Magnetic induction mapping of magnetite nanocrystals above and below the Verwey transition using electron holography

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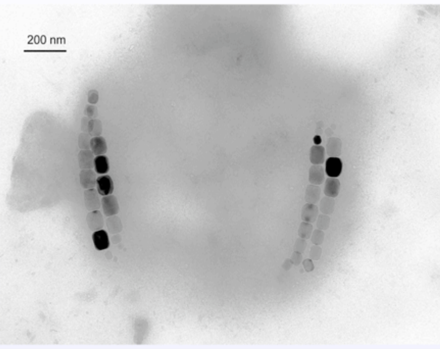
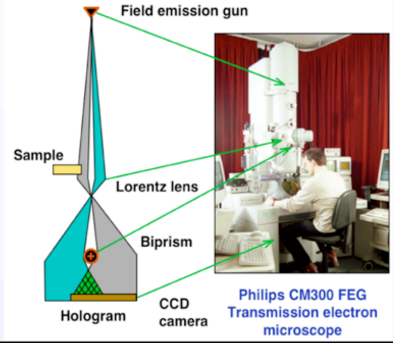


Electron Holography

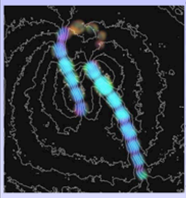
Electron Holography is a transmission electron microscopy (TEM) technique that allows the phase shift of an electron wave to be recorded. The phase shift is sensitive to electric and magnetic fields in a sample, and can be used to obtain information about these fields at the nanometre scale[1]. A schematic ray diagram for electron holography is shown on the right, together with a photograph of a Philips CM300 TEM. Below is a representative electron hologram of two double-chains of magnetite crystals in a single bacterial cell. These 'magnetotactic' bacteria were gathered from a stream in Hungary, and are common throughout the world. A typical bright field image of a cell is shown on the left.

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 on the left.

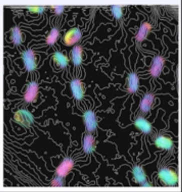


Philips CM300 FEG Transmission electron microscope

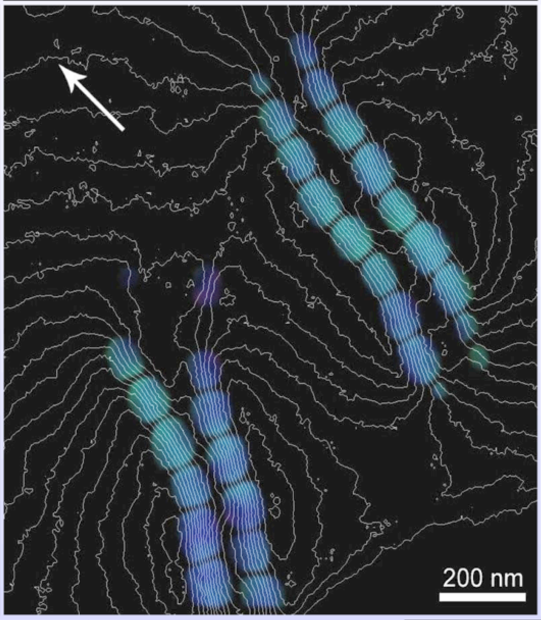
Nanomagnetism



The magnetic properties of closely spaced nanoparticles result from a delicate balance between the competing effects of particle size, morphology, crystallography and spacing, as well as external factors such as temperature and applied magnetic field. Linear chains of ferrimagnetic magnetite crystals, such as those found in magnetotactic bacteria, provide a model system for studying the fundamental effects that influence the magnetic properties of nanoscale magnets[2]. Examples of the complexity of the magnetic fields in these systems is shown in the figures above and below. Magnetite crystals from different bacterial strains can have different arrangements and different shapes - from slight deviations in chain alignment to scattered crystals with complex magnetic interactions, as shown below.

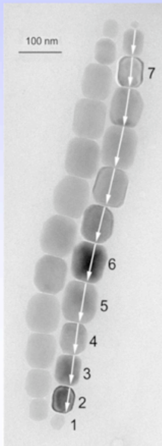


Small deviations in morphology can cause large differences in magnetic behaviour. The figures shown below are acquired from two double chains. An external magnetic field has been applied in perpendicular directions, shown by the white arrows. Part of one chain has reversed magnetically in Figure b).



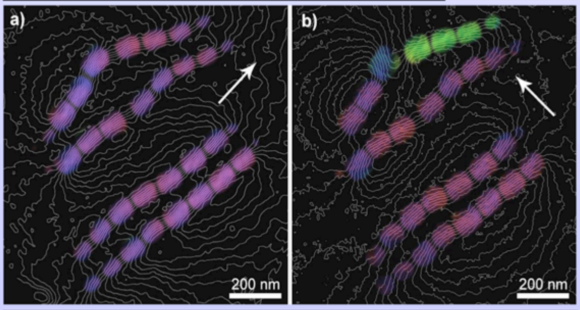
Biomagnetism

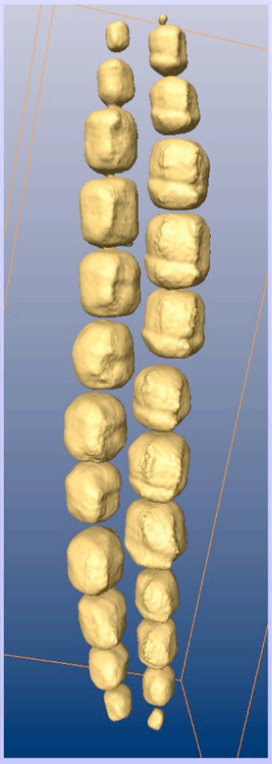
Magnetite crystals in bacteria act as compass needles, allowing the cells to move only parallel to the Earth's magnetic field[3]. These are not the only organisms that contain such minerals though. Birds are thought to use a similar process to navigate, with the magnetic particles located in their beaks.



Even humans contain magnetic nanocrystals in various organs of the body, and in proteins like ferritin. By considering how these crystals behave in simple organisms like bacteria, we hope to understand further the role they play in higher organisms.

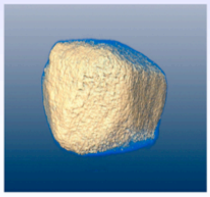
Some of this work involves using the technique of electron holography to examine magnetite crystals from the human brain, which may be associated with neurodegenerative diseases such as Alzheimer's disease. The characterisation of these minerals and their magnetic properties may therefore have important consequences.

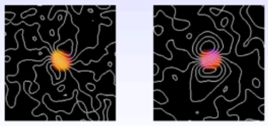




Temperature dependence of magnetisation

As well as acquiring holograms at room temperature, similar information can be obtained with the sample cooled using liquid nitrogen. Below 119K, magnetite passes through the 'Verwey' transition, and undergoes a phase change that alters its magnetic properties[4]. The magnetisation increases in magnitude, and the crystallographic easy axis of magnetisation changes[5]. This effect is seen by acquiring two holograms of an isolated nanocrystal, firstly at room temperature and then below the Verwey transition (at ~90K). The direction of magnetisation changes by ~30° between the two images.



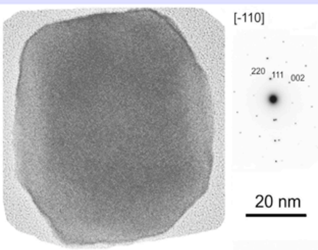


The 3D tomographic reconstruction of this crystal (left) allows its 3D shape and crystallography to be correlated with its magnetic properties.

Electron tomography and high-resolution TEM

Electron tomography is a TEM technique that allows the 3D shapes and chemical compositions of materials to measured. The 3D reconstruction of a double magnetite chain, shown on the right, was obtained from a series of high-angle annular dark field images acquired over a large range of sample tilt angles. The 3D image complements the electron holographic data by providing morphological and crystallographic information about the nanocrystals, which has an impact on their magnetic behaviour.

High-resolution TEM allows the magnetite crystals to be imaged at close-to-atomic resolution. By combining this information with diffraction patterns (shown on the right), the crystallographic orientation of a crystal can be determined accurately. In these bacteria, the chain axis is parallel to the [111] direction of the crystals - the easy axis of magnetisation.



Conclusions

Electron holography and associated techniques allow magnetic interactions between nanoscale magnetite crystals to be studied directly. The need to understand these effects has implications both for our fundamental understanding of magnetic interactions between closely-spaced magnetic nanocrystals and for understanding the presence of magnetite crystals in a wide range of organisms.

References

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