Condensed-matter physics

Misbehaviour in metals

Philip B. Allen

A numerical study by Gunnarsson and Han[1] on page 1027 of this issue sheds new light on the electrical resistivity of complex metals. Resistivity is a basic property of materials, defined as electrical resistance per unit length of a wire of unit cross-sectional area. Standard measurements, such as the variation of resistivity with temperature, material purity and magnetic field, can tell us a lot about electrons in matter. In simple metals we can treat electrons as a gas, allowing the resistivity to be analysed in detail. But in more complicated metals, such as those studied by Gunnarsson and Han, the situation is more confusing.

In an ordinary gas, like the air we breathe, the uncharged molecules are well separated from each other, fly around at random thermal velocities (typically 1 km s^{-1}), and occasionally bump into each other. The mean distance between collisions is about 100 nanometres (100 times bigger than the mean distance to the next molecule). The particles are small and weakly interacting. By contrast, in a liquid the molecules continually bump into each other. In the 1870s, Ludwig Boltzmann invented a statistical theory that successfully describes the behaviour of gases and has since been adapted to describe a huge range of phenomena in physics and engineering. Unfortunately, it can't work for liquids, and no corresponding theory has ever been found[2].

In a simple metal, such as copper, there is one 'free' negatively charged electron for each positively charged copper ion in the crystal lattice. In 1904, Lorentz applied classical Boltzmann gas theory to these electrons (Fig. 1). On the face of it, the idea looks wrong, as electrons are neither dilute nor weakly interacting. They should collide after moving only a fraction of a nanometre, like molecules in a liquid. Nonetheless, gas theory does work for ordinary metals. Bloch later added quantum effects to show how electron waves diffract around the crystalline array of ions, not colliding until they encounter an impurity or a thermally displaced ion. But all these theories ignored interactions between electrons. In 1956, Landau introduced new ideas that led to our modern understanding of metals.

Through Landau's work we have come to recognize that, rather than having 'free electrons', a conducting metal actually has 'quasiparticle excitations' carrying the electrical current. These quasiparticles closely resemble electrons, and obey a modified gas theory. So electrons in copper behave like particles in a dilute gas. The electrical resistivity has been explained in fine detail, including the way it increases with temperature, as the distance between collisions reduces. In this semiclassical picture, the distance between collisions cannot be smaller than the lattice spacing, so the resistivity cannot be calculated reliably beyond a maximum temperature or impurity level.

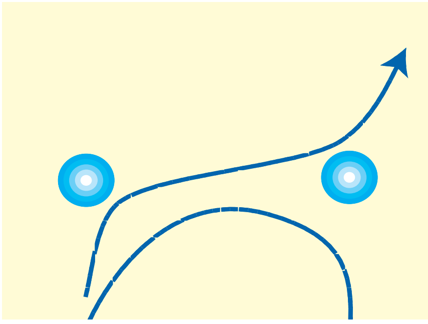

Figure 1 **Modelling electrons as a gas. If one collision ends before the next begins (upper trajectory), classical Boltzmann gas theory applies. Otherwise (lower trajectory) the effect of the two collisions is not additive and gas theory fails. This is the problem with Boltzmann theory when a dilute gas is compressed into a dense liquid. In metals the quantum version of Boltzmann gas theory has more subtle problems leading to failure in complex metals, such as the metallic fullerenes studied by Gunnarsson and Han[1], and high-temperature superconductors.**

The lack of a 'Boltzmann theory for liquids' is a big problem when it comes to interpreting resistivity in more complicated metals. For example, in high-temperature superconductors the resistivity continues to rise even as the distance between collisions gets too short to justify gas theory. Similar effects occur in superconducting metals made from 'buckyballs' (C_{60} molecules) doped with alkali metals[3]. There are suspicions that electronic behaviour in these exotic metals may be radically different from that in conventional metals.

Gunnarsson and Han[1] now model the resistivity of these 'metallic fullerenes' using quantum-mechanical π-electrons of the outermost shell of the C_{60} molecule, coupled to vibrations of the molecule that are also treated quantum mechanically. The electrons can hop from C_{60} to C_{60}, with partially disordered hopping because the C_{60} molecules are not fully in line with the crystal lattice. This model contains much of the physics expected to control the behaviour of the electrons, and is too complicated to solve except by a computer simulation. The result of the model is a plot of resistivity against temperature that agrees with the experimental observations. The theory yields the same answer as a naive model in which there is no fundamental limit to the mean distance between collisions, at least for fullerenes.

What are the implications of Gunnarsson and Han's discovery? The Landau theory that underlies the modern theory of ordinary metals has a built-in circularity: one cannot prove that electrons in copper behave like particles in a gas, but one can show that this is a mathematically consistent possibility[4]. Other possibilities exist, the most dramatic being conventional superconductivity, in which attractive interactions between electrons destroy the quasiparticle gas phase of electrons at low temperatures, replacing it with the superconducting phase with zero resistance. The particles that fly around in a superconductor are then no longer electron-like quasiparticles, but become 'Bogoliubov quasiparticles'. Their electrical charge is altered from the usual value because the particles are a subtle mixture of negatively charged electron and positively charged 'hole'. These quasiparticles obey gas laws, but not the electronic version[5].

A second alternative to the Landau theory is Anderson localization (Fig. 2). This is a theoretical possibility that arises when the electrons suffer very strong scattering from defects. As defect density increases, electrons evolve from free travelling waves into trapped wave packets that are unable to diffuse (localization). A third, more pedestrian possibility is paradoxically less well understood: as defect density or thermal ionic displacements increase, distances between collisions can reduce to the atomic-spacing level and resistivity can stop increasing and 'saturate' (Fig. 2). This saturation of resistivity is reminiscent of the evolution of a classical gas into a classical liquid, where gas theory no longer applies. Several other options (spin- and charge-density waves, for example) are also known.

Do the known options exhaust all the possibilities? Surely not. For example, a peculiar phase occurs in two-dimensional metals in strong magnetic fields, where electrons and magnetic flux can combine to form new com-

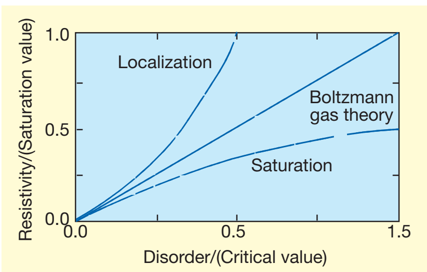

Figure 2 **Alternative forms of electrical resistivity. The straight line shows the prediction of quantum gas theory, which works for simple metals. The other options (Anderson localization and 'saturation') might apply when materials contain a high density of defects or strong scattering from thermal disorder.**

posite quasiparticles with fractional charge. The enigma of high-temperature superconductivity, which occurs in copper-oxide metals, has been driving the search for new theories. Above the temperature (around 100 K) where superconductivity disappears, the electrical resistivity of the copper oxides is highly unusual. The temperature dependence suggests some sort of quasiparticle gas, but the scattering is so strong that liquid behaviour should be seen[6]. This is often interpreted as evidence for a new exotic electron phase.

In their model for fullerenes, Gunnarsson and Han[1] find no indication that the electrons have formed such a phase. They also argue that the quantum Boltzmann gas picture continues to work reasonably well into the liquid-like regime, where it does not really apply. So, for this model, it appears that unusual resistivity can be reconciled with ordinary behaviour. A similar theory for copper-oxide metals above their high superconducting transition temperature is needed. But this will be an even bigger challenge. Strong magnetic electron–electron interactions will need to be included in the calculation before the copper oxides can be adequately modelled. ■

Philip B. Allen is in the Department of Physics and Astronomy, State University of New York at Stony Brook, Stony Brook, New York 11794-3800, USA.
e-mail: philip.allen@sunysb.edu

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Linguistics

Talking trees tell tales

Rebecca L. Cann

On page 1052 of this issue[1], Russell Gray and Fiona Jordan describe how they have used a tool from molecular taxonomy, the 'parsimony' method, to examine patterns of DNA sequence change over time and to probe the history of a group of languages. Parsimony is a central principle in the cladistic approach to evolutionary biology; it holds that the evolutionary tree requiring the fewest transformations of characters should be preferred. Words do not fossilize. Yet they leave evidence of their evolution in the populations that speak them, in much the same way that genes reveal the evolutionary history of the populations that transmit them.

Gray and Jordan's subject of study is the spread of the Austronesian language family eastwards across the Pacific several thousand years ago. What makes their approach novel is the explicitly quantitative test of the hypothesis that the evolution of a material culture, as traced by archaeological artefacts and other evidence, can be mapped onto the evolution of a language family in ordered and nested steps.

Both comparative linguists and archaeologists are interested in the apparently rapid expansion of the first humans to reach remote Oceania, the region containing Pacific islands beyond the Bismarck Archipelago that includes traditional Polynesia along with parts of Micronesia and Melanesia (Fig. 1). Expansion began with a drive out of southeast Asia, southern China, Taiwan or Indonesia about 6,000 years ago. The exact geographical location of the founders of what would eventually become a unique, deep-ocean voyaging culture is not known for sure. But a linguistic analysis by Robert Blust[2] favours a homeland in Taiwan, and Gray and Jordan's analysis proceeded on that basis.

The earliest settlements in Fiji, western Polynesia and New Caledonia came less than 500 years after a push out of western Melanesia, and there is genetic evidence that Austronesian voyagers mixed along the way with coastal residents of Papua New Guinea and Vanuatu. Archaeological sites indicating colonization of islands beyond the Bismarck Archipelago are associated with the Lapita cultural complex, named after a characteristic type of pottery. Residents of these islands, presumed to be descendants of the original voyagers, speak languages grouped into the Austronesian family, which now contains about 1,200 distinct languages.

Parts of the sequence of initial colonization have been obscured by subsequent trading and warfare, along with depopulation and replacement in modern times resulting from disease epidemics. Also, gaps in the archaeological record, however short, may reflect either actual pauses in the speed of colonization or simply the lack of exploration of — and so evidence from — coastal sites that now lie under water.

It seems that Austronesian voyagers apparently stopped and rested for about a thousand years between the settlement of western Polynesia and the rest of remote Oceania. Blust suggested that this hiatus was due to a pause before the invention of the double-hulled sailing canoe that could cross the wider stretches of sea involved. Further, some archaeologists have long held that Polynesians did not acquire their full suite of cultural attributes (such as the use of particular crop plants, domestic animals and wayfinding techniques, and of durable goods such as tools, pots and textiles) until they mixed and traded with, and presumably learned from, nearby resident Melanesians. So the picture is highly complicated. A systematic tool that could reveal hidden subgroups among similar Austronesian

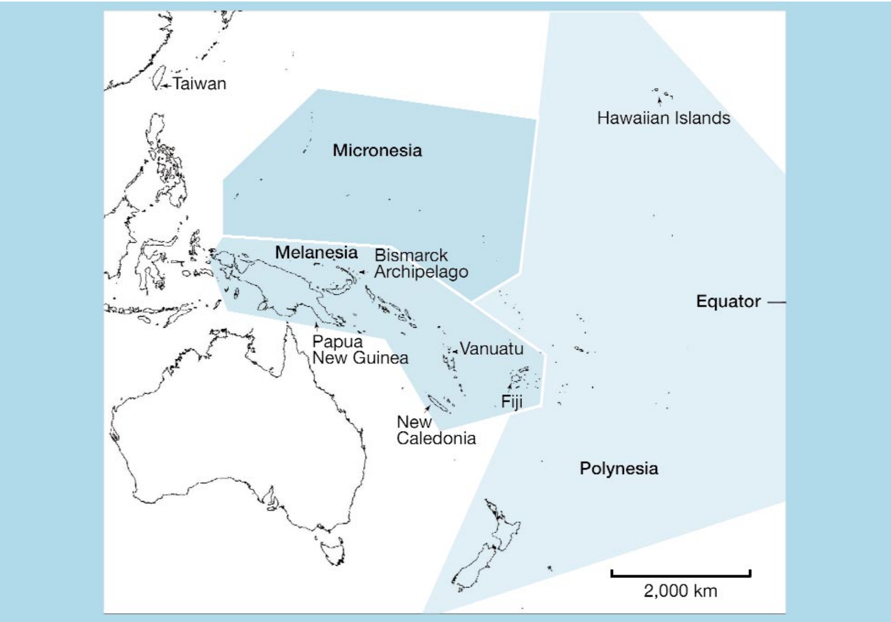

Figure 1 **Peopling the Pacific. One view — the 'express train' theory[5,6] based on archaeological evidence — is that, starting in Taiwan, the human colonization of the western Pacific proceeded swiftly and was complete within 2,100 years. Gray and Jordan's analysis[1] of Austronesian languages lends support to this idea and shows how the molecular tools of evolutionary biology can be applied to linguistics. Some of the island groups (such as Marshall and Gilbert in Micronesia, and Cook and Marquesas in Polynesia) do not show on the map at this scale. Redrawn from ref. 1.**