

# Optical trapping of Magnetic Helical Bacteria

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The magnetosomes inside the bacterium *Magnetospirillum magnetotacticum* are 30-70 nanometer in size and can in principle be arranged into patterns of nanomagnets by trapping the host bacteria with multiple optical traps. We describe a first experiment with this type of bacterium in an optical trap, estimate its magnetic field and suggest some applications.

## 1 Introduction

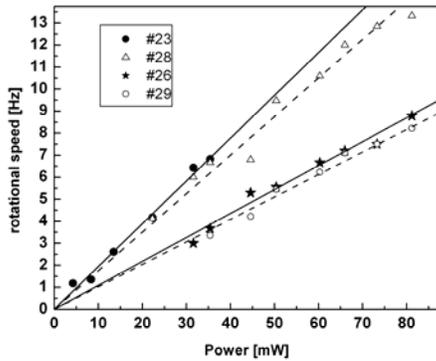
Since their discovery by Richard Blakemore in 1975 [1] magnetic bacteria have attracted attention due to their ability to grow single domain, cuboctahedral iron oxide ( $\text{Fe}_3\text{O}_4$ ) nanoparticles. As biologists unravel the mechanism of magnetosome formation [2] and magnetoreception [3, 4], physicists become interested in their usefulness in nanodevice fabrication. The cuboctahedral, single crystalline structure of the magnetosomes can help to align multiwalled carbon nanotubes during growth [5]. Removed from their host bacteria, they can be placed as single linear chains in peptide nanotubes, where they then act like magnetic nanowires [6]. A controlled assembly of magnetic nanoparticles has been achieved by steering the motion of living magnetic bacteria with the magnetic fields of microelectromagnetic arrays [7]. The motion of magnetic bacteria in a rotating magnetic field was analyzed recently [8]. In the following, we describe a first experiment with helical, magnetic bacteria in optical tweezers.

## 2 Experiment

Our optical tweezers consisted of a Laserdiode with wavelength 658nm which was focused through a 63x microscope objective. The focus had a diameter of approximately 0.9  $\mu\text{m}$  and 80 mW power at maximum. This microscope lens was also used to observe and film the bacteria. The intense laser beam holds the bacterium as with tweezers, but allows it to rotate freely around its own axis. *Magnetospirillum magnetotacticum* cells were obtained frozen from ATCC (*American Type Culture Collection*). The frozen cells were resuspended in phosphate buffered water (0.625mM  $\text{KH}_2\text{PO}_4$ , pH 7.2, adjusted with NaOH) to prevent osmotic rupture. The cells are helical, range from 4 – 5  $\mu\text{m}$  in length [1] and swim in a corkscrew like fashion using bipolar flagella. Its body has a diameter of

about 0.5  $\mu\text{m}$ , with roughly one left handed helical turn per cell. A droplet of a solution containing the bacteria was placed between a slide and cover glass sealed together to reduce bulk flow. This sample was then placed in the focus of the optical tweezers.

We observed a number of *Magnetospirillum magnetotacticum* cells and trapped them in the focus, where they oriented vertically upon capture and started to spin. Linear momentum transfer from the incident laser light causes the helical bacterium in the optical trap to rotate [9, 10]. The cells rotated clockwise as we expect it from a helical structure with left-handed symmetry. The rotational speed of the bacteria depends on the laser intensity. At low Reynolds numbers, the terminal rotational speed of each *Magnetospirillum magnetotacticum* should increase linearly with the photon flux, i.e. with the laser intensity. To verify this, we picked various *M. magnetotacticum* and measured their rotational speed with respect to the intensity of the tweezing beam in the trap (fig.1). Some of the bacteria reached a rotational speed of 13 rot/s. This is comparable to the rotational speed of birefringent vaterite crystals (diameter 5-7 $\mu\text{m}$ ), which were made to rotate by spin angular momentum transfer from light [11]. Rotating helical bacteria could thus create a similar microfluidic flow of 200  $\mu\text{m}^3\text{s}^{-1}$ . However, the slope angle of the helical pitch varies from specimen to specimen and how fast a bacterium rotates at a certain power varies accordingly. We saw a variation between 0.1 and 0.2 [Hz/mW].



**Fig. 1** The rotational speed of a bacterium depends linearly on the laser intensity. Depicted are the rotational speeds of four different bacteria. The slope between different specimens varies from 0.1 to 0.2 [Hz/mW]. Solid lines indicate the gradient for nearby solid data points, dashed lines belong to nearby hollow data points.

### 3 Theoretical considerations

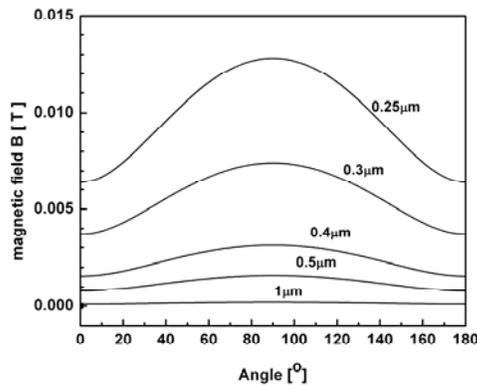
*M. magnetotacticum* has a magnetic momentum of approximately  $10^{-15} \text{Am}^2$  [7, 8] and the chain of magnetosomes is about  $1 \mu\text{m}$  long. Therefore, the Earth's magnetic field of  $\sim 0.05 \text{mT}$  exerts a maximum torque

$$N_{\text{max}} = \mu B \approx 0.05 \times 10^{-18} \text{Nm} .$$

The force acting on the bacterium is then

$$F_{\text{max}} \approx 0.1 \text{pN} .$$

This force is approximately 10 times smaller than the flagellar force of similar bacteria [10], which seems to indicate that the bacterium can use its flagella to align with or against the Earth's field.



**Fig.2** The magnetic field generated by the magnetosomes versus angle with the dipole's axis at various distances from the dipole. The uppermost line shows the field strength at the position of the membrane.

The magnetosomes generate a dipole field  $B$  given by

$$B = \frac{\mu_0 \mu}{4\pi r^3} \sqrt{1 + 3 \sin^2 \theta} ,$$

where  $\theta$  is the angle with the dipole's axis (fig. 2). At the membrane ( $\sim 0.25 \mu\text{m}$ ), it is  $\sim 200$  times stronger than the Earth's field, but it is very small at  $0.5 \mu\text{m}$ , which would be the distance between two bacteria side by side.

### 4 Outlook

Since *M. magnetotacticum* has a helical shape, it rotates when held in optical tweezers due to the momentum transfer from the tweezing light. It can thus be used as a microrotor for microfluidic flow applications [9, 10, 11]. In addition, we suggest using multiple optical traps to create a defined array of *M. magnetotacticum*. In order to preorient the bacteria and their dipole moments, a homogeneous magnetic field can be applied. Several line foci can then drag and orient the bacteria and their nanometer wide dipoles into the required position.

### 5 Support

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