Pebbles in the nodal pond

Jan Zaanen

Rippling patterns of electron waves in a copper oxide match the expectation for a certain kind of excitation — another step towards understanding why copper oxides superconduct at far higher temperatures than other materials.

Perhaps the first image that comes to mind when thinking about waves is the interference pattern on the surface of a pond after some pebbles are thrown in. According to quantum physics, electrons can behave like waves, and so give rise to similar phenomena: the 'pebbles' are imperfections in the medium, scattering the electron waves, and the 'ripples', or interference fringes, can be seen through a scanning tunnelling microscope (STM). On page 592 of this issue, McElroy *et al.*[1] show that such patterns can be used to study the details of a special kind of electron wave — so-called nodal fermions — that occurs in high-temperature superconductors.

Scanning tunnelling microscopes are remarkable machines. Tuned the right way, they can image the wavefunctions (essentially, the probability distributions) of electrons directly. Beautiful images have been captured of electron waves, for example, in the vicinity of imperfections on the surfaces of simple metals (Fig. 1a), and surrounding artificially tailored nanostructures such as 'quantum corrals' (see, for example, ref. 2). These phenomena have long been understood. Far more exciting from the perspective of fundamental physics is the application of STM imaging in the context of high-temperature superconductivity.

Although discovered more than 15 years ago, high-temperature superconductors continue to fascinate physicists. They are copper oxides that superconduct — that is, offer no resistance to the flow of electric current — at unusually high temperatures (typically 100 K), and their electrons behave very differently from those in simple metals[3]. It seems that there are unusually strong interactions between the electrons in a high-temperature superconductor, but the full story is still a mystery.

Images from an STM, like those recorded by McElroy *et al.*[1], would show wave-like patterns if the high-temperature superconductors behaved as simple metals. But in fact the real-space maps look completely different. Instead of a 'pebbles-in-a-pond' pattern, they show a pattern composed of irregular but basically straight lines, forming a more or less orderly texture[1,4], like fabric woven from raw silk (Fig. 1b). When images such as these were first seen[5], many experts took them to be evidence for 'stripes'. Stripes are a form of order in copper oxides, known to compete with superconductivity, that cause the electrons to come to a standstill in regular patterns. Although stripe signals might be hidden in the data[5,6], it is now clear that most of what is seen has nothing to do with stripes. Instead, the raw-silk texture is caused by electron waves being scattered by imperfections. But these waves are very different from the 'pebbles-in-a-pond' waves in simple metals — they are 'nodal fermions', special electron waves associated with the unconventional nature of the superconducting state in copper oxides.

If the raw-silk patterns are associated with nodal waves, they should be composed of a total of 16 different modulations, each having a unique dependence on the energy of the scattered electrons. Using Fourier analysis to nail down the precise properties of the waves, McElroy *et al.* have identified all of these modulations in their STM data and have reconstructed in great detail the behaviour of the underlying nodal fermions. Their results confirm earlier observations of these nodal states in photoemission experiments, but go far beyond them in terms of the detail revealed.

The existence of nodal fermions is implied by the 45-year-old Bardeen–Cooper–Schrieffer theory of conventional superconductivity (extended to include *d*-wave symmetry). So their detection by McElroy *et al.* might seem unexciting. But in fact there is more to it. This work is an experimental innovation that has opened up a new window of observation on the mystery of high-temperature superconductivity. Although the nodal waves might seem at first sight to be quite conventional, there is evidence suggesting that they are much more fragile than the electron waves in normal metals. It appears that they behave like quantum waves only when the system as a whole is in a macroscopic quantum state — that is, when it is superconducting[7].

McElroy and colleagues' experiments have sprung a great surprise, showing just how different these excitations are: when the electron energy approaches that of the superconducting gap (associated with the short timescale on which the physics giving rise to superconductivity originates), the STM patterns change in a sudden and dramatic way. The raw-silk texture disappears, and is replaced by a very different pattern (Fig. 1c)[1,8]. I call these patterns 'quantum salad-dressing'[9]: there seem to be two very different states of electron matter present that, like oil and vinegar, do not want to mix. These findings suggest that, at high energies, the electron system reveals its true nature as a strongly interacting quantum fluid, which is expected to bear some similarities to a classical fluid. Only when the energy becomes

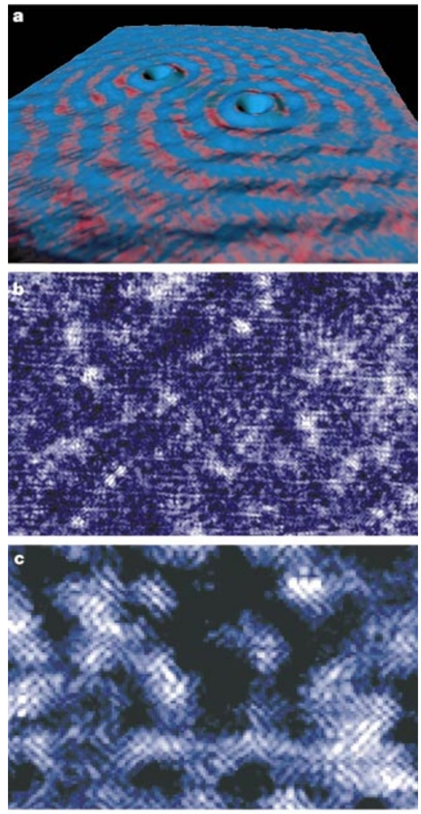

Figure 1 **Electron waves. With a scanning tunnelling microscope, quantum-mechanical wave patterns can be observed directly: when electrons in conventional metals such as copper scatter off imperfections in the crystal lattice** (a), **a pattern of ripples forms[2]. McElroy *et al.*[1] have similarly detected interference patterns in a high-temperature copper-oxide superconductor** (b). **At first sight, these do not look like waves, but more like fabric woven from raw silk. In fact, these patterns are caused by special electron waves, called nodal fermions, that occur in high-temperature superconductors. McElroy *et al.* also show that, contrary to theoretical expectations, the patterns suddenly change when the electron energy is raised** (c), **shedding new light on the mysterious nature of electron states in copper-oxide superconductors.**

low enough does the quantum coherence of the superconducting ground state take charge, and excitations then act like 'simple' quantum-mechanical waves.

The great potential of this technique lies in its unique sensitivity to the coherent, wave-like nature of the excitations. It should now be possible to investigate some of the burning issues in the field. For instance, the interplay between stripes and nodal fermions is a contentious issue. Although the presence of a very weak remnant of stripe order in the best superconductors is still debated[1,6], stripes usually appear only when superconductivity is suppressed. Magnetic fields are the natural enemy of superconductivity: patches of stripe-like order around lines of concentrated magnetic flux (vortices) have already been detected in STM images[10,11]. Do stripes destroy the nodal fermions? Nobody knows, but using STM imaging it should be possible to take a direct look.

An intriguing question is what happens to the raw-silk texture when the temperature rises. There are indications that increasing temperature is detrimental to nodal excitations, but so far the evidence is rather indirect[7]. The capacity of the STM to probe quantum coherence is unique, and I anticipate spectacular results in this area in the near future. If our present understanding is correct, the raw-silk texture should disappear quickly with rising temperature, telling an exciting story about the delicate role of quantum physics in this strange electron system. ■

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Developmental biology

How neurons avoid derailment

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During development, neurons extend thin protrusions that must choose between alternative routes. A study of this process in fruitflies unites two previously disparate protein families.

In many ways, the developing nervous system resembles a city at rush hour, with large numbers of neurons — up to 10^{12} in humans — extending thin protrusions called axons that take highly specific routes to reach their destinations. This ability of axons to choose one particular path from many alternatives is essential for precise wiring of the nervous system. On page 583 of this issue, Yoshikawa and colleagues[1] present the next chapter in the unfolding story of how axons find their way.

The central nervous system of the fruitfly (*Drosophila melanogaster*) embryo provides a simple example of pathway selection, as axons growing across the midline of the nervous system — thereby connecting the left and right halves of the animal — choose between two alternative routes. Roughly half the axons in each body segment choose the anterior route, establishing an anterior axon bundle (commissure); the other half take the posterior path, establishing a posterior commissure.

Ideas about the mechanism behind this decision began to take shape in 1999, from work by Bonkowsky *et al.*[2] on Derailed, a member of the well-studied RYK family of receptor proteins that span the cell membrane. They found that Derailed is both necessary and sufficient to direct axons through the anterior commissure. It is expressed specifically on axons that choose the anterior route; without this protein, the axons take a variety of paths across the midline, often wandering between the commissures. Moreover, if Derailed is experimentally misexpressed in neurons that normally send axons through the posterior route, these axons switch to the anterior path.

To further explore how Derailed works, Bonkowsky *et al.* used a soluble, labelled version of the extracellular portion of the protein as a probe on tissue. This detects any cell-surface binding partners (ligands) for Derailed. (In fact, it appears to measure the distribution of any 'free' ligand — ligand that is not already bound to natural Derailed — a detail that will become more important below.) In this way, the authors detected a potential binding partner specifically in the posterior commissure. The implication was that Derailed directs axons into the anterior commissure by repelling them from the region of ligand expression in the posterior commissure. But the identity of the Derailed ligand (and the ligands of RYK-family receptors in general) remained unknown.

Yoshikawa *et al.*[1] now fill this gap in our knowledge of the Derailed ligand, with the revelation that it belongs to the Wnt family of secreted signalling proteins. Wnt proteins have long been known to be essential in animal development: they regulate cell-fate determination, cell proliferation and movement, and tissue polarity[3,4]. Inappropriate activation of Wnt signalling leads to colorectal and other cancers in humans[5]. Moreover, Wnts regulate the formation of connections between neurons and their targets (other neurons or muscle)[6,7]. The signalling pathways through which Wnts control cell fate and tissue polarity have been studied in depth, but how they exert their effects on neuronal projections has largely been a mystery. By showing that *Drosophila* Wnt5 functions through Derailed, Yoshikawa *et al.* uncover a role for Wnt signalling in axon guidance. Their findings also reveal a connection between two previously disparate but large fields of research — the study of Wnt proteins and of RYK-family members.

Yoshikawa *et al.* were led to Wnt5 by using a clever genetic screen for regulators of Derailed activity. As Derailed misexpression switches axons that would normally project through the posterior commissure into the anterior commissure, the authors reasoned that reducing the function of genes that promote Derailed signalling might cause these axons to switch back. After systematically examining animals that had reduced function in many different genes, the authors found that reducing the activity of the *wnt5* gene lessened the ability of misexpressed Derailed to switch axons into the anterior commissure. Further genetic analysis showed that *wnt5* mutants have similar axon-guidance defects to *derailed* mutants, consistent with the idea that these genes work together during normal development. Moreover, overexpressing Wnt5 throughout the midline of otherwise normal animals completely prevented the anterior commissure from forming, whereas Wnt5 overexpression in *derailed* mutants had no such effect. These results imply that Wnt5 repels Derailed-expressing axons.

So, Wnt5 and Derailed function together to guide axons into the anterior commissure. But do these proteins actually interact? This seemed likely, given that the extracellular portion of Derailed contains a region that is related to a previously characterized Wnt-binding domain. To find out for sure, Yoshikawa *et al.* used the Derailed extracellular domain to probe *Drosophila* extracts, and found that this domain did indeed bind to Wnt5. Moreover, the soluble, labelled extracellular domain of Derailed (used previously[2] to probe for Derailed ligands) failed to bind to *wnt5* mutant embryos, but bound both commissures when embryos overexpressed Wnt5. So, genetic and biochemical data indicate that