

Mesoscopic Texture in Manganites

From atom-scale stripes to micron-scale patches, manganites exhibit a wealth of fascinating phase-separated behavior.

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One expects a single crystal to be precisely what its name implies: a periodic array of atoms, in which each unit cell is identical to any other. But in certain oxides of manganese, a spectacularly diverse range of exotic electronic and magnetic phases can coexist at different locations within a single crystal. This striking behavior arises in manganites because their magnetic, electronic, and crystal structures interact strongly with one another. For example, a ferromagnetic metal can coexist with an insulator in which the electrons and their spins adopt intricate patterns.

The complexity of such phases, and the apparent near balance between them, comes as a surprise. In systems with multiple phases, one expects any given set of external conditions to overwhelmingly favor one phase over all others. But in chemically homogeneous manganites it turns out to be surprisingly easy to achieve phase coexistence using a wide range of tuning parameters. One can, for example, tweak a sample's chemical composition or microstructure, apply a magnetic or electric field, strain the sample elastically, or illuminate it with electromagnetic radiation. The ease with which phase coexistence can be obtained is not the only surprise. Intriguingly, evidence is accumulating for magnetic, electronic and crystallographic texture on "mesoscopic" length scales—that is, over tens or hundreds of nanometers.^{1,2} Figure 1 and the cover of this issue show two examples.

The first evidence for phase coexistence in manganites dates back to Ernie Wollan and Wally Koehler's pioneering neutron scattering studies of the 1950s.³ At that time, manganites (see box 1 on page 27) had just begun to attract the interest of physicists. The first report of electrical and magnetic measurements on manganites, by Harry Jonker and J. H. van Santen, appeared in 1950.⁴ In that paper, Jonker and van Santen reported the discovery of a ferromagnetic conducting phase below room temperature in $\text{La}_{1-x}\text{Ca}_x\text{MnO}_3$ for values of x between 0.2 and 0.4. Shortly afterward, Clarence Zener, Junjuri Kanamori, John Goodenough, and several others established the basic theoretical

framework that scientists use today.⁵

Manganites and the phase separation effects they display fell out of fashion until the 1990s. Although the University of Manitoba's Allen Morrish, Clark Searle, and their collaborators reported significant magnetoresistance effects in single crystal $\text{La}_{0.69}\text{Pb}_{0.31}\text{MnO}_3$

in 1969, there was no technological incentive for further pursuit. What re-ignited manganite research was the 1994 discovery by Bell Labs' Sung-Ho Jin and collaborators⁶ that a several-tesla magnetic field could induce a 1000-fold change in the resistance of a heat-treated epitaxial thin film of $\text{La}_{0.67}\text{Ca}_{0.33}\text{MnO}_3$. Dubbed "colossal magnetoresistance" (CMR), this effect arises because the applied magnetic field drives a phase transition from an insulating paramagnet to a spin-aligned metal (see box 2 on page 27). Thus, whereas Jonker and van Santen reduced the temperature to reach the conducting spin-aligned phase, Jin and his colleagues applied a magnetic field.

The paramagnetic insulator and the ferromagnetic metal are just two species in a zoo of magnetic, electronic, and crystalline phases that are now being heavily investigated. In some manganites, the valence-band electrons appear to be fully spin-polarized. Manganites are therefore ideal for spin-injection and spin-tunneling devices, which could become technologically significant once high-temperature material analogs are developed.

Although efforts to explore and exploit magnetoresistance in manganites continue, much of today's research now focuses on phase separation and mesoscopic texture. In the past few decades, a variety of imaging techniques have been developed, and have made it possible to study manganites on length scales ranging from microns down to angstroms. The richness of the observed phenomena reflects the complex ways in which manganites can adapt to their local environment. This new and exciting area of research is what our article is about. We will try to explain the manganites' capacity for self-organization using a selection of colorful images.

The many phases of manganites

Manganites display three electronic phases: an insulating electronic solid, a poorly conducting electronic liquid, and a metallic electronic gas. In classical systems, the gas is the high-temperature analog of the corresponding liquid. But in manganites, the gas and liquid electronic phases have a quite different relationship. The metallic gas is a degenerate Fermi gas that is stable at low temperature. The electronic liquid is a classical and viscous disordered fluid that results from large thermal fluctuations; it is therefore stable at high temperature.

Great diversity arises in manganites because the

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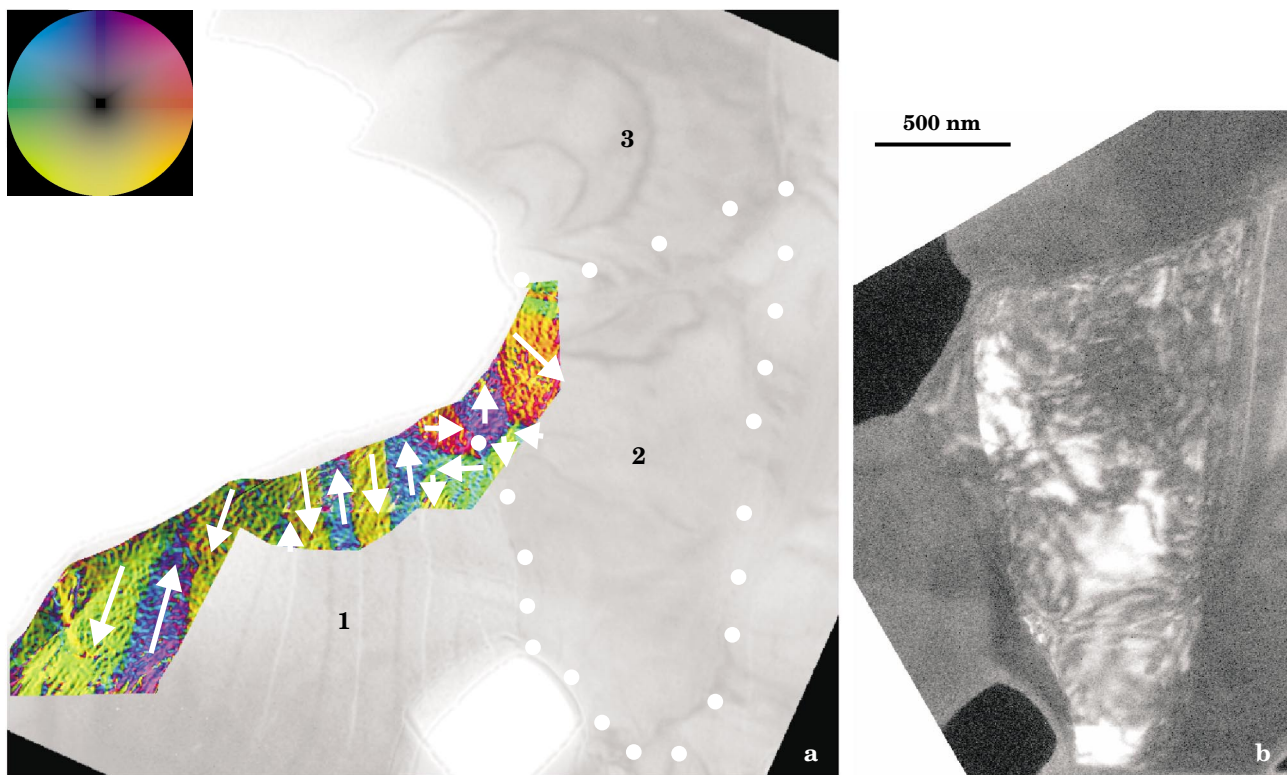


Figure 1. This sample of polycrystalline manganite ($\text{La}_{0.5}\text{Ca}_{0.5}\text{MnO}_3$ at 90 K) exhibits surprising phase behavior from grain to grain. In (a), three grains, numbered 1–3, are viewed with electron holography (color overlay) and transmission electron microscopy. Grain 1 is ferromagnetic, whereas grain 3 is in a charge-ordered phase that possesses no net magnetic moment. Such phase coexistence is expected. However, grain 2 is surprising. When viewed in dark field (b), mesoscopically textured bright regions of strong charge-order appear that coincide with the fully ferromagnetic domains seen in (a). This observation represents the discovery of a new and unexpected phase: Charge-order and ferromagnetism were previously thought to be mutually exclusive. (Adapted from J. C. Loudon, N. D. Mathur, P. A. Midgley, *Nature* **420**, 797, 2002.)

materials' magnetic and crystalline structures overlay the three basic electronic phases. In fact, the electronic solid phase itself displays exciting diversity, but in this article we label all electronic solid phases "COI" (charge-ordered insulator). All electronic liquid phases are labeled "PM" because the associated magnetic structure is usually paramagnetic. In addition, we label all electronic gas phases "FMM" because they turn out to be ferromagnetic metals. The labeling scheme is a simplification that we stick with for historical reasons. If we were re-initializing the field, we might use each letter of a three-letter abbreviation to describe each of the magnetic, electronic, and crystal structures of a given manganite phase. But even that scheme would be too simplistic.

The COI, FMM, and PM phases may be plotted on a schematic diagram such as figure 2. At any point in the diagram, the thermodynamically stable phase depends on the relative strengths of two competing processes: double exchange and the Jahn–Teller effect (both described in more detail below). The vertical axis of the phase diagram is temperature, which influences the two-way competition in that ordered phases typically form below a few hundred kelvin. Although several tuning parameters can constitute the horizontal axes, we have chosen to use the electron–phonon coupling parameter λ . The coupling parameter reflects the two-way competition more directly than temperature and measures the strength with which valence electrons interact with the crystal lattice.

Double exchange and the Jahn–Teller effect originate in the microscopic nature of manganites—specifically, in the distorted cubic network of manganese–oxygen bonds.

On each manganese atom, three highly localized electrons combine to form a large single magnetic moment, termed the core spin. The configuration of core spins throughout the lattice—that is, the magnetic structure—is intimately connected with the configuration of additional manganese valence electrons. To various degrees, the valence electrons may either be localized or free to move between adjacent manganese sites. A very large exchange interaction aligns the spin of each potentially itinerant valence electron with the nearest core spin.

Delocalization of the valence electrons favors ferromagnetism because the kinetic energy of an itinerant carrier is minimized when all the core spins are aligned. Zener's theoretical treatment of the delocalization involved a two-step process in which electrons jump between manganese sites by way of the intervening oxygen atoms. He called the transfer double exchange.⁵ The competing tendency, toward localization, comes about through the Jahn–Teller effect, in which a valence electron stabilizes a local distortion of the oxygen octahedron surrounding each manganese atom. In this way, a carrier can be trapped by a self-induced crystal distortion.⁷

Energetically, the competition between double exchange and Jahn–Teller may be understood as follows. Double exchange delocalizes the valence electrons, lowering their kinetic energy. However, delocalized electrons suppress the Jahn–Teller effect (and electron–phonon coupling effects in general) and therefore can't exploit those processes to lower their energy further. By contrast, localized valence electrons save energy because they produce Jahn–Teller distortions. However, localized electrons have

a higher kinetic energy.

At low temperatures, the competition between double exchange and Jahn–Teller typically leads to ordered phases. Double exchange can win the competition and delocalize the manganese valence electrons when the core spins (along with carrier spins coupled by Hund’s rule) are well aligned. The resulting phase is therefore the FMM. By contrast, victory for the electron–phonon interaction stabilizes a crystalline array of Mn^{3+} and Mn^{4+} . Six years ago, Rutgers University’s Sang-Wook Cheong (then at Bell Labs) and his collaborators observed such an array, which appeared in transmission electron micrographs as a set of stripes (see PHYSICS TODAY, June 1998, page 22). Stripe ordering in manganites results from long-range structural correlations that, in turn, result from the coupling of each manganese atom to the neighboring manganese atom through a shared oxygen atom. Because the manganese valence electrons are localized, stripe phases are electrically insulating. In the absence of strong double exchange and at sufficiently low temperatures, the neighboring localized electrons’ spins are usually antiparallel (antiferromagnetic) because of a virtual exchange process called superexchange. We refer to the dazzling array of such phases as charge-ordered insulators, COIs.

At high temperatures, thermal fluctuations disorder the manganese spins and manganites become paramagnetic for all values of λ . But consider the situation at intermediate lattice coupling (indicated by λ_0 in figure 2). On heating the FMM, core spin fluctuations reduce the double exchange hopping of the valence electrons and tip the balance in favor of the Jahn–Teller effect. The resulting PM phase is like a molten version of the COI—that is, it behaves as a viscous electronic liquid. Electrically, the phase is a highly resistive insulator because the localized electrons combine with the lattice distortions that tend to localize them.

The original CMR effect discovered in 1994 arises in this high-temperature PM phase (see box 2). A large magnetic field of several tesla will align the disordered core spins and tip the balance back towards a delocalized double exchange metal. The colossal magnitude of the concomitant reduction in resistance arises from the highly insulating nature of the high-temperature PM state when $\lambda \approx \lambda_0$. As $\lambda \rightarrow 0$, the high-temperature PM state becomes metallic and only modest magnetoresistance effects are seen. But when $\lambda \gg \lambda_0$, magnetoresistive effects many orders of magnitude larger than the original CMR effect are observed: Although the low-temperature COI phase is extremely resistive, it may be converted to a spin-aligned metal with a magnetic field.

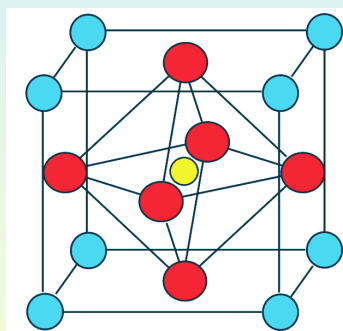
What about phase coexistence? In general, some degree of phase coexistence is likely in any system that exhibits a first-order phase transition, that is, a transition with discontinuous jumps in order and a latent heat. Low-temperature phase transitions between the COI and FMM and the thermally induced melting of the COI to a liquid PM are first order. By contrast, the magnetic transition from FMM to PM may be a continuous second-order transition if the lattice coupling is sufficiently weak (that is, as $\lambda \rightarrow 0$). However, the same transition becomes first order near where the three phase boundaries meet.

The story that emerges from even the sketch of figure 2 is that manganites can host several first-order phase transitions between phases that have completely different electrical and magnetic properties. Because these phases involve relatively small modifications of the local atomic arrangement, they can cohabit within a single crystal. Manganites are unusual in that phase coexistence is so widespread, and the reasons are still subject to debate.

Macroscopic phase coexistence is just one extreme.

Box 1. Manganite Crystal Structure

Manganites share the same crystal structure as the mineral perovskite. Each manganese atom (yellow) is surrounded by six equidistant oxygen atoms (red) to form a regular MnO_6 octahedron. The six oxygen atoms occupy the faces of a cube. Between the octahedra, at the corners of the cubes, lies a mixture (blue) of trivalent rare earth (Re) and divalent alkaline earth (Ae) cations. These cations act as a charge reservoir for the manganese–oxygen bonds. Manganites have the general formula $\text{Re}_{1-x}\text{Ae}_x\text{MnO}_3$, and the overall manganese valence ranges from 3+ (atomic $3d^4$ configuration at $x = 0$) to 4+ ($3d^3$ at $x = 1$).



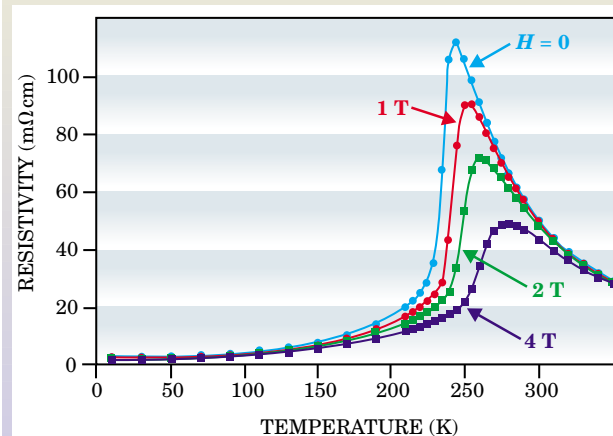
One feature that makes manganites so interesting is that intertwined structures can arise over a range of length scales. Whenever the range extends to scales so small that the many-body concepts of thermodynamics no longer apply, it is better to refer generally to texture within a single phase, rather than to phase separation.

Imaging the texture

Phase coexistence was first observed back in the 1950s using neutron diffraction, but the most convincing identi-

Box 2. Colossal Magnetoresistance

Qualitatively, colossal magnetoresistance (CMR) may be understood as follows. A large magnetic field of several tesla aligns atomic spins on the manganese sites. When this happens, manganese valence electrons can flow easily from one manganese site to another through the intervening oxygen atoms. As a result, applying a magnetic field reduces the electrical resistance. This reduction can sometimes be as large as a “colossal” factor of 10^7 because the material is so highly insulating before the field is turned on. The graph below shows the resistivity of $\text{La}_{0.75}\text{Ca}_{0.25}\text{MnO}_3$ as a function of temperature in various applied magnetic fields. The field-induced suppression of the resistivity is a manifestation of the CMR effect. (Adapted from P. Schiffer, A. P. Ramirez, W. Bao, S.-W. Cheong, *Phys. Rev. Lett.* **75**, 3336, 1995.)



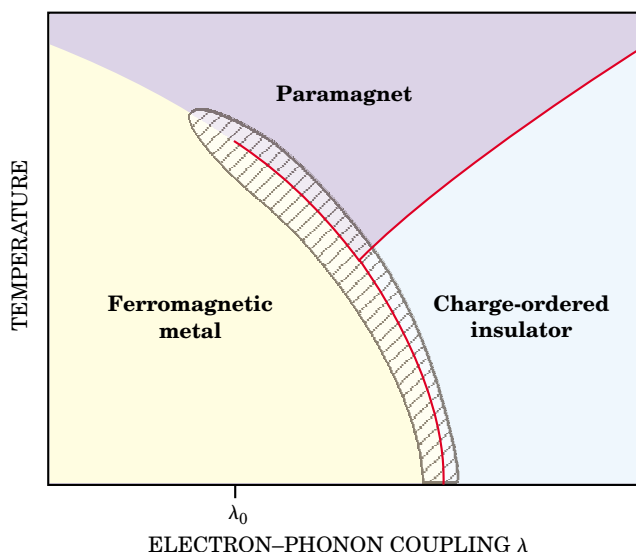


Figure 2. Generic phase diagram for manganites. The tuning parameter λ measures the strength of the electron–phonon effects that localize the potentially itinerant manganese valence electrons. At small λ , the ferromagnetic transition should be continuous (second order). When λ exceeds the intermediate value λ_0 , discontinuous (first order) phase transitions appear (red lines). Colossal magnetoresistance (CMR) effects are found near the first-order phase boundary of the ferromagnetic metallic (FMM) phase (hatched area). Mixed phases and mesoscopic texture occur near the first-order boundaries.

fication of texture—and especially of the length scales on which it occurs—comes from a growing number of imaging experiments. We describe a few here.

In the first such experiment to be published, Cheong demonstrated phase separation in a particular manganite that had been known previously to exhibit both COI and FMM phases.⁸ He and his colleagues identified submicron COI patches using dark-field transmission electron microscopy (TEM). The two phases looked different under the microscope because charge order confers a new periodicity on the crystal lattice.

Last year, Christoph Renner, Gabriel Aeppli, and Yeong-Ah Soh of NEC's Research Institute in Princeton, New Jersey, combined scanning tunneling microscope (STM) spectroscopy with atomic resolution STM imaging to study samples provided by Cheong and Bog-Gi Kim. The NEC researchers found two distinct and separated phases: Surface regions that have a periodic superstructure—believed to be due to charge ordering—have a semiconducting gap, whereas regions that lack charge ordering are

metallic.⁹ And as figure 3 shows, Renner and his colleagues managed to image the boundary between the two regions, showing it to be atomically sharp. Surprisingly, this evidence for phase separation appeared well above the bulk transition temperature.

The two studies just described relied on inferences to identify the ferromagnetic parts of the jigsaw puzzle. But recently, the group of Alex de Lozanne (University of Texas at Austin) investigated a thin film using a low-temperature magnetic force microscope (MFM). By exploiting the sample–tip interaction, de Lozanne and his collaborators could directly image and track submicron ferromagnetic patches, which appear dark in figure 4. As the experimenters varied the temperature, one might have expected the patches to be pinned—if not by any film defects that are present, then by strain fields generated by the intervening, and possibly COI, regions. Instead, FMM patches formed and deformed with surprising fluidity and mobility.

One suspects that strain fields may always ultimately determine the patterns of submicron coexistence that emerge from the TEM, STM, and MFM studies. Indeed, soon after such studies began, Matthias Fäth, John Mydosh, and Jan Aarts of the University of Leiden's Kamerlingh Onnes Laboratory in the Netherlands demonstrated that the microstructure of a thin film could prevent the FMM phase from forming homogeneously. The Leiden researchers made this discovery using an STM to probe a manganite composition that was expected to become wholly FMM either on cooling or on applying a magnetic field. But instead of a uniform tunneling current in their STM, Fäth and his collaborators found a current that varied on a submicron scale, which suggests the coexistence of metallic and insulating patches. One infers the insulating regions to be the PM phase—that is, material that failed to transform to the FMM state, probably due to strain. The intrinsic degree of homogeneity in the FMM phase of manganites has not been fully established. But in the Leiden experiment, the texture conferred by the microstructure was so robust that it was not completely destroyed, even by a large magnetic field of 9 T.

Soh and her collaborators from NEC, Bell Labs, Argonne National Laboratory, and Cambridge University have explicitly demonstrated that strain determines the

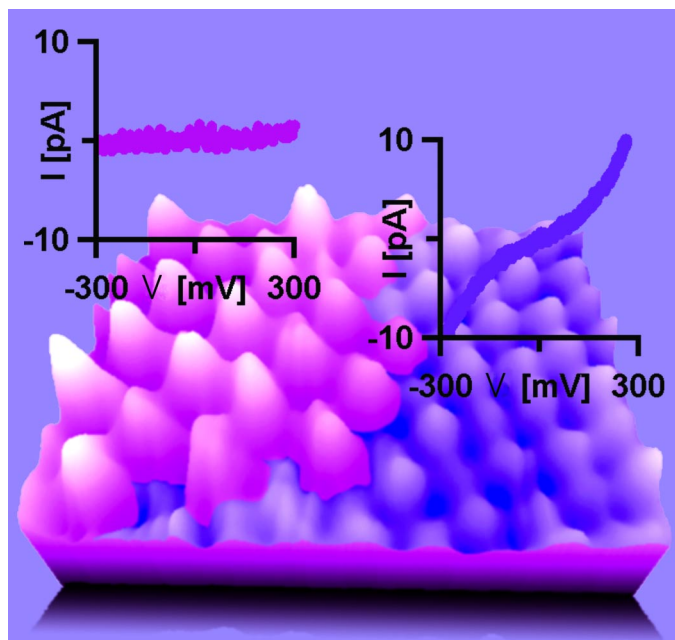


Figure 3. An atomically sharp short-lived boundary separates an insulating charge-ordered phase (left, pink) from a weakly conducting charge-disordered phase (right, purple), as shown in this room-temperature scanning tunneling microscope image of $\text{Bi}_{0.24}\text{Ca}_{0.76}\text{MnO}_3$. In the charge-ordered phase, the I - V curve displays insulating behavior, whereas the charge-disordered phase shows an ohmic, metallic regime near zero voltage. The origin of this difference appears to be related to the structure. In the charge-ordered phase, the Mn^{3+} and Mn^{4+} ions arrange themselves in a regular, repeating pattern that doubles the unit cell. Although it was not possible to actually take I - V curves on either side of a boundary, the evidence for phase separation is compelling. (Adapted from ref. 9.)

local properties of a manganite. Soh's team mapped the grain boundary region of a FMM manganite film in two ways: first with temperature-dependent MFM, and then with x-ray microdiffraction (see figure 5). The two maps—of the local out-of-plane lattice constant and the local Curie temperature—bore a direct correlation to one another. Specifically, the observed lattice distortions were found to produce 20-K variations in the Curie temperature on submicron length scales.

Manganites can also adapt to their environments on shorter, atomic scales. It is known that different types of COI phase with increased periodicity can be obtained by changing the valence electron concentration. But even at the simple doping of $x = 1/2$ where alternating stripes are favored, Cambridge University's James Loudon and Paul Midgley and one of us (Mathur) have discovered, using both TEM and electron holography, a new phase that is both ferromagnetic and charge ordered (figure 1). These two properties used to be thought mutually exclusive because charge delocalization is required to promote ferromagnetism by double exchange. The new phase must be magnetically homogeneous because the holographic technique finds the full spin-aligned moment per manganese atom of $3.5 \mu_B$. But the new phase doesn't have to be structurally homogeneous. If, instead, the phase contains texture that is below the 20-angstrom resolution of the TEM, then one would still say that a new phase, rather than phase separation, has appeared, because, thermodynamically speaking, a phase can't be too small.

Although unexpected, the new charge-ordered ferromagnetic phase is, in retrospect, plausible. Hopping by nearest-neighbor charge carriers alone, rather than by double exchange, could be sufficient to promote ferromagnetism. Because the new phase is not widespread over the sample, one presumes that it only forms for certain types of local strain field.

Tuning the texture

The competition between localizing and delocalizing electronic propensities in manganites determines the materials' physical properties. Many parameters can be adjusted to tune the competition's outcome, but the most fundamental tuning parameter is chemistry. By selecting a mixture of divalent and trivalent cations of different sizes to go in between the MnO_6 octahedra, it is possible both to change the number of valence electrons and, independently, to produce MnO_6 rotations. These rotations tweak the local electronic structure and modify the susceptibility to distortions of the MnO_6 octahedra.

Because different phases are stabilized at different valence electron densities, the possibility of electronic phase separation is widely discussed in the literature. But Coulomb interactions are large and therefore modulation of the overall charge density can occur only over very short

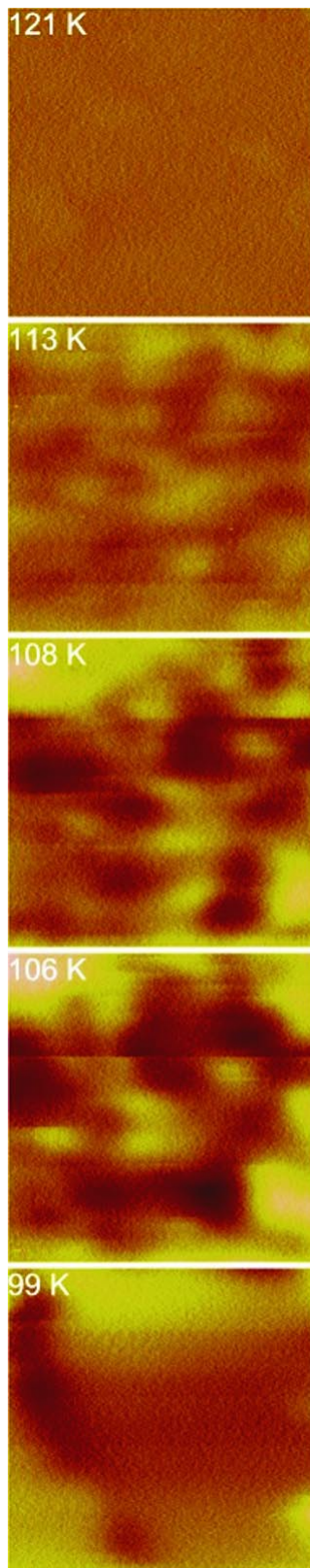


Figure 4. Changing the temperature through a metal-insulator transition leads to surprisingly fluid changes of magnetic texture. This sequence of magnetic force microscopy images shows a $5 \mu\text{m} \times 5 \mu\text{m}$ patch of a $\text{La}_{0.33}\text{Pr}_{0.34}\text{Ca}_{0.33}\text{MnO}_3$ thin film. No magnetic contrast appears in the highest-temperature image (at the top). As the temperature is reduced, ferromagnetic regions appear as dark patches. Inferred to be metallic, the connected patches are thought to provide a conducting pathway for charge carriers. The dark patches grow and move around during the cooling sequence, eventually coalescing, as seen in the bottom image. (Courtesy of Alex de Lozanne, University of Texas at Austin.)

distances—as one sees in the stripe phases themselves. The larger-scale texture observed in experiments is thus more likely to be mediated by long-range elastic coupling between different phases that possess similar valence electron densities.

The elastic, or strain, coupling arises because the manganite crystal structure is so strongly tied to the magnetic and electronic structures. A nucleating region of one phase with a particular crystal distortion can favor the growth elsewhere of a different phase or of a differently aligned twin of the same phase. In this way, the elastic energy is minimized. Domains of different phases formed like this can grow, and a delicate balance that is externally tunable can be established.

It is interesting to ask whether such a balance represents the true equilibrium phase separation that is expected whenever a thermodynamic system is subject to a constraint, such as a liquid and gas mixture confined in a box. The alternative is nonequilibrium phase separation, which can arise in two ways. In the first, kinetic effects can prevent the attainment of equilibrium and create a metastable balance, which is what happens when a liquid supercools through its solidification point. In the second, inhomogeneities and disorder can locally favor one phase over another and pin the domain pattern. But note that the experiment shown in figure 4 demonstrates that this pinning does not necessarily happen: Surprisingly, the domain structure remains fluid on cooling.

How might one identify whether an experimentally observed example of phase separation represents true equilibrium?

Pablo Levy and Francisco Parisi of Argentina's atomic energy commission have used a clever trick in their study of polycrystalline manganite samples that exhibit slow dynamics. During a pause in cooling, they found that the electrical resistance would relax over the course of many hours. But they could speed things up by applying a magnetic field. If they applied too large a field, the sign of the relaxation reversed. In other words,

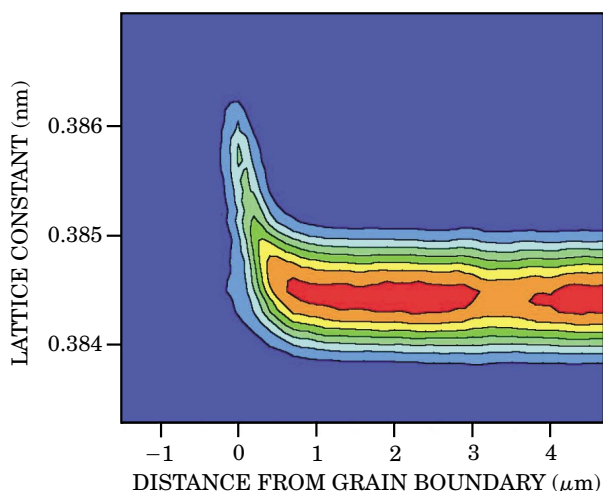


Figure 5. X-ray microdiffraction reveals how the strain in a thin film of $\text{La}_{0.7}\text{Sr}_{0.3}\text{MnO}_3$ changes at a grain boundary. The contours indicate the strength of the diffracted signal and range from low (blue, off the Bragg peak) to high (red, on the Bragg peak). In the experiment, a submicron beam illuminates a patch of the grain. As the beam is stepped across the grain, the Bragg peak shifts, revealing a change in the out-of-plane lattice constant c . In the grain interior, epitaxial strain causes in-plane tensile stress that reduces c from an unstrained value of 0.3880 nm to a range of values centered around 0.3845 nm. On approaching the grain boundary, the strain relaxes continuously within the last micron of approach. (Adapted from Y.-A. Soh et al., *J. Appl. Phys.* **91**, 7742, 2002.)

a true equilibrium indeed exists, and it can be overshoot. Interestingly, because the material remembers the largest field it has experienced, the sample functions as a memory device.

A wider context

Ordinarily, it is difficult to explain how a system commonly appears close to a phase boundary where the free energies of the very different phases are nearly the same. But in this article, we have argued that a simple competition to localize and delocalize valence electrons in manganites is ultimately resolved by complex, phase-separated structures over a wide range of length scales. In making our case, we have made many simplifications.

We did not dwell on the dramatic consequences of varying the density of valence electrons through chemical control. Also, we did not say much about the many different COI phases: The structural correlations described earlier cause complex rotations of the MnO_6 octahedra, exotic orderings of the electronic orbitals, and commensuration effects that relate to periodicity mismatches between the crystal lattice and the magnetic and electronic lattices.

Also, our attempt to identify three basic phases is incomplete. For example, there is a charge-disordered ferromagnetic insulating phase. As recently shown by Bas van Aken and Thomas Palstra of the University of Groningen in the Netherlands, this phase is ferromagnetic because of superexchange between an alternating arrangement of Jahn–Teller distorted MnO_6 octahedra. As a further simplification, we did not fully bring out how material microstructure will shift phase boundaries and introduce multiphase regions. In fact, temperature–composition phase diagrams are different for single crystals, sintered powders, free powders, coherently strained thin films, and relaxed thin films. We did not even begin to describe layered or hexagonal manganites.

Despite the many complexities, the broad outlines of the story are simple and the principles apply not only to manganites. Manganites are examples of strongly correlated electron systems near the metal–insulator transition that Nevill Mott first outlined more than 50 years ago, around the time manganites began to be explored. Near the Mott transition, the opposing forces of delocalization (due to kinetic energy) and localization (due to the repulsive Coulomb force between electrons) are finely balanced. Although the particular properties of each physical system are special, this motif is widespread and rich in phenomena. In the high- T_c cuprate superconductors, the motif appears in the competition between superconductivity and

insulating antiferromagnetic charged stripes. In two-dimensional electron systems subjected to high magnetic fields, it appears in electronic Wigner crystallization and the fractional quantum Hall effect. In highly excited semiconductors, it appears in exciton liquids and electron–hole plasmas. And in $(\text{Ba},\text{K})\text{BiO}_3$, it appears in charge density waves and superconductivity.

Mesoscopic and mixed phases certainly have fascinating potential. Vic Emery of Brookhaven National Laboratory and Steven Kivelson of UCLA argued that a similar array of phases, analogous to those in liquid crystals, could, in the long run, make it possible to locally control the electronic structure and properties without atomic-scale fabrication. In manganites, for example, a simple magnetic domain wall in the ferromagnetic metallic phase could spontaneously develop an insulating barrier of the charge-ordered phase—the ultimate spin-tunnel junction. Alternatively, in the cuprates, perhaps it will become possible to embed a superconducting thread within an insulating matrix when the thread and the matrix are made of identical material.

With these and other ideas, one is entering a realm of inorganic materials science that is reminiscent of the complex self-organized structures seen in soft condensed matter physics or polymer science. However, one must remember that only an unprecedented effort in the control of chemistry and materials, together with astonishing developments in nanoscale imaging and measurement, provides this glimpse of the future.

We thank Gabriel Aeppli, Alex de Lozanne, James Loudon, Paul Midgley, Christoph Renner, and Yeong-Ah Soh for providing and discussing images. We are grateful for discussions with Pablo Levy, Andy Millis, Montu Saxena, and Bas van Aken. We thank Britta Kleinsorge for commenting on drafts of this article.

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