Condensed-matter physics

Superconductivity probed in twisted graphene

Paritosh Karnatak & Christian Schönenberger

A superconducting state can be induced in a twisted carbon-based material, but it can't be described with conventional theory. A technique using high-frequency circuits could reveal the mechanism behind this fascinating state. **See p.93 & p.99**

When layers of the carbon-based material graphene are stacked together and twisted relative to each other at special angles, their electrons behave as if they have very large masses, slowing them to a near standstill[1,2]. Depending on the density of the electrons, this leads to one of two states. The electrons either repel each other strongly, yielding an electrically insulating state, or they pair up to form a superconducting state – one in which electrical resistance becomes zero. But the nature of this superconductivity is puzzling and it's not known exactly why the electrons pair up. In two papers in *Nature*, Tanaka *et al.*[3] (page 99) and Banerjee *et al.*[4] (page 93) investigate superconductivity in twisted graphene using circuits that can detect subtle properties of these electron pairs.

Typically, like charges repel each other, whereas opposites attract. However, in a periodic lattice, such as a crystal, the behaviour of electrons is determined by quantum mechanics. This can result in changes in the sign of their charge or in their mass, and they become 'quasiparticles'. Complex interactions ensue: the strength with which these quasiparticles repel each other can vary drastically between weak and strong, and quasiparticles with like charges can even attract each other enough to form pairs, which is what happens in a superconductor. Periodic lattices can therefore be engineered to induce fundamental changes in the interactions between electrons (or the quasiparticles they form), leading to the emergence of new states of matter[1].

Graphene, which comprises a single layer of carbon atoms arranged in a honeycomb lattice, is an excellent material for effecting such changes – especially when it is stacked and twisted such that superconductivity can emerge[2]. One reason that superconductors made from twisted graphene are interesting is that they share key similarities with a class of materials known as high-temperature superconductors, which potentially have practical applications. Another reason to study twisted-graphene-based superconductors is that they are easier to probe than other superconducting materials, because they are straightforward to fabricate, and their electron density can be tuned easily.

In the past few years, researchers have advanced our understanding of superconductivity in twisted graphene by studying a key property known as the superconducting gap. This gap describes a range of energies that only pairs of electrons can have – single electrons cannot exist alone with energies in this range. Experiments designed to investigate this gap have revealed that the superconductivity in these graphene-based materials is unconventional – it does not fit neatly into any theoretical framework derived so far[5,6].

To better understand this behaviour, Tanaka *et al.* studied superconductivity in twisted bilayer graphene and Banerjee *et al.* in twisted trilayer graphene, by measuring a property called the kinetic inductance. Kinetic inductance arises because there is an energy associated with the electron pairs' motion, and it depends on the pairs' mass and density. It reveals, therefore, crucial details about the superconductor. Kinetic inductance has previously been studied in twisted-graphene systems[7,8]. But this approach requires the measurement of aspects of the electrons' quantum-mechanical wave-like nature.

Another strategy involves measuring a property called impedance, which quantifies a material's opposition to the flow of an alternating current. In superconductors, the kinetic inductance gives rise to this impedance; the electron pairs are continually accelerated and decelerated by the alternating current, and this costs energy, making them oppose changes in the current. In low-frequency circuits, impedance is zero, so Tanaka *et al.* and Banerjee *et al.* instead used high-frequency circuits (Fig. 1).

Both groups measured kinetic inductance by incorporating twisted graphene into a type of circuit called a resonator, which responds strongly to microwave signals at a particular (resonance) frequency. Banerjee and colleagues' circuit was engineered to have a resonance of around 350 megahertz, whereas Tanaka and colleagues' circuit was tuned to resonate at around 4 gigahertz. Such high-quality resonators are known for their ability to measure tiny changes in inductance[9].

The authors' inductance measurements allowed them to estimate a quantity called superfluid stiffness, which is related to the inverse of the kinetic inductance. Superfluid stiffness can reveal clues about the superconducting gap's symmetries – the ways in which it changes when the momenta of the quasiparticles undergo transformations, such as rotation or reflection. These symmetries can offer key insights into how the electrons

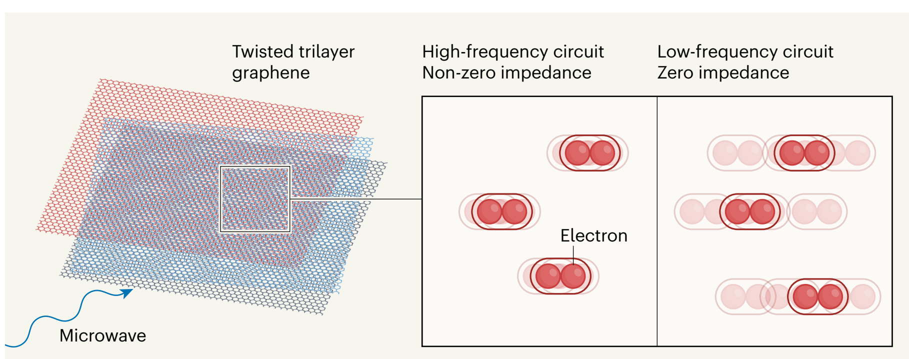

Figure 1 | Superconducting behaviour in twisted graphene. Stacking and twisting sheets of the carbon-based material graphene can give rise to a superconducting state, in which electrons pair up and electrical resistance becomes zero. Tanaka *et al.*[3] studied superconductivity in twisted bilayer graphene (not shown) and Banerjee *et al.*[4] studied it in trilayer graphene. To do so, they measured a property called kinetic inductance, which arises because there is an energy associated with the electron pairs' motion, and depends on the pairs' mass and density. It therefore reveals crucial details about a superconductor. The kinetic inductance gives the material an impedance – a measure of its opposition to the flow of an alternating current. Both groups incorporated their material into high-frequency circuits stimulated by microwave signals. The electron pairs undergo tiny, rapid oscillations, which generates an impedance that can be used to calculate kinetic inductance. Such measurements cannot be undertaken with low-frequency circuits, in which impedance is nearly zero as a result of the larger and slower oscillations of the electron pairs.

pair up, and might enable the formation of quasiparticles for use in quantum computers.

If the superconducting gap stays the same under any rotation, the superfluid stiffness is expected to have an exponential dependence on temperature. However, this dependence can deviate from an exponential if the gap is more complex; for example, if there are 'nodes' at which the gap closes. In this case, single electrons are permitted to have energies and momenta that wouldn't be allowed in the absence of the nodes. Both groups of authors report deviations from the exponential dependence, but there are subtle differences: Banerjee *et al.* found that the superfluid stiffness had a linear dependence on temperature in twisted trilayer graphene, which could indicate a nodal gap, whereas Tanaka *et al.* found a power-law dependence for twisted bilayer graphene, which they explain by a gap that is not uniform in shape.

Tanaka *et al.* also report a superfluid stiffness that is too large to come from the nearly stationary quasiparticles in twisted bilayer graphene. Instead, the authors attribute it to quantum geometry – a property that can increase the velocity of quasiparticles that would otherwise be at a standstill, thus potentially increasing the superfluid stiffness[10,11]. By contrast, although Banerjee *et al.* do not neglect quantum geometry, the authors largely explain their results by considering how the electrons repel each other in twisted trilayer graphene.

Understanding the 'glue' that binds the electrons in a superconductor is a key step towards the ability to custom-design superconductors for various technological applications. However, directly probing the pairing mechanism is difficult, and researchers have worked for decades to understand the mechanisms in different superconductors. The search continues, but the development of sensitive experimental probes, such as the two reported by the authors of the studies, will surely accelerate its progress.

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Molecular biology

The X chromosome influences brain ageing

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Older female mice show poor spatial memory when their paternal X chromosome is inactive and only the maternal copy is active. This phenomenon could be responsible for variation in age-related cognitive decline among women. **See p.152**

In her 1969 autobiography *I Know Why the Caged Bird Sings*, poet and author Maya Angelou remembers her mother as both a hurricane and a rainbow, symbolizing the contrasting nature of the extremes of their relationship. On page 152, Abdulai-Saiku *et al.*[1] report a study in mice showing that gene-expression patterns that are passed from mothers to daughters might have similarly contrasting effects on memory at different stages of life. In doing so, they present new evidence for the paradigm of 'inter-female' variation.

In mammals, most chromosome pairs are the same between males and females, but one pair, the sex chromosomes, is different. Typically, females have two X chromosomes (XX), whereas males have one X chromosome and one Y chromosome (XY). Sex chromosomes not only influence a developing embryo's sex and the formation of eggs or sperm in later life, but also differences in anatomy, physiology and disease susceptibility between the sexes. Researchers are beginning to narrow down the causes of these effects with startling precision.

For instance, women are more prone than men to autoimmune diseases such as lupus, partly because they typically carry two X chromosomes. The resulting elevated level of the X-chromosome gene *Tlr7* is a probable contributor in this predisposition[2]. By contrast, men seem to benefit from the presence of the Y chromosome: it can be lost with age in some cells, which is associated with increased risk of Alzheimer's disease[3]. Unravelling which sex-chromosome genes are responsible for these effects is a major goal in personalized medicine.

The number of X and Y chromosomes is important for sex differences, but another influential process is genomic imprinting. Most genes are expressed from both copies of a chromosome, one of which is inherited from the mother and the other from the father. But some genes are expressed only from the maternal copy or only from the paternal one. Most of these 'imprinted' genes reside on the autosomes (non-sex chromosomes) and are therefore expressed at the same level between the sexes. However, this is not the case for imprinted genes on the X chromosome. In general, only females inherit an X chromosome from their father, so an imprinted gene expressed only from the paternal X chromosome (Xp) will only be expressed in daughters – which might contribute to sex differences.

Females and males inherit a maternal X chromosome (Xm), but differences can arise here from a process called X-chromosome inactivation, in which either the Xp or Xm in each cell of a female individual is repressed, or silenced. This inactivation is through epigenetic mechanisms – modifications to the genome that do not alter the DNA sequence but regulate gene expression. It prevents females from having twice as many X-chromosome gene products as males have. In males, an imprinted gene that is expressed only from Xm will be expressed in all cells, but because of X-inactivation, in females it will not.

If X-inactivation is completely random, Xm is silenced in half of all cells in a female, and half of cells will express the Xm-imprinted gene. However, if X-inactivation is skewed, the proportion will deviate, with more or less than half of the cells expressing the gene, depending on whether X-inactivation is skewed towards Xp or Xm. Because skewed X-inactivation is common in humans, differences can arise not only between the sexes but also between individual women. Abdulai-Saiku *et al.* investigated how the X chromosome influences brain ageing and cognition in mice, and provide compelling evidence that X-imprinting could indeed create inter-female variation.

The X chromosome contains many genes that are expressed in the brain, and a disproportionate number of genes involved in intellectual disability map to the X chromosome[4]. A role for X-imprinting in cognition was first suggested in the 1990s, as a result