Magnetic Microstructure of Closely-Spaced Ferrimagnetic Crystals in Magnetotactic Bacteria

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Magnetotactic bacteria migrate along geomagnetic field lines as a result of the presence of intracellular mineral grains of magnetite (Fe_3O_4) or greigite (Fe_3S_4). The ferrimagnetic crystals are typically between 20 and 200 nm in size. Here, we use off-axis electron holography in the transmission electron microscope [1] to study the magnetic microstructures of magnetite and greigite crystals in air-dried cells of magnetotactic bacteria, with sub-10-nm spatial resolution. Our results are obtained from cells that contain single and multiple chains of crystals with a range of sizes, shapes and spacings. The bacteria provide model systems for studying magnetic remanent states and magnetization reversal mechanisms in linear and two-dimensional arrangements of closely-spaced nanoscale magnets. Figure 1 shows a bright-field image of a double chain of magnetite crystals from a bacterial cell, alongside a magnetic induction map recorded from the same cell using electron holography. The spacing of the contours in Fig.1 is inversely proportional to the in-plane component of the magnetic induction within and around the crystals projected in the incident electron beam direction. Selected area electron diffraction was used to show that the [111] magnetic easy axes of the magnetite crystals are parallel to the chain axis. In contrast, the crystallographic directions perpendicular to the chain axis are distributed randomly.

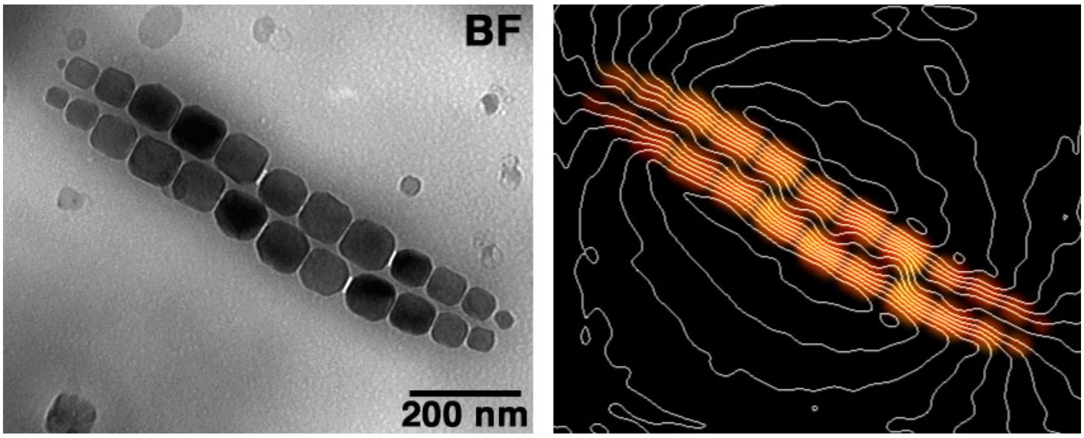

Fig. 1 Bright-field (BF) image (left) and magnetic induction map (right) of a double chain of magnetite nanocrystals from a bacterial cell.

Induction maps similar to that in Fig. 1 can be used to obtain an experimental magnetic state phase diagram that shows the combined effects of shape, crystallography and inter-particle interactions on the formation and stabilization of single domain magnetic states in linear arrangements of crystals, some of which would be expected to support multiple magnetic domains if they were isolated. Similarly, electron holography can be used to show that interactions between neighboring crystals increase the critical size at which the transition from superparamagnetic to single domain behavior takes place [2]. Our results are in close agreement with analytical models of superparamagnetism that account for crystal size, spacing and shape. The magnetic moments of individual cells can be measured quantitatively using electron holography and are found to be similar in magnetite-containing and greigite-containing bacterial strains, even though greigite crystals are usually much less well organized in the cells in terms of their crystallography, morphology and position. The measured moments of individual cells are found to be sufficient for migration along geomagnetic field lines at more than 90% of the cells' forward speeds. The effect of changes in magnetocrystalline anisotropy on magnetic microstructure are assessed by recording the magnetization directions of isolated and closely-spaced magnetite crystals both at room temperature and below the Verwey transition.

References

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