



An experimental study of magnetic interactions between biogenic magnetite nanocrystals

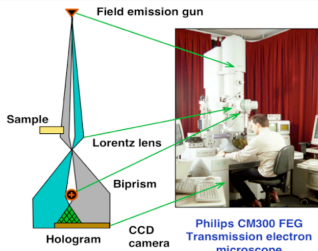
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Electron Holography

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 electrostatic and magnetic fields in a sample, and can be used to obtain information about these fields at the nanometre scale¹. A schematic ray diagram for electron holography is shown on the right, 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 on the left. As well as mapping the magnetic field, holography is also a fully quantitative technique, revealing the magnitude of fields examined.



Time-course Samples

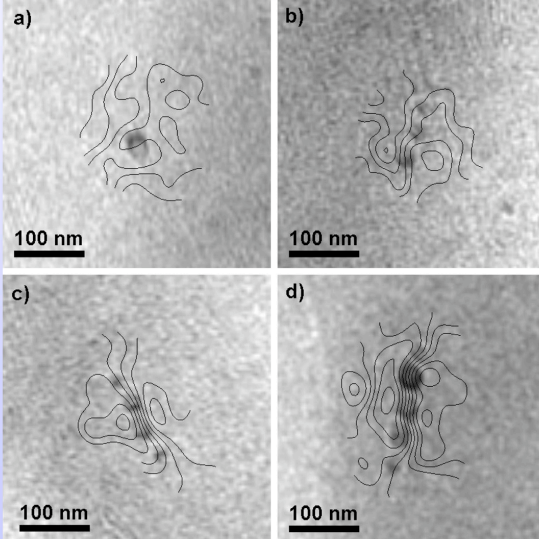
Depending on the strain of bacteria, there is variation among the morphologies of chains observed, with different crystal sizes, spacings and shapes. However, the one thing they all have in common is that they provide a single magnetic moment for orientation in the geomagnetic field. This means that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

The induction maps below are taken from a series of time-course samples, where growth of the strain *Magnetospirillum gryphiswaldense* has been arrested at varying times after the addition of iron to the growth medium. This results in chains which are at various stages of growth - from very immature chains, as seen in images a) and b), to those more fully grown, as in c) and d).

This provides a full range of samples with varying crystal sizes and spacings, each of which can be assessed in terms of its magnetic state.

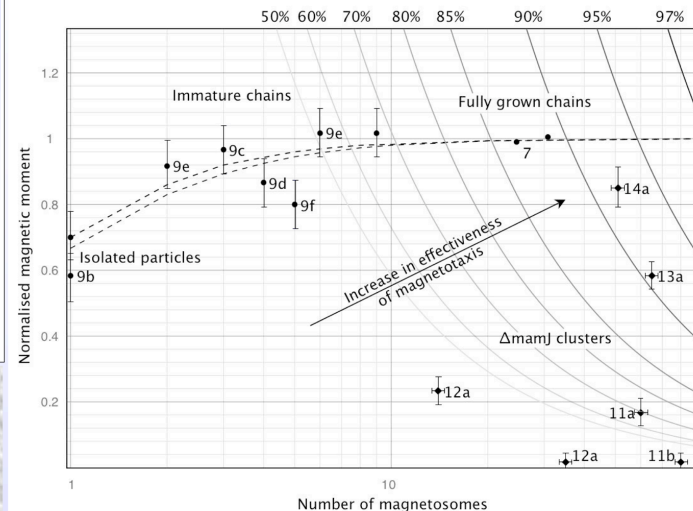
The chart to the bottom-left summarises the magnetic state of individual crystals from these samples, showing whether the crystal has a stable magnetic moment (black dots) or whether it is superparamagnetic (white dots).

There is a clear separation between the two regions, and the superparamagnetic size limit is seen to decrease as crystals get closer together, due to the interaction between adjacent crystals.



The boundary between the two regions seen in the chart on the left, can be described by the model of superparamagnetism according to Néel³, and expanded upon by Brown⁴. As shown below, the relaxation time, τ , of a magnetic moment can be related to the particle volume, V , and its anisotropy energy, H_K , as well as the field it is subject to from external sources, H_0 , in this case generated by neighbouring particles. This equation was used to produce the dotted boundaries on the chart, for varying relaxation times. Each relaxation time is represented by two lines - the right line assuming a single adjacent particle, and the left, an infinite chain of particles. In reality, these crystals will sit somewhere between these two extremes.

$$\frac{1}{\tau} = f_0 \exp \left[-\frac{\mu_0 V M_s H_K}{2k_b T} \left(1 + \frac{H_0}{H_K} \right)^2 \right]$$



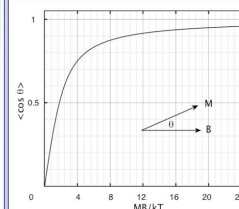
Genetic Modification of Bacterial Chains

To move away from the single magnetic moment configuration seen in wild-type cells, in order to explore more complex magnetic interactions, we need to modify the way the bacteria build these chains. The two images on the right show the crystals and field from a mutant bacterium of the *Magnetospirillum gryphiswaldense* strain.

In the wild-type strain, a protein known as *MamJ* is responsible for arranging the crystals into linear chains. By suppressing the expression of this protein in the mutant strain, we see intracellular clusters of magnetosomes formed instead⁵. These exhibit much more complex interactions, as is seen in the induction maps to the right, where significant flux density is seen in the magnetic vortices.

The magnetic moments of these mutant cells, reduced as they are, is expected to reduce the effectiveness of magnetotaxis. This is illustrated in the chart above where the magnetic moment per unit volume, normalised by the saturation magnetisation, is plotted against the number of magnetosomes in each cell.

The chart contains data points from the time-course samples, the mutant samples, and wild type bacteria. Effectiveness of magnetotaxis is shown as contours, representing the proportion of the cell's velocity that is in the field direction. This is modelled according to a Langevin function, plotted below, where θ is the deviation of the moment, M , from the field direction, B ⁶. It can be seen from the above chart that the immature cells, and those mutant cells with significant flux density show low magnetotaxis effectiveness. Fully-grown cells, are much more effective at aligning with the applied magnetic field.



References and Acknowledgements

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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, for optimal growth conditions².

The image to the left shows a magnetic induction map of the field produced by two double chains of magnetite crystals, from a wild magnetotactic bacterium collected in Hungary. The chains produce a single, stable magnetic moment, and interactions between the chains can be seen.

Electron holography, being a fully quantitative technique, also allows the magnetic moment to be calculated from the phase map according to the equation

$$m_y \approx + \left(\frac{h}{e} \right) \int_{chain} \Delta \phi_{mag}(x, y) dl$$

