limit. The small size, and reduced magnetic signal means that the induction is much more difficult to map, and often lost in noise. However, the images on the right show a selection of some of these particles where the magnetic induction has been successfully mapped.

Inserting magnetic crystals into nanotubes like this has the potential to form the building blocks of new high-tech electronic components, and in particular, spintronics. If a spin-polarised electron is passed along a nanotube such as this, then the presence of a magnetic field will alter its resistance, depending on which way the particle is magnetised. Applying magnetic fields to these particles to switch their polarisation could therefore alter the resistance of these spin polarised electrons.



Isolated Crystal

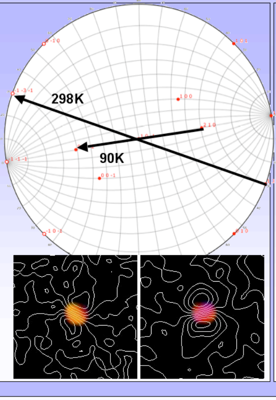
Chains and arrays of magnetosomes from bacteria provide a good insight into the interactions between magnetic nanocrystals. However, other effects such as shape anisotropy and magnetocrystalline anisotropy are masked by this dominating behaviour.

Examination of a single, isolated magnetosome limits the effect of interactions, and so here, the role of other anisotropic effects can be seen. An isolated 50nm magnetosome is shown in the holograms below at room temperature (in orange) and at 90K (in red).

At room temperature, the magnetisation lies in plane (deduced from quantitative observation of the field, fitted to a theoretical model) and along the [131] direction in the magnetite. This corresponds to the longest diagonal dimension of the crystal, showing that shape anisotropy dominates behaviour at room temperature.

However, at 90K, the magnetite has passed through the Verwey transition [4], where it undergoes a phase change from cubic to monoclinic, and acquires a new easy axis of magnetisation [5]. In-plane, the magnetisation has swung by ~30° , and fitting quantitative data to the model shows it is also ~40° out of plane. This corresponds to the [120] direction, which is close to the new easy axis, showing that magnetocrystalline anisotropy is playing a much more important role in the magnetic behaviour.

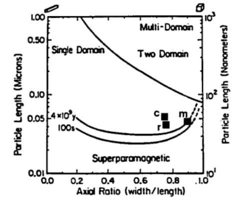
The stereogram above the two induction maps displays the crystallographic directions of the magnetic moments at the two different conditions.



Conclusions and further work…

Electron Holography provides an insight in the magnetic behaviour of many diverse system, from biological to technological, all of which are related by the presence of nanoscale magnetic elements.

The aim here is not just to characterise the behaviour of each individual system magnetically, but to draw all the data together in an experimental phase diagram of nanomagnetic systems, that will map shape, size, anisotropies and temperature dependence. A theoretical equivalent of this is shown below in the form of a 'Butler-Banerjee' map [6]. All data seen here has the potential to form an empirical point on such a map.



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