Condensed-matter physics

A strange metal from a failed superconductor

Nicholas P. Breznay

The curious electrical resistance that gives strange metals their name has been seen in a failed superconductor, in which disorder interferes with the material's ability to achieve zero resistance below a critical temperature. **See p.205**

Above a certain temperature, the electrical resistance of copper–oxygen ceramic materials (called cuprates) increases in direct proportion to their temperature, reaching values far above the reasonable limits of electrical conduction[1]. This behaviour cannot be attributed to the way electrons usually interact with one another, or with atomic nuclei, and it has no widely accepted explanation – a trait that has given these materials the name of bad, or strange, metals. On page 205, Yang *et al.*[2] report this strange-metallic behaviour in a thin-film cuprate containing yttrium, barium, copper and oxygen ($YBa_2Cu_3O_{7-\delta}$), in which nanopatterning enhances the disorder present in the material. Moreover, they find that this behaviour occurs at lower temperatures than expected, redrafting the accepted strange-metal blueprint.

The first surprises about cuprates emerged in 1986, when it was shown that they can be tuned to become magnetic or to carry electricity with zero resistance (superconduct) below a critical temperature that is much higher than physicists thought possible[3]. No unifying theory exists for these decades-old findings, but many researchers think that the materials' strange-metallic behaviour presents an even greater puzzle.

Despite its inexplicability, strange-metallic behaviour seems to be everywhere. Enormous efforts are being made to derive a rigorous theory that explains why it shows up in a range of materials – from iron-based superconductors[4] to ruthenium-based compounds[5] and twisted bilayer graphene, in which each layer is a single sheet of carbon atoms and the layers are twisted relative to each other[6]. These solids all host exotic phenomena, such as high-temperature superconductivity, which makes the occurrence of strange-metallic behaviour in these systems all the more intriguing[7]. It is tempting to assume that something ties them all together.

So what makes a metal strange? Common electronic states of matter – ordinary metals, semiconductors and insulators – can all be described using electrons as the fundamental building block of the state. When electrons interact with one another in ordinary metals, they induce an electrical resistance that varies with the square of the temperature. But strange metals are different: as well as having an electrical resistance that scales proportionally with temperature, when these metals are subjected to a magnetic field, this resistance sometimes also increases linearly with the strength of the field[8].

Yang *et al.* saw just this behaviour in thin films of $YBa_2Cu_3O_{7-\delta}$, which would otherwise be superconducting below a critical temperature. The authors drilled a triangular array of nanometre-sized holes in the films using reactive-ion etching, a kind of atomic sand-blasting (Fig. 1). The thinness of the film, combined with these holes, introduced disorder into the system, and this disorder is known to suppress the superconductivity[9] – a trait for which such materials are sometimes known as failed superconductors. The lattice of holes left behind an array of connected island nodes, and Yang *et al.* showed that the electrical resistance exhibited linear dependence on both temperature and magnetic field strength. In doing so, the authors showed that this material can transition from a failed superconductor to a strange metal.

To understand why this finding stretches the collective imagination about strange metals, it's helpful to know a little more about how electrons behave in solids. Electrons are fermions, named after Italian physicist Enrico Fermi, which are particles that are characterized by having a spin (associated with intrinsic angular momentum) that takes half-integer values. By contrast, particles known as bosons, after Indian physicist Satyendra Nath Bose, have integer spin. So far, strange-metallic behaviour has been observed only under conditions in which electrons were originally thought to behave individually (as fermions),

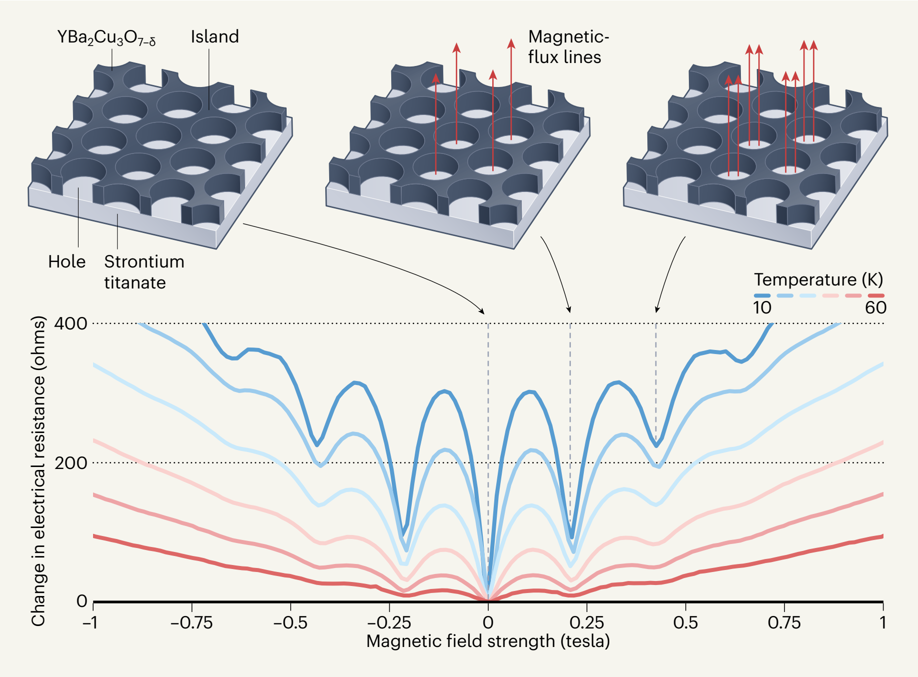

Figure 1 | A strange metal exhibits oscillations in electrical resistance. Yang *et al.*[2] drilled an array of nanometre-sized holes in thin films of the cuprate material $YBa_2Cu_3O_{7-\delta}$ grown on a substrate (strontium titanate), resulting in a pattern of connected islands. In a magnetic field, the quantum nature of the electrons on such islands makes it energetically favourable to have an integer number of magnetic-flux lines through each hole. When the field strength takes non-integer values, the cuprate's electrical resistance increases, resulting in oscillations as the field strength is changed. Yang *et al.* measured such oscillations in the electrical resistance of $YBa_2Cu_3O_{7-\delta}$ and found that the oscillation amplitude increased with decreasing temperature. These oscillations have not been seen before in a material, such as $YBa_2Cu_3O_{7-\delta}$, hosting strange-metallic behaviour, in which electrical resistance increases linearly with temperature. (Adapted from Fig. 1 in ref. 2.)

or collectively, through a quantum-mechanical property known as entanglement[10,11].

But theories of superconductivity rely on the idea that pairs of electrons can be described as composite particles that act like bosons with integer spin. And materials with superconducting (and hence bosonic) character show a peculiar response to applied magnetic fields when disorder is introduced with a microscopic pattern of holes[12]. The quantum nature of the bosons on the islands requires that an integer number of magnetic-flux lines threads through the holes – each carrying a quantum of magnetic flux (Fig. 1). When the applied magnetic field lies between these integer values, the material's electrical resistance increases. The result is a bosonic calling card: oscillations of resistance with changing magnetic field strength. And Yang and co-workers' sample showed precisely this response below the critical temperature for superconductivity – offering direct evidence that a strange metal exhibits electronic transport with bosonic character.

The leading theoretical descriptions of strange metals are as varied as the materials that show strange-metallic behaviour – some even draw on surprising connections to black-hole physics[13,14] – but a consensus model has yet to emerge. Possible connections to an underlying anomalous metallic phase are even more speculative. As the temperature approaches zero, the electrical resistance of many disordered 2D superconductors reaches a constant, non-zero value – but this behaviour is impossible according to theories that describe non-interacting electrons. Sometimes termed a bose metal, this anomalous state is similarly in need of a consensus microscopic theory, despite more than two decades of theoretical and experimental attempts to devise one[15]. Conclusive evidence that an anomalous metal lies at the zero-temperature limit of a strange metal would be a major result.

The present study leaves several questions open. First, on a technical level, it seems that control of the patterning process was key to Yang and colleagues' findings. An earlier paper by members of the same group reported a similar system[16], but strange-metallic behaviour was observed in the present study only when the patterning was made more uniform than that of the previous study[2]. Quantitative investigation of the interactions between nodes could address this issue.

Second, assuming that strange-metallic behaviour can lurk in sufficiently disordered superconductors, why hasn't it been routinely observed in the panoply of materials and systems studied so far? An experiment reported last year counters this concern: nanopatterned films of the superconductor iron selenide also show electrical resistance with a linear dependence on temperature, suggesting another instance of strange-metallic behaviour in a system characterized by bosons[17].

These findings are as fascinating as they might be challenging to reconcile. The work of Yang *et al.* represents an intriguing opportunity to unite two frontiers – strange metals and disordered superconductors – whose collective description would represent a major step forward for condensed-matter physics.

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Archaeology

Beads reveal long-distance connections in early Africa

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Beads made from ostrich eggshells, produced by people over the past 50,000 years, provide evidence for a long period of social connection between eastern and southern Africa, followed by isolation and then reconnection. **See p.234**

"Let's keep in touch!" is a phrase commonly used to indicate a social bond formed between people. Ideally, such bonds are maintained even across long distances and over the passage of time. Today, keeping in touch is easy, whether through a call, a text message, social media or the now omnipresent virtual meeting. However, what traces might remain of signs of social relationships from 50,000 years ago, and why is investigating these ancient relationships useful? Miller and Wang[1] present data on page 234 suggesting that small beads made of ostrich eggshell (OES) and fashioned into jewellery were exchanged between groups across eastern and southern Africa as part of long-distance social connections over the past 50,000 years. These relationships, across immense distances, then broke down about 33,000 years ago – around the same time as major climate changes occurred – and were renewed only about 2,000 years ago, the authors suggest.

Ostrich-eggshell beads were (and still are) commonly used to make jewellery, such as headbands and necklaces, as well as to decorate clothing and bags[2]. Studies indicate that the exchange of OES beadwork is a key way to forge social ties between different groups of foragers, both in modern and in historical times. These ties between communities might have provided social safety nets for groups falling on hard times and contributed to interactions that led to the spread of genes and ideas[3,4]. Similar practices of bead exchange are cautiously considered when studying the deeper past. OES beads – and the jewellery they were used for – are thought to be items that would probably have been exchanged between socially connected groups, and therefore indirectly suggest the presence of past social networks.

Archaeologists study bead characteristics, such as bead diameter and geochemistry, as a way to trace bead movements across past landscapes and to explore past social connections[5–7]. Miller and Wang emphasize the need to consider the features of individual beads because each step in the manufacturing process reflects deliberate choices that can be influenced by social and cultural norms. These norms, or styles, are typically shared between socially connected groups and diverge when groups have weaker social links, or none at all. Differences in bead diameter can therefore be considered stylistic choices and can inform our understanding of past social connections, because groups that are socially connected can be assumed to produce beads with similar