

PERSPECTIVES

tion via the TCA cycle in neurons, before lactate production by astrocytes replenishes the extracellular lactate pool.

Although the present study clarifies a number of issues in both brain energetics and functional brain imaging, it also holds the promise of finding a solution to other unanswered questions. For example, the strategy of Kasischke *et al.* may resolve whether excitatory (glutamatergic) and in-

hibitory (GABAergic) activities have the same impact on brain energetics and elicit similar imaging signals. The remarkable findings of Kasischke and co-workers leave us eager to see the next answer that comes to light.

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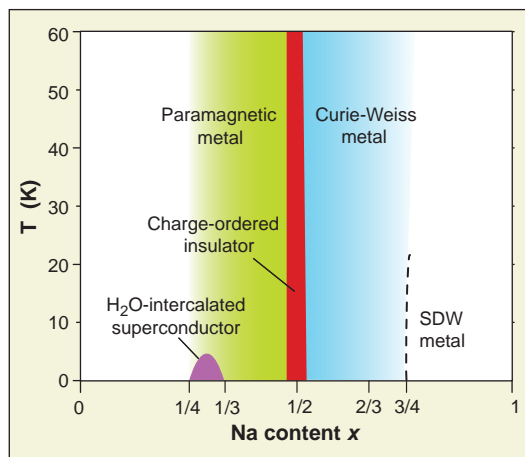
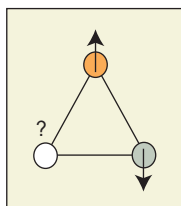
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PHYSICS

Electronic Frustration on a Triangular Lattice

N. P. Ong and R. J. Cava

Imagine that you are hosting a dinner with an odd number of people in the party. You quickly realize that it is impossible to seat every guest between two members of the opposite sex. This is hardly a calamity, of course. However, for electrons living on a triangular lattice, the concept of “geometrical frustration” in the face of strong electric (Coulomb) mutual repulsion is a crucial, decisive factor that shapes their behavior (see the figure, left panel). In an insulating material, the Coulomb repulsion force is relieved if each electron can point its spin antiparallel to that of its nearest neighbors. On most lattices, this is readily implemented and leads to a state in which spins alternate up and down along each bond direction (the Néel state). On a triangular lattice, however, the geometric arrangement frustrates such ideal regularity. As implied in the figure, two of the three electrons in each triangle must share the same spin orientation. At a temperature of 0 K, the spins remain in a disordered quantum state with no discernible pattern, often called a “spin liquid.” Understanding the spin-liquid state is a major goal of the science of strongly correlated materials (these are materials in which the Coulomb force is very large relative to familiar metals such as gold). Further, the problem is greatly enriched if the electrons are free to hop between sites and carry an electrical current. Does this electron itinerancy relieve the geometrical



Electronic seating arrangements. (Left) Geometrical frustration on a triangle. Should the empty site be spin-up or spin-down? (Right) Phase diagram of Na_xCoO_2 . [Adapted from (4)]

frustration? Does the disordered quantum spin state leave its imprint on the conductivity? Can these electrons form “Cooper” pairs to produce superconductivity?

These theoretical questions are relevant to recent experiments (1–5) on the cobalt oxide Na_xCoO_2 in which the Co ions define a layered triangular lattice (and the Na ions are sandwiched between CoO_2 layers). Initial results (1) obtained on as-grown materials with x close to $2/3$ showed that the material is an excellent, if unremarkable, electrical conductor. However, its magnetic susceptibility—a measure of how well a magnetic field aligns the electron spins—is decidedly odd. In a metal, the fraction of electron spins that can be field-aligned is very small and steadily shrinks to zero with decreasing temperature. By contrast, in Na_xCoO_2 , the susceptible spin population just equals the population of carriers with positive charge (“holes”) and stays un-

changed with falling temperature (2, 3). The susceptibility resembles that of an insulator that is frustrated from attaining the ordered Néel state as described above. This Janus-like ambivalence—metallic in charge conduction but insulator-like in spin alignment—has been dubbed a “Curie-Weiss metal” (4).

Equally puzzling in the initial study (1) was the finding that Na_xCoO_2 has an enhanced thermopower. In metals, an electrical (or charge) current involves the flow of electrons, but because electrons carry entropy, the charge current is accompanied by an electronic heat current. The thermopower measures the ratio of the heat to the charge current. As a rule, the thermopower in metals is very small because in an electric field, nearly equal populations of electrons and holes flow in opposite directions. A recent experiment (3) has unearthed a vital clue to the large thermopower in Na_xCoO_2 . At 2 K, a magnetic field completely suppresses the thermopower to zero (this is possibly the first such observation in any solid). Quantitative estimates confirm that the vanishing of the thermopower coincides with the complete alignment of the spins by the field (3). By inference, this implies that the thermopower derives mostly from the spin entropy carried by the holes in the Curie-Weiss phase.

An even bigger surprise emerged when it was found that water molecules intercalate readily to form a layer between the Na ions and the CoO_2 layer. If the waterlogged sample $\text{Na}_x\text{CoO}_2 \cdot y\text{H}_2\text{O}$ is cooled below 4 K, it becomes a superconductor (5). The superconducting phase is restricted to the narrow interval $1/4 < x < 1/3$ (6). The essential role of water molecules in stabilizing the superconducting state is being intensely investigated (6–9). An important factor seems to be the ability of water molecules to screen the strongly fluctuating electrostatic potential of the Na ions from the charge carriers in the CoO_2 layers. A second question is whether the pairing sym-

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metry is unconventional (as in the cuprates). However, measurements of the superconducting properties are greatly hampered by the difficulty of growing single crystals with the optimal water content; preparing crystals by electrochemical deintercalation may be the key (8).

As noted, the hole density in Na_xCoO_2 may be increased by reducing the Na content x . In principle, with maximum Na content ($x = 1$), there are no holes on the lattice. As the Na content is reduced, the holes increase in proportion until every lattice site is occupied at $x = 0$. Determining how the electronic properties vary with hole concentration is essential for understanding this material. Recent progress has allowed the phase diagram to be established in the range $1/4 < x < 3/4$ (see the figure, right panel) (5). As known from earlier work (3, 6), the interval $x < 0.4$ includes the superconducting phase (with water intercalation), whereas the region near $x = 2/3$ harbors the Curie-Weiss metal described

above. The different hole densities in the two phases are confirmed by Fermi surface measurements with photoemission spectroscopy (10). Do these two distinct phases evolve smoothly into each other? The phase diagram reveals that the answer is no. Unexpectedly, a new state, occupying a strip centered at $x = 1/2$, rises like a firewall between them. In this state, the material is a very poor electrical conductor. Apparently, with half of the sites occupied by holes, the system has found a new way to accommodate both the strong Coulomb forces and geometric frustration by firmly localizing the holes (so they lose their ability to carry a current). The mechanism for the formation of this “charge-ordered” insulating phase is currently an open issue. Finally, for $x > 3/4$ there are hints that the material attains very weak magnetic ordering [a spin density wave (SDW) metal, as shown in the figure] at low temperatures.

Since the discovery of cuprate superconductivity in 1986, researchers in con-

densed matter physics have increasingly turned to novel materials—notably manganates, ruthenates, and nickelates—in which strong electron-electron interactions prevail. As in Na_xCoO_2 , the array of phenomena uncovered presents a major challenge to conventional ideas. Nonetheless, steady progress has occurred in the difficult task of incorporating strong electron interactions into the quantum theory of solids.

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ANTHROPOLOGY

Getting to Know *Homo erectus*

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The period from 1 million to 500,000 years ago (~1 to 0.5 Ma) is well represented in the human fossil records of Europe and Asia. Sites containing such fossils include Ceprano, Italy (~0.9 to 0.8 Ma), the TD-6 level at Atapuerca's Gran Dolina, Spain (~0.78 Ma), Trinil, Indonesia (1 to 0.7 Ma), some parts of the Sangiran Dome, Indonesia (1.5 to 1 Ma), Lantian, China (~1 Ma), and probably Zhoukoudian, China (0.55 to 0.3 Ma). By contrast, Africa has been unusually uninformative about this part of human evolution. Three partial mandibles unearthed more than 50 years ago at Tighenif (Ternifine) in Algeria (~0.7 Ma) are similar in dental morphology to specimens from Gran Dolina (1), but the former are rarely mentioned in the literature. The question thus remained: Where are the African fossils? The recent discovery of the partial Daka skull (~1 Ma) at the Bouri site, Middle Awash, Ethiopia (2), provided part of the answer. On page 75 of this issue, Potts *et al.* (3) now report that the archaeologically and faunally rich site of Ologesailie, Kenya, has divulged its first hominid fossils: a partial frontal and more fragmentary temporal bone dated 0.97 to

0.9 Ma. Like the Daka specimen, these fragments (KNM-OL 45500) were assigned to the species *Homo erectus*.

Potts *et al.* correctly assess the “*Homo erectus*” debate: “The entire sample of fossils from Africa, Asia, and Europe exhibits wide morphological variation that some researchers divide into multiple lineages and others place in a single, polytypic species.” They opt for the latter hypothesis and conclude that “comparison of the KNM-OL 45500 with other crania . . . illustrates that metric and qualitative similarities cut across temporal and spatial groups of fossil specimens.” Assuming that a vast array of specimens of differing morphologies constitute the same species, favorable comparisons between some of them in one or a few morphologies are expected, especially if primitive retentions and shared derived features are not sorted out. But this doesn't clarify the question, “What is *H. erectus*?” One is left primarily with the traditional approach to the genus *Homo*: *H. erectus* is not *H. habilis*, *H. heidelbergensis*, or *H. sapiens*, whatever they are. But there is a simple and systematically valid way in which one might unpack the morphological confusion: Begin with the original name-bearer of *H. erectus*, the type specimen, which was discovered in the late 19th century by Eugène Dubois at Trinil.

The Trinil skull cap is distinctive in having a very low and long profile with a bluntly V-shaped occipital bulge (see the figure, panels A and B). In rear view, it is extraordinarily broad relative to its height. Its shelf-like, laterally flaring, and apparently rather thin brow ridges flow back smoothly into a gently sloping frontal plane. Near the foot of this rise, in the midline, is a pair of depressions that delineate between them an anteroposteriorly oriented “keel-like” structure. The sides of the brain case are minimally puffy. Specimens that share most of these features, but with a wide range of individual variation in their expression, come from Sangiran (panels C, D, and F). Some specimens of this substantial assemblage preserve a temporal bone (missing in Trinil) with unusual morphology: Unlike other mammals, this hominid's intracranial sigmoid sinuses were not single, but arborized prior to draining into the jugular veins (panel E). The Trinil/Sangiran sample also demonstrates that long-touted “*H. erectus*” features—very thick cranial bone, markedly puffy cranial side walls circumscribed by thick temporal lines, and pronounced midline keeling—are only variably expressed, if at all. Only the chunky Sangiran 4 specimen approaches this description (4) (panel F).

Do we see any of the consistent Trinil/Sangiran *H. erectus* cranial features in other hominid fossils? Not in the Javanese Ngandong specimens (1 to 0.36 Ma), the Sambungmacan (1 to 0.2 Ma) or Ngawi (undated) specimens, or those from Zhoukoudian or any other Chinese site (Dali, Hexian, Jinniushan, Lantian, Maba,

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