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A metal left spinning

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of their cryptochrome raises the possibility that vertebrate cryptochrome does the same job, and might even explain why the light-detecting properties of the protein have been evolutionarily conserved in mammals[13]. In any case, Gegear and colleagues' results open a new avenue of investigation for magnetoreception — that of genetic and molecular analysis. ■

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MATERIALS SCIENCE

A metal left spinning

Zachary Fisk and Stephan von Molnár

Conductors and semiconductors usually behave like conduits for fluids of electrons. But sometimes the electrons' spins conspire to produce unconventional behaviours that can be turned off and on with magnets.

The theory of Landau–Fermi liquids is a remarkably simple but effective model to describe the behaviour of conventional metals. It views metals as consisting of a liquid of independent, mobile electrons with spin and charge, responding to applied magnetic and electric fields. That individual electrons strongly repel each other as a result of their identical electronic charges is accommodated in this picture by an adjustment to the effective electron mass. Semiconductors doped with atoms carrying either more or fewer electrons than the host atoms a re also explained by this model. Instances in which this picture fails are therefore of considerable interest, and understanding how to produce such materials has both fundamental and technological potential. The possibility of a systematic method of inducing non-Landau–Fermi-liquid states is the claim in the paper by Manyala *et al.*[1] on page 976 of this issue.

The authors have taken the semiconductor ferrosilicon (FeSi) and replaced a few per cent of its iron atoms with manganese (Mn). This element comes just before Fe in the periodic table, having one less electron than Fe in its outer shell. Replacing an Fe atom with Mn in the semiconductor's cubic lattice introduces a 'missing electron', known as a hole. Holes act like electrons but with positive charges; a collection of holes will act exactly like a collection of electrons, apart from moving in the opposite direction in applied electric fields. As with electrons, holes have a spin of 1/2 with an associated magnetic moment.

Manganese atoms carry their own magnetic moment corresponding to a spin of 1 in the FeSi semiconductor. In metals containing atoms from first-row transition elements (scandium to zinc, which includes Mn and Fe) that have local atomic moments, the spin of any mobile electrons or holes (collectively known as carriers) and the local moment preferentially line up anti-parallel, because the carrier attempts to compensate for the local atomic moment. When Mn substitutes for Fe, there are not enough carrier spins to balance the Mn atom's spin completely, because each spin-1 Mn atom appears in the lattice accompanied by a single spin-1/2 hole. A pair of carriers would be needed to compensate for this spin-1 moment, but then the moment of a Mn atom elsewhere would be left uncompensated.

The detailed experiments of Manyala *et al.*[1] show that Mn-doped FeSi does not behave in the manner expected of the standard metallic state of a doped semiconductor; for example, it has an anomalous relationship between electrical resistance and temperature. This non-Landau–Fermi behaviour arises because, even at temperatures below 2 kelvins, undercompensated atomic spins interact with the spins of the free carriers, affecting their degrees of freedom. However, Manyala and colleagues found that applying a sufficiently large magnetic field at low temperature froze the free spins in a single orientation, restoring the expected metallic behaviour.

The suggestion that undercompensated doping provides a general route to non-Landau–Fermi behaviour is a seductively simple idea. But FeSi is an unusual semiconductor whose low-temperature semiconducting state has developed out of a solid with strongly temperature-dependent magnetic properties. This may or may not be relevant. FeSi could simply be an easily accessed venue into which a dopant carrying a local moment incompletely balanced by the net carrier moment can be introduced. It is therefore important for the studies of Manyala *et al.*[1] to be repeated in a more conventional semiconductor.

One might wonder whether similar effects to those occurring with Mn doping of FeSi might occur when doping with cobalt (Co). This is the element just to the right of Fe in the periodic table, and so would provide additional electrons rather than removing them. Cobalt even has a larger atomic moment (of spin 3/2). However, Manyala *et al.*[1] found that Co-doped FeSi becomes magnetically ordered at low temperatures, abolishing all the spin degrees of freedom associated with local moments, leaving no source for behaviour as a non-Landau–Fermi liquid. There are also atoms with local moments that couple to carrier spins in a non-compensating fashion, a process known as preferential spin alignment. Most of the rare earth metals are of this character, including gadolinium, which has a 7/2 spin moment. But no known non-Landau–Fermi liquid associated with this non-compensating situation has yet been seen.

Manyala and colleagues propose that doped semiconductors based on elements in groups III and V (for example gallium arsenide, GaAs) could be used to produce non-Landau–Fermi liquids. There is a considerable volume of literature on low-level doping with Mn in these semiconductors, especially in indium arsenide[2–4]. The extreme of doping, MnAs, is a ferromagnet (as is MnSi) but transition metals do not incorporate well or to high levels with group III–V elements, in contrast with the ease with which Mn dopes FeSi. Magnetic measurements indicate that with Mn replacing between 2% and 18% of the indium atoms, the sum of all spin exchange interactions produces antiferromagnetic behaviour (the moments align in a regular way, cancelling each other out and leaving the material with no overall magnetic moment), the strength of which decreases with decreasing Mn content. For materials with less than 2% Mn the exchanges result in ferromagnetic behaviour (individual moments align to reinforce each other)[3,4]. When Mn doping falls below 1.8%, corresponding to less than 2.2×10^{19} holes per cubic centimetre, the materials display long-range ferromagnetism with a transition temperature (around 7 kelvins) above which ferromagnetism breaks down[3].

It seems that group III–V semiconductors with Mn doping near 2%, where the exchange between local and carrier spin is small, could provide favourable conditions in which to find systems lying between Landau–Fermi liquid and non-Landau–Fermi liquid states. In these semiconductors Mn has a spin of 5/2. In addition, the concentrations of free electrons and/or holes can be controlled independently of Mn content by the addition of impurities, which allows the preparation of materials close to the insulator–metal transition. This would be a major advantage over the FeSi system, because the effects of the type and density of carriers could be studied in detail. In FeSi only aluminium, which substitutes for Si and introduces additional holes, can have this role.

Broader applications of the principles described by Manyala *et al.*[1] to wide classes of well-characterized semiconductors offer the opportunity of new approaches to the understanding of the breakdown of conventional Landau–Fermi liquid theory and with it a possible route towards the control of strong electronic correlations in solids for useful purposes. ■

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BIOGEOCHEMISTRY

Who lives in the sea floor?

Ann Pearson

The sediments that blanket the sea floor contain tremendous numbers of microorganisms. This deep marine biosphere, which is probed by deep-sea drilling, is a new frontier for microbiologists and geochemists.

On page 991 of this issue, Lipp *et al.*[1] add to the debate over the nature of life in the sea floor. They report that most cells in deep-sea sediment are members of the domain Archaea and not of the other domain of the prokaryotes, the Bacteria. Although both are differentiated from the eukaryotes — which include ourselves — in lacking a nucleus, Archaea and Bacteria are fundamentally different from each other in their biochemistry, metabolism and evolutionary history. This in turn profoundly influences their role in Earth's biogeochemical cycles.

A century ago, the suggestion that the ocean's deep sediments had inhabitants — organisms far removed from the oxygenated, light-filled surface of Earth — would have been preposterous. Life *on* the sea floor was well known; such fauna were sampled during the voyage of the HMS *Challenger* (1872–76), in an expedition that is widely recognized as marking the birth of modern oceanography (Fig. 1). The first hint of a rich microbial biosphere *in* the sea floor came only much later[2], and it was not until the 1990s that microbial cells in deep sediments were enumerated systematically[3,4]. In parallel, geochemists showed that inorganic solutes in sediment pore-waters usually react in the order predicted by thermodynamic principles, but at rates exceeding expectations for abiotic processes[5–7]. Thus biologists and chemists agree: there must be a 'deep biosphere'. But what populates it? And how do the organisms concerned adapt their metabolic strategies to sustain life at the limits of energetic viability[8,9]?

The deep biosphere is large, and, at least in aggregate, it is 'alive'[10,11]. The data almost defy imagination — on the order of a million cells in every cubic centimetre of sediment buried half a kilometre below the sea floor, or more than 50% of all microbial cells on Earth[12]. The overall order of magnitude is the same as the biomass of all surface plant life. In investigating what kind of cells they are, Lipp *et al.*[1] conclude that, deeper than 1 metre below the sea floor, it is Archaea, not Bacteria, that contribute the bulk of sedimentary microbial biomass. If true, Archaea would be the most abundant cell type in the marine system, rivalling Bacteria in total numbers globally.

Lipp *et al.*, however, are far from the first to approach the question of the phylogeny of sedimentary prokaryotes. Previous efforts generated conflicting results[10,11,13], and a hung jury has been declared[14] over the question of the predominance of Bacteria or Archaea. But why the protracted debate? Part of the problem lies in the distinction between 'living' cells, total cells (including inert or dead cells), and/or cells that are in between, persisting in an undefined degree of stasis. This leads to ambiguity about what should or should not be counted. Adding to the confusion, nearly every report so far also has used a different combination of analytical techniques, and consideration of those techniques is essential to understanding the issues.

The fluorescent stains acridine orange and DAPI detect all cells — alive or dead — that contain any remnant of DNA. But they cannot reveal phylogeny or activity. So, to discriminate between Bacteria and Archaea, molecular methods have been used in various combinations. These include approaches that detect ribosomal RNA (rRNA) or intact polar lipids (IPLs) of cell membranes (both are proxies for live cells), or that quantify rRNA gene copies from extracted DNA. Of these techniques, *in situ* fluorescent tagging of ribosomes in methods known as FISH or CARD-FISH produce the most disparate (indeed, opposite) results[10,11,13]. Although potentially an ideal

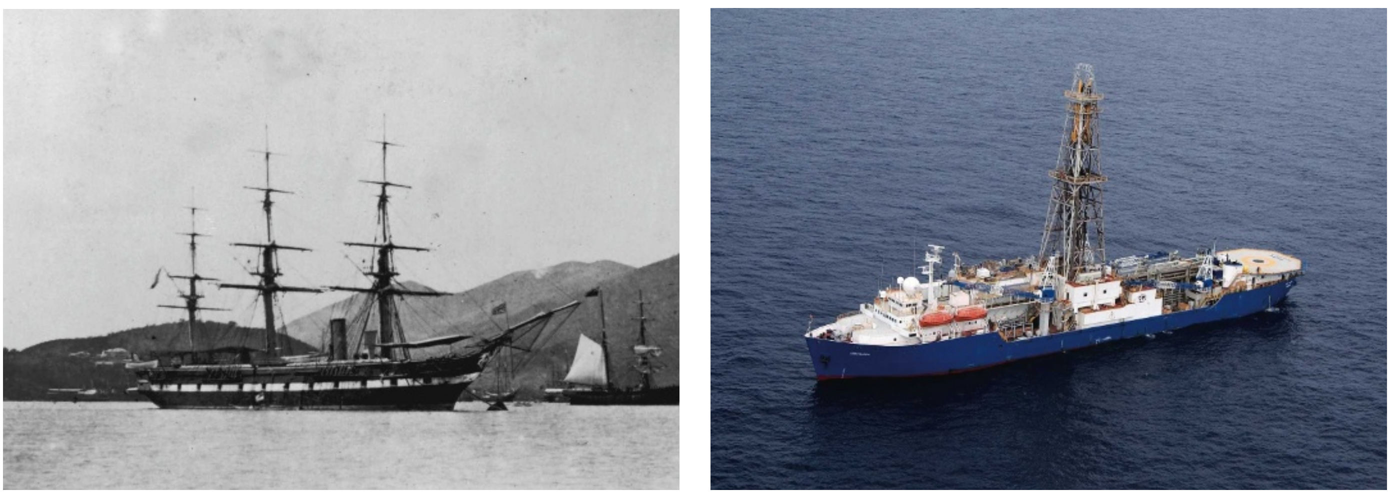

Figure 1 | Sea change. HMS *Challenger* (left), whose voyage in the 1870s opened eyes to the fauna living on the floor of the deep sea, and the drill ship *JOIDES Resolution*, mainstay of the Ocean Drilling Program and subsequent Integrated Ocean Drilling Program, which has provided the cores from which much of the information about life in deep-sea sediments has been gleaned.