MATERIALS SCIENCE

Multiferroics as Quantum Electromagnets

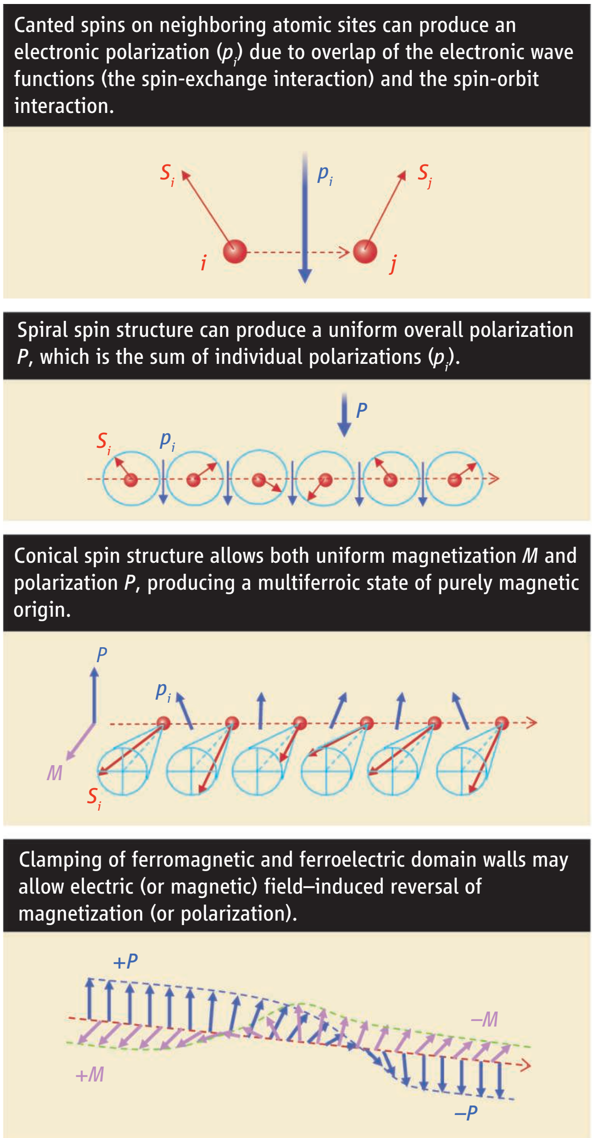
Conventional electromagnets are made from coils of wire, but the search is on for materials that become magnets simply by applying an electrical current. Compounds with unusual spin arrangements offer many possibilities.

Yoshinori Tokura

The term "electromagnetism" comes from the fact that the electric and magnetic fields are generally not independent of one another. A changing magnetic field produces an electric field (electromagnetic induction), whereas the motion of electric charges, or electric current, generates a magnetic field (the Biot-Savart law). Typically, electromagnets are wire coils or loops, which tend to be bulky and difficult to fabricate. Would it be possible to devise an electromagnet made from a nano- or micrometer-scale material (not in the form of a coil) that could be activated by simply applying an electric field or current? The answer is perhaps yes, but the issue is not straightforward at all. The magnetoelectric (ME) effect in a solid—that is, the induction of a magnetization (*M*) by means of an electric field and the induction of an electric polarization (*P*) by means of a magnetic field—was presumed to exist by Pierre Curie (*1*), who considered the analogy of the electromagnetic phenomena in a vacuum and in a solid. This analogy is important today from the standpoint of applications: The highly efficient control of magnetism by an electric field or electric current in a solid may advance the technology of spin-electronics (spintronics) technology, such as magnetic storage and magnetic random-access memory. Since the ME effect was first confirmed in the 1960s by Russian scientists, many magnetic materials have been shown to produce this effect (*2*). Nevertheless, the magnitude of the observed ME effect has been too small for practical devices.

Multiferroics, the materials in which both ferromagnetism and ferroelectricity can coexist, are the prospective candidates that can potentially host what might be called a giant ME effect. Here, the prefix "ferro" originally refers to iron, which shows a spontaneous *M* controlled by a weak magnetic field. Likewise, ferroelectricity refers to the spontaneous *P* controllable with an electric field. In multiferroics, the coexistent spontaneous *M* and *P* may respond to relatively weak magnetic and electric fields, respectively. Thus, a naïve expectation is that the large ME effect may be driven by weak electric or magnetic fields, if the *M* and *P* are closely coupled. The problem is how to design such a multiferroic material and how to enhance its *M-P* coupling. In the recent literature there have been reports of some polar (that is, having built-in *P*) crystals that can also show the spontaneous *M* of ferromagnetism, particularly the perovskite structure involving Bi^{3+} or Pb^{2+} ions as well as magnetic ions. In general, these polar ferromagnets can show very interesting linear and nonlinear optical properties arising from the ME response in the optical frequency region (*2*, *3*), yet the coupling between *M* and *P* at the electronic ground state has remained very small.

A useful hint for designing strong *M-P* coupling has recently been obtained by the discovery of ferroelectricity in the spiral-spin magnets (*4*–*6*), as schematically shown in the figure. There are many possible spin arrangements in magnetic materials. For example, when the spins on the adjacent atomic sites are canted from each other (see the figure, first panel), the horizontal mirror-plane symmetry is lost, and polarization can be generated along the vertical direction. Recently, it has also been theoretically shown (*7*) that the overlap of the electronic wave function between the two atomic sites with canted spins generates a genuine electronic polarization via the relativistic quantum-mechanical effect called the spin-orbit interaction. When the spins form a spiral modulation along a specific crystallographic direction (see the figure, second panel), then every nearest-neighbor pair produces a unidirectional *P* and hence should generate a macroscopic *P* of electronic (spin) origin. The direction of the polarization can be completely determined by the clockwise or counterclockwise rotation of the spin along the spiral propagation axis, called the spin helicity. In those compounds, the spontaneous polarization can be easily controlled by an external magnetic field of specific direction (*4*, *5*), which may be viewed as a giant ME effect. The multiferroics based on this mechanism are in what is called the conical spin state (see the figure, third panel), where the transverse spiral component coexists with the uniform magnetization component along the cone axis. These spiral and conical spin states are widely seen in complex transition-metal compounds like spinels and perovskites, where competing exchange interactions of the



Designing better magnets. Possible spin superstructures in the multiferroics with strong coupling between magnetism and electricity.

The author is in the Department of Applied Physics, University of Tokyo, 7-3-1Hongo, Bunkyo-ku, Tokyo 113-8656, Japan and in the Spin Superstructure Project, Exploratory Research for Advanced Technology Office, Japan Science and Technology Corporation, Tsukuba 305–8562, Japan. E-mail: tokura@ap.t.u-tokyo.ac.jp

Published by AAAS

neighboring spins can cause such a periodically modulated spin structure.

With the existence of ferroelectricity of magnetic origin, a new aspect is expected to emerge in the ME effect. Such a multiferroic state may in most cases compete with another ME phase, say a paraelectric-antiferromagnetic phase. Therefore, the application of a magnetic (or electric) field may induce a first-order phase transition between those ME phases, resulting in the magnetic (or electric) control of the ME phases and hence control of the *P* (or *M*). In fact, this is the microscopic origin of the magnetic *P*-control as observed for some magnetic ferroelectrics (*4*, *5*). The critical tuning of the ME phase competition may produce the giant ME phenomena, such as the electric-field induction of the ferromagnetic phase, that is, a quantum "electromagnet."

An even more remarkable characteristic expected for the multiferroics is the electric (magnetic) reversal of the *M* (*P*) vector. As shown in the fourth panel of the figure, the multiferroics of purely spin origin may exhibit the clamping of the ferromagnetic and ferroelectric domain walls, and this fixes the relative direction of *M* and spin helicity (or equivalently *P*) across the domain wall. This may provide a low energy–consuming way of achieving electrical *M*-reversal in future spintronics. All these fundamental investigations on the multiferroics have just started in the research community, including the effort to explore the tailor-made mutiferroics made with magnetic-dielectric superlattices as well as nanoscale self-organized materials. The fast pace of this research effort promises an exciting time ahead for multiferroic materials.

References

1. P. Curie, *J. Phys.* **3**, 393 (1894).
2. M. Fiebig, *J. Phys. D Appl. Phys.* **38**, R123 (2005).
3. J. H. Jung *et al.*, *Phys. Rev. Lett.* **93**, 037403 (2004).
4. T. Kimura *et al.*, *Nature* **426**, 55 (2003).
5. N. Hur *et al.*, *Nature* **429**, 392 (2004).
6. G. Lawes *et al.*, *Phys. Rev. Lett.* **95**, 087205 (2005).
7. H. Katsura, N. Nagaosa, A. V. Balatsky, *Phys. Rev. Lett.* **95**, 057205 (2005).

10.1126/science.1125227

PLANT SCIENCE

Microtubules Make Tracks for Cellulose

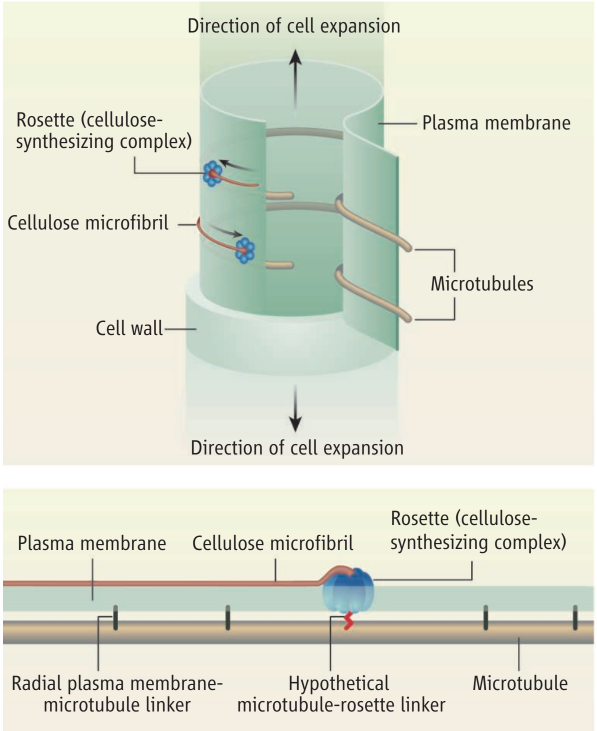
Cellulose fibers encircle plant cells and help support the cell and the whole plant. They are laid down in this pattern as they are spooled out by enzymes that track along microtubules in the cell.

Clive Lloyd

In a remarkable series of biological transformations, green plants convert carbon dioxide into cellulose fibers stronger than steel. These thin threads of polymeric glucose are wrapped around growing cells, lending structural support to the plant as it extends further into the environment. The fibers are not simply secreted into the plant cell wall in a haphazard fashion but are deposited in ordered layers that still allow the cell to expand. For more than 40 years, it has been known that the alignment of these cellulose fibers (microfibrils) in the cell wall often coincides with cytoskeletal microtubules tethered to the cytoplasmic side of the plasma membrane (see the figure). Despite this coincidence, there has never been direct proof that microtubules provide a guidance mechanism for the alignment of cellulose microfibrils. Now, on page 1491 of this issue, Paredez *et al.* (*1*) provide that proof.

Plants explore the environment, not by cell movements, but by massive cell expansion that is driven by influx of water into a central vacuole. The resulting cellular swelling exerts a force that is nondirectional. As explained by Green in 1962 (*2*), such a force can be channeled along an axis by "hoop-reinforcement" caused by the winding of cellulose microfibrils around the cell, perpendicular to the direction of expansion. In the early 1960s, before the discovery of microtubules, the anti-mitotic drug colchicine was known to dissolve the "spindle fiber protein" comprising the mitotic spindle. Because Green found that the hoop-like order of fibers in the plant cell wall was also destroyed by colchicine, he predicted that a form of "spindle fiber protein" in the cytoplasm would provide a template for the orderly placement of cellulose in the cell wall. Soon after, Ledbetter and Porter (*3*) published their landmark paper on the electron microscopy of plant cells, revealing the presence of cytoplasmic cortical microtubules. These colchicine-sensitive structures appeared as long filaments that circumnavigated the cell, just beneath the plasma membrane, in hundreds of transverse hoops that mirrored the organization of cellulose microfibrils in the cell wall. This parallelism between the two systems marked the beginning of the so-called microtubule-microfibril syndrome, but instead of heralding a period of consensus, the field has been largely divided in its interpretation ever since.

Missing from this relationship between microtubules and microfibrils was the cellulose-synthesizing machinery itself, but another technical advance



Microtubule railroad. Microtubules that lie beneath the plant cell's plasma membrane serve as tracks for membrane-associated cellulose synthases (rosette structures) to travel along. As it moves, the synthase deposits a cellulose microfibril into the adjacent cell wall. It is not yet known if there is a direct link between cellulose synthase and microtubule.

The author is in the Department of Cell and Developmental Biology, John Innes Centre, Norwich NR4 7UH, UK. E-mail: clive.lloyd@bbsrc.ac.uk