Measuring magnets on a micron scale

A remarkable account of the micro-measurement of single haematite grains provides data that are to late to provide reassurance for palaeomagnetism, but no doubt help tape manufacturers to better things.

THE use of rock magnetism to reconstruct the Earth's magnetic history depends on the assumption that the magnetization of grains of presumably ferromagnetic material in a rock remains stable for millions or even hundreds of millions of years. In the early days of the 1950s, when the first evidence of past reversals of the Earth's magnetic field began to come to light, there was understandably some anxiety that the succession of magnetic reversals might be artefacts of some environmental fluctuation, perhaps a change of temperature.

Of course, the theoretical people were ready with undemanding reassurance. Find a magnetic particle with dimensions comparable with or smaller than a magnetic domain, and you will find it to be remarkably stable under external influences. One guru was E.C. Stoner from the University of Leeds, but the most comforting reassurance of all came from Louis Néel of Grenoble, who cut the figure of a provincial bourgeois professional who might just as easily have been a banker as a physicist.

The argument was that a sufficiently small particle might be magnetized in one direction or the opposite, that the two states would be separated from each other by an energy barrier and that, if the barrier height were known, the likelihood of switching would be simply described by an expression of Arrhenius type, an exponential function with exponent E/kT, where E is the energy, T the temperature and k is Boltzmann's constant.

But even the comfort that Néel exuded did not prevent some brave spirits from seeking to isolate magnetic particles from the rocks that they had already measured in the hope of measuring their magnetic properties individually. There were obvious difficulties. The magnetic particles might shatter more (or less) easily than the matrix particles in a grinding machine, selecting them (with a permanent magnet) might make them switch direction and, in any case, they were so small that nobody was clear what should be done with them. Attempts to work out something from microwave absorption failed.

Only now, it seems, have those ambitions been fulfilled, at least to judge from an article by M. Lederman and S. Schultz from the University of California at San Diego, and M. Ozaki from the Yokohama City University (*Phys. Rev. Lett.* **73**, 1986–1989; 1994). What the authors have done is to study the magnetization of γ-haematite (Fe_2O_3) particles that span a fivefold range of size downwards in size from 0.30 μm.

How has that been done? With a magnetic force microscope, or MFM, of course. And what is that? It is an atomic force microscope in which the force is not mechanical, but is generated by a microsolenoid. The haematite particles were selected for measurement from those deposited on the grid of a transmission electron microscope. Both were picked to have large aspect ratios (roughly 5:1) on the grounds that they would then be unambiguous single domains, that the magnetization would be along the major axis of the ellipsoid and that the coercive force would be large.

The coercivity of haematite is indeed very large, under no circumstances less than 900 Oe. Predictions by Stoner in the late 1940s that it is more difficult to reverse the direction of a single magnetized domain by applying a field in the opposite direction are indeed confirmed. Over 90°, the coercive force ranges from roughly 900 Oe to more than 1,500 Oe. The underlying model is that when the external field is applied at a largish angle relative to the ellipsoid axis, the magnetization will rotate, but otherwise it will have to turn back on itself.

But Lederman and his colleagues are seeking to fry other fish. By their account, there has recently been evidence that collections of many small particles do not properly follow the expected Arrhenius law. In particular, for a collection of magnetized particles in an external switching field, the proportion retaining their original direction should be an exponentially decreasing function of t/τ, where t is the time and τ is a characteristic time proportional to $\exp(E/kT)$, and which of course may differ from one particle to another.

Specifically, previous experiments (with several particles) are said to have found that the magnetization of a sample is proportional to the logarithm of the time. The obvious explanation, that the characteristic times τ of the particles are widely distributed over some range, is hardly falsifiable for a collection of particles, given that the distributions of τ may be virtually chosen at will. But the data have also been used to suggest that novel phenomena, such as quantum tunnelling, may be responsible.

So Lederman and his colleagues set out to study the probability of the reversal of the magnetization of single haematite domains by applying a powerful field in one direction followed by a carefully measured field in the opposite direction for an interval ranging from a few milliseconds to 10 seconds. It is obviously a tedious business; the tip of the MFM has to be withdrawn on each occasion, and the whole observation repeated dozens of times to provide statistics for an estimate of the frequency of switching, or for a single data-point.

How well does it work out? The conclusion is that the Arrhenius law does not apply. (Presumably an article demonstrating that it did would "not have succeeded in the competition for space", as the euphemism has it.) But the interpretation offered is of more than passing interest.

Comparing the variation of switching probability at different switching fields and different times, the authors conclude that a field in direct opposition to the magnetization of a single domain will nucleate magnetization in its own direction at several points. Then, the argument goes, the likelihood that the whole domain will switch will be determined not by a single barrier energy, but by the chance that geometrically separate nuclei will afterwards grow together. Newly named phenomena are not required.

Many will recognize in that statement a neat problem waiting for a solution, that of calculating the probability that two or even several nuclei of nucleation points in a domain will come to determine the magnetization of a whole magnetic domain. But it may be too late to summon a graduate student to carry out the task; by all accounts, numerical solutions are already under way.

For what it is worth, nowhere in the article do Lederman and his colleagues refer to the problems of the pioneer palaeomagnetism community, but that is hardly surprising. For the truth is that the old worry has been exorcised by the widespread recognition that reversals of the Earth's magnetic field do actually occur, and that the magnetized particles in rocks keep a largely faithful record of them.

And, of course, the people with a now-vivid interest in the probability that an external field will switch the direction of magnetization are the manufacturers of magnetic recording tape, forever seeking fidelity in recording. The great Néel, for all his style and foresight, can hardly have foreseen how the demands of technology would belatedly drive experimenters into unearthing data that would have been invaluable 40 years ago.

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