Ferromagnetism in Freshwater Bacteria

RICHARD P. BLAKEMORE,* RICHARD B. FRANKEL,† and RALPH S. WOLFE‡
*Department of Microbiology, University of New Hampshire, Durham, New Hampshire; †Francis Bitter National Magnet Laboratory, Massachusetts Institute of Technology, Cambridge, Massachusetts; and ‡Department of Microbiology, University of Illinois, Urbana, Illinois

ABSTRACT

Magnetotactic bacteria isolated from swamp water were grown in pure culture in the laboratory. This newly isolated species was cultured in the magnetic and the nonmagnetic state. Magnetic cells, which were rich in iron, also produced particles similar to those found previously in other magnetic bacteria of marshes and bogs. By contrast, their nonmagnetic counterparts had much lower iron levels and lacked the crystal structures. Mössbauer spectroscopic analyses of whole cells of magnetic bacteria indicated that they contained the mineral magnetite.

Morphologically diverse magnetotactic bacteria (Fig. 1) normally present in marine and freshwater environments (Blakemore, 1975) aligned with, and swam in a preferred direction in, the geomagnetic field (Kalmijn and Blakemore, 1977). Most of the cells observed in various mud samples swim northward and downward. Reversal of the ambient magnetic field with a small permanent magnet (Fig. 2) or with Helmholtz coils (Kalmijn and Blakemore, 1977) caused the swimming cells to make large U-turns within seconds and swim in the opposite direction. Killed cells also oriented in uniform magnetic fields as low as 0.1 G (1 G = 10^{-4} T).

As a result of cell remagnetization studies, Kalmijn and Blakemore (1978; see also *Scientific American*, 1978, 238: 72-73)

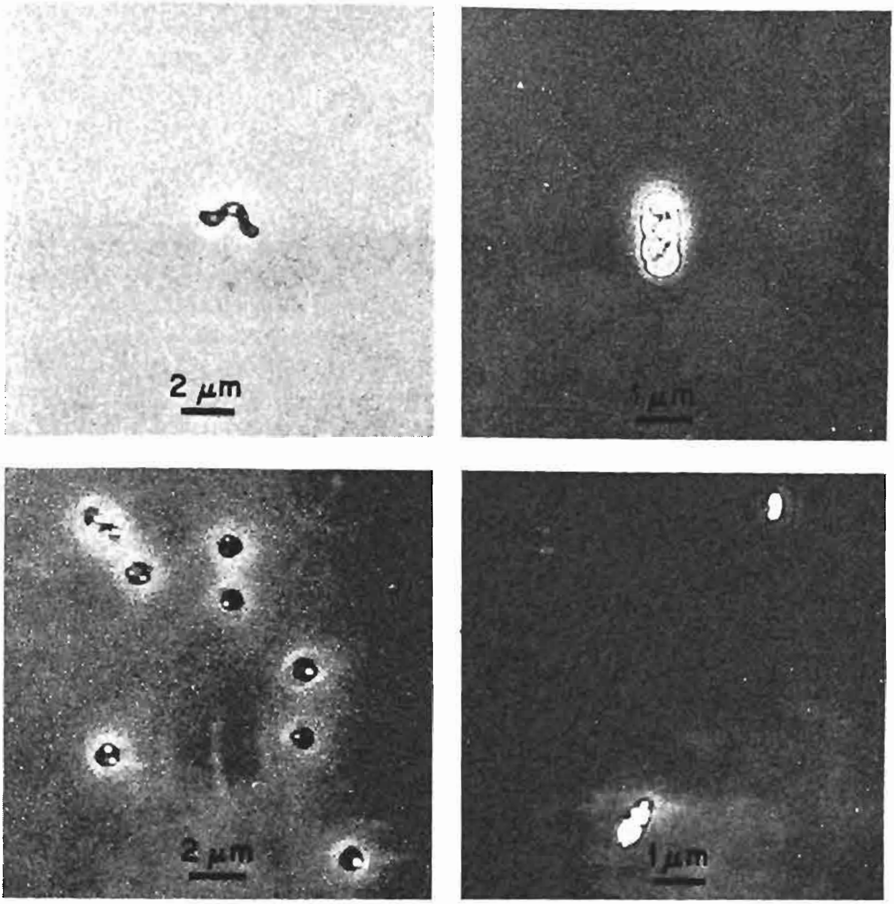

Fig. 1 Representative magnetic bacteria separated from sediments by application of nonuniform magnetic fields (by phase-contrast microscopy).

concluded that these bacteria oriented through a direct ferromagnetic response and exhibited properties characteristic of single magnetic domains.

Intracytoplasmic chains of granules or crystals were present in both marine [Fig. 3(a)] and freshwater [Fig. 3(b)] magnetic bacteria collected from muds. In the predominant marine form present in Eel Pond (Massachusetts) the particles were found to contain iron as a major element (Blakemore, 1975).

Fig. 2 Timed exposure (several seconds) of swimming bacteria by dark-field microscopy. U-shape tracks (arrows) indicate paths of cells that have made 180° turns in response to reversal of a small bar magnet held 10 cm away. Magnetic field at the microscope caused by the magnet was roughly 0.5 G.

MATERIALS AND METHODS

Blakemore and Wolfe recently isolated a magnetic bacterium from a freshwater swamp (unpublished results). This unclassified *Spirillum* has remained magnetic through repeated growth transfers in the laboratory. A population of nonmagnetic cells was derived from a culture of this new organism by successive cloning of cells grown under conditions unfavorable for magnetism (i.e., high nutrients and lowered culture-medium iron levels).

Cells were mass cultured in 10-liter glass carboys in a medium containing 10% (vol./vol.) filtered bog water as the principal

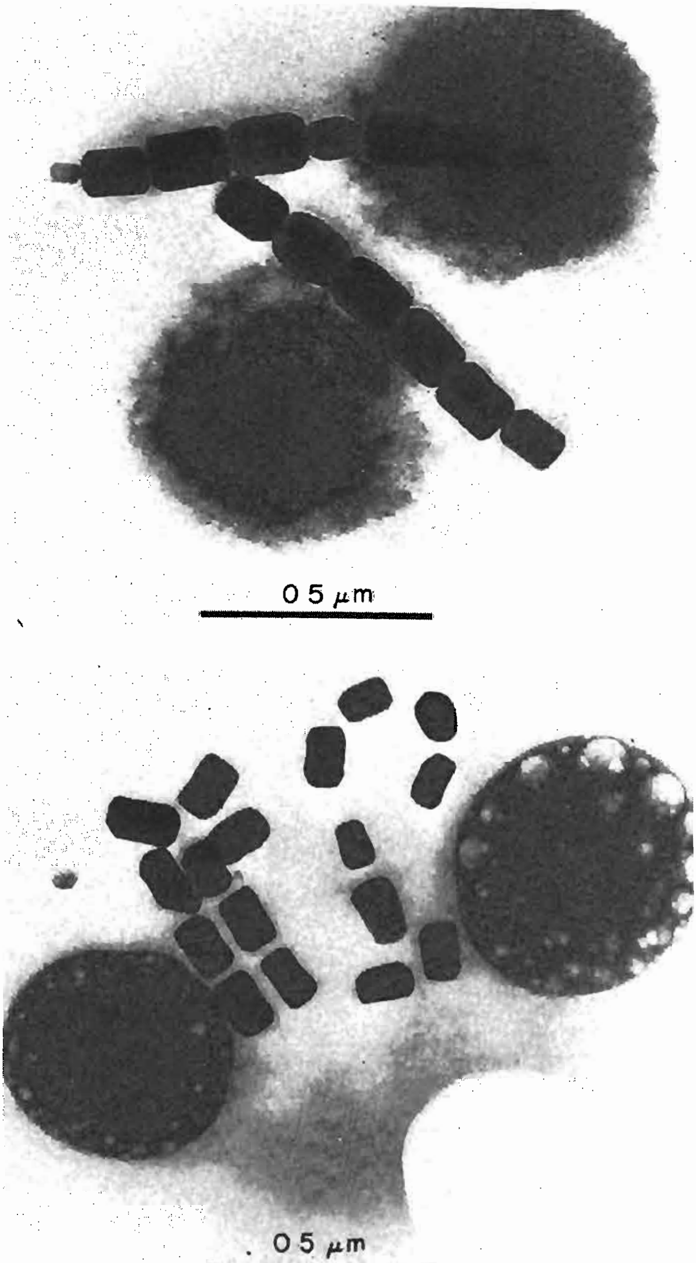

Fig. 3. Iron-containing crystals within magnetic bacteria. Electron micrograph of unstained cells of the predominant type found in (a) a marine marsh and (b) a freshwater swamp.

(undefined) source of iron and perhaps other nutrients. Cells were harvested by centrifugation and washed three times in distilled water. The washed, intact cells were freeze-dried and the resulting cell powders were used for elemental and Mössbauer analyses.

RESULTS

Cells of the magnetic *Spirillum*, but not of the nonmagnetic form, contained chains of crystals similar to those described previously (see Fig. 4). In other important physiological and taxonomic characteristics, the two forms are identical.

The elemental composition of magnetic and nonmagnetic forms of this species were compared by means of energy dispersive X-ray analysis. Results indicated that magnetic cells had a significantly higher iron content than nonmagnetic cells. Results of atomic-absorption spectrophotometry of acid-digested whole cells indicated that 1.5% of the dry weight of magnetic bacteria was iron. This value was 13 times that for nonmagnetic cells. Values for nonmagnetic cells were only slightly higher than published values for other heterotrophic bacteria. These results suggested that iron was localized in the crystals of magnetic bacteria. The results also suggested that it might be possible to analyze whole cells by means of Mössbauer spectroscopy without ^{57}Fe enrichment.

The Mössbauer spectrum for magnetic cells (Fig. 5) was compared with published spectra of magnetic and nonmagnetic iron-containing substances. The spectrum for magnetic cells resembled most closely the spectrum of the ferromagnetic mineral magnetite ($FeO \cdot Fe_2O_3$). Pure magnetite was analyzed under similar conditions (data not shown), and minor differences in the two spectra were observed. These may relate to differences in the types of samples (i.e., magnetite in biological material as compared with pure stoichimoetric magnetite) or may indicate the presence of additional iron-containing substances in magnetic cells. These and other possibilities are currently under investigation.

DISCUSSION

Magnetite is normally associated with the *Chiton radula* (Lowenstam, 1962) and is presumably present in insects (Gould, Kirschvink, and Deffeyes, 1978). Studies with magnetic bacteria have directly related the presence of this ferromagnetic substance to cell orientational responses in weak (0.1-G) stationary magnetic fields.

Fig. 4 Electron micrograph of thin-sectioned magnetic cell of strain MS-1. Note chain of crystals within cytoplasmic region. Bar length, 0.25 μm.

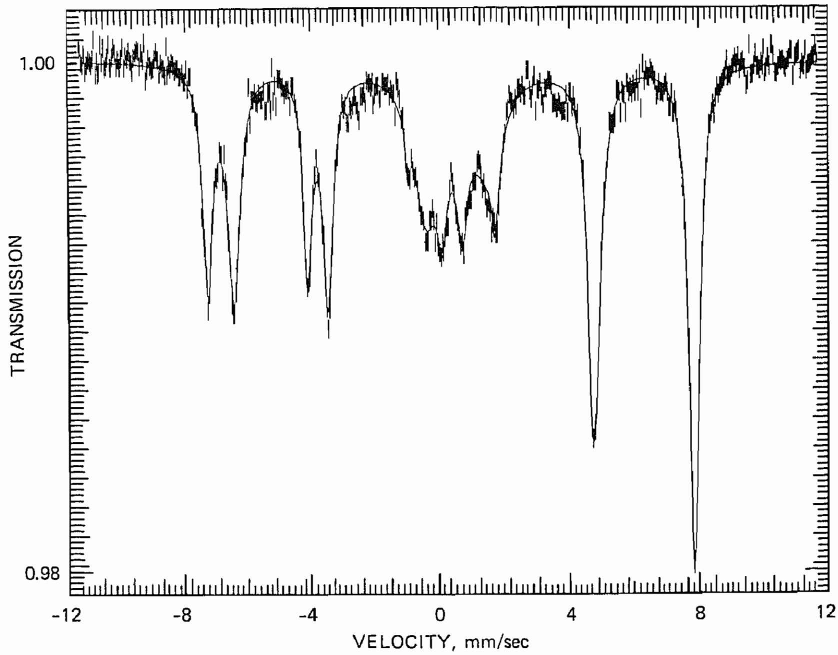

Fig. 5 Mössbauer spectrum, at room temperature, of 350 mg of freeze-dried cells of strain MS-1 grown in medium containing bog water. The solid line is a theoretical least-squares fit to the data, assuming Lorentzian line shapes.

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