Condensed-matter physics

Electrons go loopy in a superconductor

Morten H. Christensen & Turan Birol

Measurements indicate that electrons move in loops between the atoms of an intriguing class of superconducting material. Such dynamics breaks key symmetries of the crystal lattice — suggesting the material hosts a rare state of matter. **See p.245**

The exotic properties of materials can often be traced to the collective behaviours of their electrons. These behaviours give rise to different electronic phases of matter, which physicists identify by studying symmetries of the material: a broken symmetry signals a new electronic phase. One such phase is a charge density wave, in which electrons organize into a pattern of high and low concentrations of electric charge. On page 245, Mielke *et al.*[1] report that a material belonging to a group of compounds known as kagome superconductors[2,3] exhibits a charge density wave with electron dynamics that break time-reversal symmetry — the electronic state is different depending on whether time is moving forwards or backwards. Writing online in *Nature*, Nie *et al.*[4] show that a charge density wave alters the spatial symmetries in the crystal lattice of a related kagome superconductor.

Superconductors are materials that conduct electricity without loss — a property that can be attributed to their electrons forming pairs known as Cooper pairs. Both groups studied forms of the kagome superconductors AV_3Sb_5, in which V is vanadium, Sb is antimony and A can be potassium (K), caesium (Cs) or rubidium (Rb). The vanadium atoms are arranged in a single layer on a kagome crystal lattice; this is made up of corner-sharing triangles and is named after a Japanese method of wicker-basket weaving. The layer is interwoven with two different lattices of antimony atoms, and wedged between hexagonal lattices of A atoms (Fig. 1a).

Materials with kagome lattices have fascinating properties that arise because the wavefunctions of their electrons (which represent the states of the electrons, including their spatial extent) can wind around themselves to make knots. This can result in, for example, topologically insulating phases, in which the surface of a material is electrically conductive, but its interior is an insulator[5].

The fact that a charge density wave occurs in KV_3Sb_5 had already been established[6]. However, Mielke and colleagues' results show that this wave is unusual in that the electrons break time-reversal symmetry. The most natural explanation for this is that the electrons are moving in clockwise or anticlockwise loops between the atoms, forming a phase known as a loop-current phase (Fig. 1b). That this causes time-reversal symmetry to break can be understood as follows: take a video of a loop-current phase and play it in reverse, and the state in the backwards video will differ from the state that was originally filmed.

To detect signatures of the time-reversal-symmetry breaking, the authors used a technique called muon spin rotation and relaxation spectroscopy. Muons are elementary particles similar to electrons, except that they are more than 200 times heavier and have a finite lifetime. At the end of this lifetime, they decay into lighter particles, including positrons (the antiparticles of electrons).

When muons are injected into a material, they interact with their local environment through their internal angular momentum. This angular momentum is sensitive to electronic current loops, so that, as the muons decay into positrons, differences in the way the angular momentum evolves can be detected, signalling the presence of current loops. Mielke *et al.* observed changes in the evolution of the muons at different temperatures, and concluded that time-reversal symmetry is broken at the temperature at which the charge density wave appears.

Loop-current phases have long been suggested to underlie exotic phenomena across a range of materials[7,8]. In the kagome lattice, more than 180 types of loop current have been proposed to exist[9]. Mielke and co-workers' findings provide invaluable insights for the task of narrowing down the list of possible candidates in KV_3Sb_5. Many complementary experimental approaches are also being used to study these phases in all three vanadium antimony kagome compounds (see, for example, refs 10–12). Nie *et al.* undertook one such study by probing a combination of elastic and electrical resistive properties to try to better understand the nature of the charge density wave in CsV_3Sb_5.

The kagome lattice has a six-fold rotational symmetry, which means that rotating it by 60° will not alter the shape of the lattice. As a consequence, any observable physical quantity related to this lattice also has a six-fold symmetry. Surprisingly, Nie and co-workers' findings indicate that the charge density wave breaks this symmetry, implying that the electrons move along a preferred axis in the lattice. This discovery is key to understanding the unconventional superconductivity in these

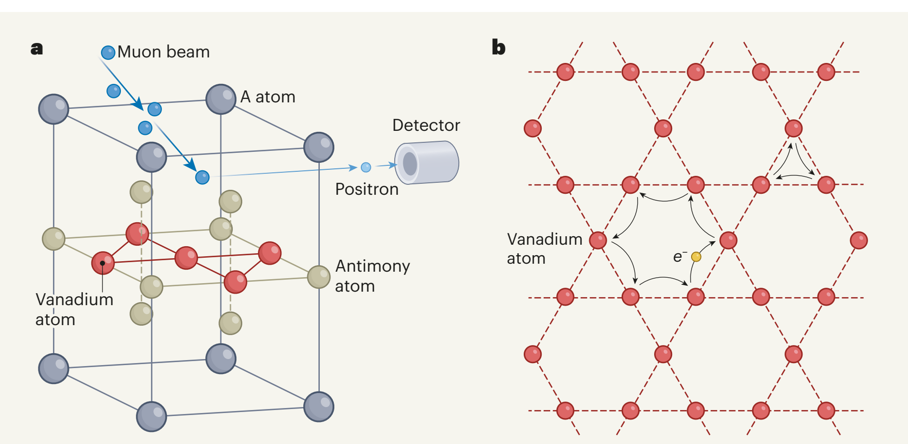

Figure 1 | Probing electron dynamics in a kagome superconductor. a, Materials of the form AV_3Sb_5 (where A can be potassium, caesium or rubidium) have a crystal lattice comprising a single layer of vanadium (V) atoms arranged as an array of corner-sharing triangles known as a kagome lattice, between layers of antimony (Sb) and A atoms. Mielke *et al.*[1] showed that, in KV_3Sb_5, electrons (e^-) break time-reversal symmetry, which is unbroken only if the dynamics is the same for time moving forwards and backwards. To observe the breaking of time-reversal symmetry, the authors injected the material with muons, which are elementary particles that decay into lighter particles, including positrons (the antiparticles of electrons). Nie *et al.*[4] used a different approach (not shown) to demonstrate that spatial symmetries are broken in CsV_3Sb_5. **b**, Electrons can break time-reversal symmetry by moving in closed loops (black arrows) between the atoms. In the example shown, if time is reversed, the arrows are flipped, resulting in a different phase.

compounds, which requires first grasping the nature of the charge-density-wave phase from which it emerges.

The observation of time-reversal symmetry breaking is essential to our efforts to describe exotic and rare types of superconductivity. In particular, Mielke and colleagues' work provides a key ingredient for developing a model to describe the vanadium antimony kagome systems. Among the crucial questions to be addressed is the relative importance of the reorganization of electrons compared with the vibration and displacement of the atoms in the lattice. Although much of the theory of charge density waves relies on these atomic displacements, the very existence of a loop-current phase implies that the electrons have a central role, which is also in line with Nie and colleagues' findings.

A robust model must also reconcile the presence of time-reversal-symmetry breaking with superconductivity. This, in itself, is an exciting prospect for the broader field of topological superconductivity, in which the Cooper pairs take on the topological properties of the electronic wavefunctions. As well as being fascinating, topological superconductors might have future applications in quantum computing. The results of these two studies clearly bring fresh insight into symmetry breaking in kagome superconductors, and this will no doubt motivate further research into these intriguing materials.

Morten H. Christensen is at the Niels Bohr Institute, University of Copenhagen, 2100 Copenhagen, Denmark. **Turan Birol** is in the Department of Chemical Engineering and Materials Science, University of Minnesota, Minneapolis, Minnesota 55455, USA.
e-mails: mchriste@nbi.ku.dk; tbirol@umn.edu

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Neuroimmune interactions

Neurons in the brain recall gut inflammation

David Brea & Henrique Veiga-Fernandes

The nervous and immune systems interact in a bidirectional manner. It emerges that inflammation in the body activates brain cells that, when later reactivated, can trigger a recapitulation of the inflammatory response.

Interactions between the nervous and the immune systems have been a topic of great interest over the past few decades. Neuronal signals can affect immune functions, and immune cells can modulate the activity of neurons in the brain and spinal cord, or in the rest of the body (known as the periphery), in health and disease[1,2]. Writing in *Cell*, Koren *et al.*[3] demonstrate that inflammation in the abdominal cavity results in the stimulation of certain neurons in a brain area called the insular cortex, or the insula. Artificial reactivation of these 'immune-imprinted' neurons is sufficient to generate organ-specific recall of inflammatory responses that resemble the initial inflammatory episode.

Using a model of inflammatory bowel disease (in which a chemical called DSS is given to mice in their drinking water to induce intestinal inflammation), the authors investigated whether intestinal inflammation leads to the activation of certain brain areas. To do this, they used mice genetically engineered to express a fluorescent marker molecule in active (but not inactive) neurons when the animals were treated with the drug tamoxifen. The authors compared the fluorescent labelling in the brains of tamoxifen-treated mice given DSS with that in the brains of control mice, which were treated with tamoxifen but not with DSS. Neurons activated during episodes of bowel inflammation were identified in the insula, a region in the cerebral cortex that is involved in sensory processing and motor control (Fig. 1a).

The authors injected an engineered virus into the insula of the genetically engineered mice so that the neurons that were activated during bowel inflammation could be specifically reactivated by treating the animals with a small molecule called

From the archive

The discovery of a key defence response, and a collection of items from an inventor that highlights advances in photography.

100 years ago

Life of Elie Metchnikoff, 1845–1916. By Olga Metchnikoff — It was at Messina ... that what Metchnikoff regarded as the great event of his scientific life occurred. It is described by him in his own words as follows: — "One day, when the whole family had gone to a circus, I remained alone with my microscope, observing the life in the mobile cells of a transparent starfish larva, when a new thought suddenly flashed across my brain. It struck me that similar cells might serve in the defence of the organism against intruders. I felt so excited that I began striding up and down the room ... [I]f my supposition was true, a splinter introduced into the body of a starfish larva ... should soon be surrounded by mobile cells ... I fetched some rose-thorns and introduced them under the skin of some beautiful starfish larvae ... I was too excited to sleep that night in the expectation of the result of my experiment, and very early the next morning I ascertained that it had fully succeeded. That experiment formed the basis of the phagocyte theory".

From *Nature* 9 February 1922

150 years ago

I trust you will kindly allow me space for a few lines on the subject of some rare specimens connected with the History of Photography, now in the possession of Madame Nièpce de St. Victor, whose husband it will be remembered was the first to employ glass, and a transparent medium (albumen) for the purposes of photography, thus discovering, to a great extent, the process of Photography as it exists at the present day. The first glass negative, or rather *cliché*, Madame Nièpce possesses, as likewise prints executed in 1848. Nièpce de St. Victor was ... one of those who have worked hard to secure natural colours in the camera, some very perfect specimens – photographs of coloured dolls – which prove distinctly that the solution of the problem is not impossible, as many believe, are also included in the Nièpce collection.

From *Nature* 8 February 1872