

## Bulk Magnetic Properties of Magnetotactic Bacteria

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**Abstract** - Bulk magnetization measurements at room temperature of freeze dried magnetotactic bacterial cells, nonmagnetotactic bacterial cells, and extracted magnetosomes from magnetotactic cells are presented. The role of the magnetosome in the magnetotactic response of swimming cells is discussed.

Several species of motile aquatic bacteria swim along the earth's magnetic field lines when dislodged from the sediments where they live [1,2]. One of these species, a magnetotactic spirillum designated strain MS-1, has been isolated and cultured in a chemically defined medium [3]. Each spirillum contains a magnetosome [4], an intracytoplasmic linear chain of approximately 20 magnetite particles which imparts a net magnetic dipole moments to the cell. The presence of magnetite was first detected by Mossbauer spectroscopy [5]. The magnetic moment of the chain is large enough to orient the cell in the geomagnetic field at room temperature [6]. The magnetite particles have a uniform size and a euhedral shape, each 40 to 50 nm on a side. They are enveloped by a membrane-like boundary layer which may maintain their linear configuration in the cell [4].

To characterize this unique biological structure we have made bulk magnetic measurements of whole, dried spirilla and isolated magnetosomes. In this paper we present magnetization data obtained at room temperature.

Magnetotactic and nonmagnetotactic variants of strain MS-1 were cultured and prepared as described previously [3,5]. Magnetosomes were not present in cells of the nonmagnetotactic variant. Freeze-dried, washed cells of each type were measured. Measurements were also made on isolated magnetosomes from the magnetotactic variant which were extracted nonmagnetically by centrifugation of sonically lysed cells.

Magnetization data up to 10 kOe were obtained on milligram size samples at room temperature using a Princeton Applied Research vibrating sample magnetometer.

The parameters characterizing the magnetization data for the whole magnetotactic cells (S-1), whole nonmagnetotactic cells (S-2), and isolated magnetosomes (S-3), are presented in Table I.

Samples S-1 and S-3 exhibited normal ferromagnetic hysteresis curves. Sample S-2 on the other hand, displayed no discernible ferromagnetic behavior. The specimen measurement was barely distinguishable from the slight diamagnetism of the empty specimen holder alone. The apparent diamagnetic susceptibility for the nonmagnetic cellular material is approximately  $-5 \times 10^{-7} \text{ G-cm}^3/\text{gm/Oe}$ .

The magnetization of whole magnetotactic cells (S-1) saturated at 1750 Oe, with a saturation magnetization  $J_s = 0.9 \text{ G-cm}^3/\text{gm}$ , equivalent to 1% magnetite by weight. The saturation remanence  $J_r$  was 47% of the saturation magnetization, very close to the 50% theoretical expectation for non-interacting uniaxial single-domain moments [7]. The coercivity  $H_c$  and coercive force of remanence  $H_{cr}$  were 220 Oe and 270 Oe, respectively.

The extracted magnetosomes (S-3) were also highly magnetic. The magnetization saturated at 2000 Oe, with a saturation magnetization  $J_s = 13 \text{ G-cm}^3/\text{gm}$ , which is equivalent to 14% magnetite by weight. The saturation remanence was only 42% of the saturation magnetization. This suggests stronger magnetic interactions in comparison to the whole magnetotactic cells, due to the higher concentration of moments in the extracted magnetosomes. These interactions account not only the higher saturation field and lower  $J_r/J_s$  ratio, but also for the significantly lower coercivity of only 105 Oe and coercive force of remanence of 140 Oe in the latter sample [7].

X-ray measurements (Table II) confirm the presence of magnetite ( $\text{Fe}_3\text{O}_4$ ) in both the magnetotactic cells and the extracted magnetosomes. The individual magnetite particles in strain MS-1 are in the single magnetic domain size range [8]. The linear configuration of the magnetosome implies a structural constraint on the position of the particle [4]. If the particles were free to move in the cytoplasm they would clump in order to reduce the magnetotactic energy.

In the linear configuration, interactions between the individual particles align the moments parallel to each other along the chain direction [9]. Thus, the entire chain acts as a single domain magnetic dipole ( $m = 10^{-12} \text{ G-cm}^3$ ) with strong uniaxial anisotropy. This is consistent with the ratio of the saturation remanence to the saturation magnetization  $J_r/J_s = 0.47$ . According to Stoner and Wohlfarth [7] this ratio approaches 0.50 for an isotropic, randomly oriented array of non-interacting uniaxial single domain magnetic moments.

If the reversal of the magnetization occurred by coherent rotation of the individual particle moments, the expected coercive force would be close to the intrinsic coercive force  $H_c = 3000 \text{ Oe}$ . The observed  $H_c = 220 \text{ Oe}$  suggests a nonsymmetric fanning mechanism for the moment reversal, as envisioned by Jacobs and Bean [9].

In conclusion, magnetotactic cells have bulk magnetic properties close to those expected for an array of weakly interacting single magnetic domains. The bulk magnetic properties of the extracted magnetosomes reflect the higher density of magnetic material with stronger interactions between the magnetosome moments. Thus the magnetism of the individual cell resides in their magnetosome. The nonmagnetotactic cells which do not contain magnetosomes are nonmagnetic. These observations confirm the magnetotactic response in MS-1 is intimately associated with the magnetosome, a unique biological structure consisting of single domain particles of magnetite that functions as a single magnetic domain. Rigid attachment of the magnetosome inside the cell with the dipole moment oriented along the axis of motility results in the directed swimming of the cell along magnetic field lines. The biological significance of magnetotaxis has been discussed [1, 6, 10].

Magnetite has been identified in several animal species [11, 12, 13], some of which demonstrate geomagnetic sensitivity. However, only in magnetotactic bacteria has the association of magnetite with the magnetotactic response been conclusively demonstrated.

We are grateful to Dr. P. Wasilewski and Dr. S. Cisowski of the Goddard Space Flight Center, and Dr. S. Foner of the Francis Bitter National Magnet Laboratory for allowing us to use their facilities. N. Blakemore assisted in the preparation of samples and E.J. Alexander obtained X-ray diffraction data. This work was sponsored by the Office of Naval Research and the National Science Foundation. The Francis Bitter National Magnet Laboratory is supported by the National Science Foundation.

Woods Hole Oceanographic Institution Contribution No. \_\_\_\_\_.

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TABLE 1. Magnetic hysteresis properties of magnetotactic bacteria strain MS-1.

Sample	Description	H <sub>c</sub> (a) (Oe)	H <sub>cr</sub> (b)	H <sub>s</sub> (c)	J <sub>s</sub> (d) (G cm <sup>2</sup> ) (per gm)	J <sub>r</sub> /J <sub>s</sub> (e)	Fe <sub>3</sub> O <sub>4</sub> Conc. %
S-1	Magnetotactic cells, freeze-dried	220	270	1750	0.9	0.47	1
S-2	Nonmagnetotactic cells, freeze-dried	Nonmagnetic to 10 kOe					
S-3	Extracted Magnetosomes	105	140	2000	13	0.42	14

<sup>a</sup>Coercive force; <sup>b</sup>Coercive force of remanence; <sup>c</sup>Saturation field; <sup>d</sup>Saturation magnetization; <sup>e</sup>Remanent magnetization/saturation magnetization; <sup>f</sup>Assuming all the magnetization due to magnetite

Table 2. X-ray diffraction data on magnetotactic bacteria strain MS-1 powders, in CuK $\alpha$  radiation. Measurements by E.J. Alexander, Francis Bitter National Magnet Laboratory, M.I.T.

DESCRIPTION	Crystal axis (hkl)	d-spacing (Å)					
		220	311	400	422	511	440
Freeze dried cells		2.95	2.53			1.63	1.492
Extracted magnetosomes		2.97	2.43	2.1	1.71	1.62	1.485
Natural magnetite standard specimen		2.95	2.52	2.09		1.615	1.485
ASTM Card 19-629		2.966	2.532	2.096	1.715	1.616	1.485