rates one needs a laser whose heat can be rapidly dissipated. In this regard gas lasers appear to be more promising than solid-state lasers. The CO_2 laser used in the 10-kJ Helios system now operating at Los Alamos (and in the 100-kJ Antares system under construction there) is the most obvious candidate. But there is some question about the coupling efficiency of the long-wavelength (10-micron) CO_2 laser light.

The Department of Energy's Inertial Confinement Fusion Program is supporting the development of several other inertial-fusion driver systems, including KrF gas lasers, with a wavelength of 0.25 microns, and light- and heavy-ion bombardment techniques. —BMS

Magnetite in bacteria linked to orientation

The birds and bees do it and—yes—even bacteria in the seas do it. Species of all these organisms synthesize tiny crystals of magnetite. The demonstration of a direct link between this magnetic material and an orientational response for at least the simplest of these organisms—bacteria—has suggested the tantalizing possibility that the magnetic material found in the abdomen of honey bees and near the skull of pigeons may play a similar guidance role. Recent studies on the bacteria have identified the magnetic particles as crystals of magnetite that fall in the narrow size range for single domains—an optimal configuration.

Richard B. Frankel of the Francis Bitter National Magnet Lab and Richard P. Blakemore, a microbiologist at the University of New Hampshire, summarized the findings on magnetic bacteria at the International Conference on Magnetism held in Munich this September. Blakemore was the first to observe, in 1975, that various species of bacteria from diverse aquatic environments contain chains of iron-rich crystals and swim consistently toward the north. In more detailed studies of this response, using a system of multiple Helmholtz coils, Adrianus Kalmijn and Blakemore (Woods Hole Oceanographic Institution) found[1] that the bacteria behave like magnetic dipoles and reverse their swimming direction in response to a reversal of the ambient magnetic field within a time period of about one second. At the suggestion of Edward Purcell (Harvard University), the pair applied short-pulsed magnetic fields of several hundred gauss and were able to reverse the intrinsic magnetic dipole of the cell itself. They further established experimentally the single-domain characteristics of these bacterial magnets.

More experiments became possible when Blakemore, together with Ralph S. Wolfe, a microbiologist at the University of Illinois, were able to isolate and culture


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a freshwater magnetic-orienting spirillum in a chemically defined medium. Frankel then joined with Blakemore in measuring[2] the properties of these cultured bacteria. Those cells grown in a medium supplied with iron developed a chain of, on the average, 22 electron-opaque crystals, each approximately 50 nm on a side. Bacteria grown in a medium depleted of iron did not develop the intracellular crystals and failed to manifest any of the orientational responses to magnetic fields. Mossbauer spectra of such nonmagnetic cells did not indicate any gamma-ray absorption. The spectra for pure cultures of cells grown in chemically defined media or in bog water were identical in most respects to that for iron in magnetite (Fe_3O_4). The two differences were in the ratio of intensities of the two lowest velocity lines, which may imply a small admixture of a γ-Fe_2O_3 phase, and in the appearance of an extra quadrupole doublet, which may indicate the presence of some iron storage protein such as ferritin.

The definitive identification of magnetite has interesting implications for the 50-nm size of the observed particles. Magnetite crystals much smaller than this would be superparamagnetic, that is, their temporary alignment with an external field would be easily disturbed by thermal activation. Cells much larger than this (above 76 nm) would be multidomain, with some components cancelling one another. Thus the crystals fall within the optimum, single-domain range. Israel S. Jacobs and Charles Bean (General Electric) had once calculated the magnetic properties of a chain of single-domain particles including the applied field necessary to cause the reversal of a chain magnetization, and their predictions of about 350 gauss agree well with the measurements by Kalmijn and Blakemore.

Knowing the volume of magnetite present allows one to calculate the magnetic moment of a bacterium and the magnetic energy in the geomagnetic field. This energy turns out to be about ten times that of the thermal energy, kT, at room temperature. Using this ratio of energies and Langevin's theory of classical paramagnetism, Frankel and Blakemore showed in their talk that each bacterium probably contains a "sufficient but not an excessive" amount of magnetite in the proper configuration to align itself with the Earth's field. This conclusion was suggested by earlier experimental work by Blakemore and Kalmijn.

Independently, Purcell and Bean had analyzed the motion of aquatic bacteria in water, assuming the orientational response was passive, that is, governed by the torque on the magnetic chain as the bacterium swims. Calculations based on this analysis would imply a response time of 0.4 sec to a reversal of the geomagnetic field, in rough agreement with the observed time of 1 sec. This result lends support to the hypothesis of a passive orientation mechanism. By contrast, Frankel remarked to us, he believes the higher organisms such as pigeons could have a magnetic sense organ based on magnetite.

Why do bacteria need to know any direction at all? Kalmijn, Blakemore and Frankel point out that in the Northern Hemisphere swimming north is also swimming downward because of the vertical component of the magnetic field there. (A bacterium is too small to distinguish up from down by the differential pressure across itself.) Bacteria would swim down toward the sediment, which they tend to habitate. To test this theory the experimenters would like to find whether bacteria in the Southern Hemisphere are south seeking. An alternative test of the same hypothesis has been undertaken at Kalmijn's lab at Woods Hole. Blakemore, Frankel and Kalmijn have studied bacteria grown in an inverted magnetic field. After some time, the predominantly north-seeking population evolved into a predominantly south-seeking one.

Many other questions may keep them and others busy. How do the bacteria collect and store iron? How do they control the crystal size? Why do only certain species synthesize?

The work on bacteria certainly suggests that the magnetite present in the honey bee[3] and the pigeon[4] serve a similar orientational purpose. No direct evidence yet exists for whether or not these organisms do indeed use their magnetic structures for navigation and if so, then how. Studies of the natural remanence at room temperature and of the decay of the remanence as the sample is warmed up from liquid-nitrogen temperatures indicate that the magnetic material in bees has a large superparamagnetic component while that in pigeons consists largely of single-domain particles of magnetite. —BGL

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