News & views

Condensed-matter physics

Superconductivity survives a strong magnetic field

Yi-Ting Hsu

A material system known as magic-angle twisted trilayer graphene exhibits superconductivity. The observation that this superconductivity persists under a strong magnetic field could lead to advances in quantum computation. See p.526

Quantum phases of matter known as superconductors transmit electrical current with zero resistance. Microscopically, this phenomenon arises from the fact that it is energetically favourable for electrons to bind into two-electron states, dubbed Cooper pairs, that move collectively and cooperatively without energy loss. A Cooper pair is said to be spin-singlet when its two electron spins (intrinsic angular momenta) point in opposite directions and the pair has a total spin of zero, whereas spin-triplet Cooper pairs have a total spin of 1, and the two electron spins can be aligned in the same direction. Most experimentally known superconductors have spin-singlet Cooper pairs; these include metals (such as lead and niobium) that demonstrate conventional superconductivity, and cuprates (layered copper oxide compounds) that exhibit unconventional superconductivity. On page 526, Cao *et al.*[1] report evidence for unconventional superconductivity associated with spin-triplet Cooper pairs.

Two-dimensional spin-triplet superconductors have attracted widespread attention because many of them are predicted to host exotic zero-energy excitations called Majorana zero modes. A well-studied example of such a superconductor is a 2D chiral *p*-wave superconductor[2]. This system breaks time-reversal symmetry (its physical properties would change if the direction of time were reversed), and Majorana zero modes are expected to exist in the cores of vortices (threads of magnetic flux) when a magnetic field is applied perpendicular to the system. Majorana zero modes are promising candidates for topological qubits — the building blocks of a type of 'fault-tolerant' quantum computation known as topological quantum computation[3,4]. Therefore, given that most known spin-triplet superconductors are 3D, experimentally established 2D spin-triplet superconductors are much desired.

In the past four years, experimentalists have started to probe quasi-2D systems consisting of stacked but slightly misaligned layers of graphene — single sheets of hexagonally arranged carbon atoms (see refs 5 and 6, for example). Such systems have rapidly gained attention because they can be easily tuned experimentally and host a rich variety of correlated quantum phases. Earlier this year, superconductivity was reported in twisted trilayer graphene[7,8], which comprises three stacked graphene layers in which the top and bottom layers are rotated at angles of θ and $-\theta$, respectively, relative to the middle layer (Fig. 1). By tuning the value of θ, the physics in twisted trilayer graphene can be investigated in regimes ranging from one in which the electrons are essentially weakly coupled to each other to one in which they are strongly coupled.

Cao *et al.* studied twisted trilayer graphene when θ is equal to the 'magic' angle of approximately 1.6° — the angle at which the system is expected to enter the strong-coupling regime. They observed superconductivity in such magic-angle twisted trilayer graphene (MATTG), and studied the spin properties of this superconductivity. Specifically, they measured the electrical resistance of MATTG at low temperatures (down to below 1 kelvin) and discovered a zero-resistance phase. They then applied a magnetic field to MATTG in the plane of the graphene layers and identified the critical field strength at which the observed superconductivity vanishes. They found that the superconductivity survives up to a surprisingly high critical field strength of nearly 10 tesla, which is not expected for spin-singlet superconductors.

Magnetic fields couple to the orbital angular momentum and spin of Cooper pairs in a superconductor. When a strong in-plane field is applied to a quasi-2D superconductor, the orbital effect is negligible. However, above a field strength called the Pauli limit, the spin effect tends to cause spin-singlet Cooper pairs,

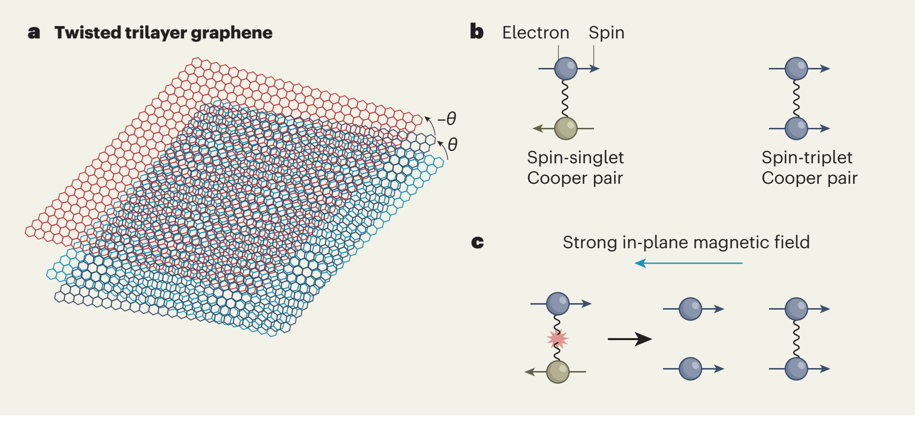

Figure 1 | Superconductivity in twisted trilayer graphene. a, Magic-angle twisted trilayer graphene (MATTG) is a system of three sheets of hexagonally arranged carbon atoms. The top and bottom sheets are aligned, and the middle sheet is rotated by an angle θ of approximately 1.6° relative to the other two sheets. **b**, Superconductivity results from electrons binding into two-electron states called Cooper pairs. In a spin-singlet Cooper pair, the electron spins (intrinsic angular momenta) point in opposite directions; in a spin-triplet Cooper pair, they can be aligned in the same direction. **c**, In the presence of a strong magnetic field in the plane of the material, a spin-singlet Cooper pair breaks apart because a phenomenon known as the Zeeman effect causes the spins to align in the same direction. By contrast, a spin-triplet Cooper pair can survive such a field. Cao *et al.*[1] found that superconductivity in MATTG persists under a strong in-plane magnetic field, and suggest that this observation is evidence for spin-triplet Cooper pairs.

which have oppositely aligned electron spins, to break apart, because a phenomenon known as the Zeeman effect causes the spins to point in the same direction (Fig. 1). By contrast, spin-triplet Cooper pairs that have electron spins aligned in a single direction parallel to the field are compatible with such a spin effect and are not bound by the Pauli limit. The in-plane critical field strength measured by Cao *et al.* in MATTG is two to three times the Pauli limit and is therefore considered evidence of spin-triplet superconductivity.

Cao and colleagues also detected a second superconducting phase that exists at even higher in-plane magnetic field strengths than does the first one, persisting above 10 tesla. On the basis of the resistance behaviour of MATTG when the field strength is increased compared with when it is decreased, the authors suggest that the two phases might be connected by a type of phase transition called a first-order phase transition. Such 're-entrant' superconductivity is reminiscent of that observed in some 3D spin-triplet superconductors, such as uranium rhodium germanium[9] and uranium telluride[10], and in the spin-triplet superfluid (zero-viscosity liquid) helium-3 (ref. 11). This similarity might provide hints about the nature of the two superconducting phases in MATTG.

The evidence reported by the authors for quasi-2D spin-triplet superconductivity in MATTG paves the way for unconventional superconductors that can be manipulated experimentally. High in-plane critical field strengths can typically develop in various ways other than in spin-triplet Cooper pairs. But these sources are unlikely to occur in MATTG owing to the negligible coupling between the spin and orbital angular momentum of electrons in graphene. Nevertheless, further measurements are needed to show whether the orbital structure of the Cooper pairs in MATTG is consistent with spin-triplet superconductivity.

Crucially, being spin-triplet does not imply that the observed superconductivity would be useful for topological quantum computation. Future work needs to study the topological properties of the superconductivity. For instance, researchers should determine whether it breaks time-reversal symmetry — an indication of possible chiral *p*-wave superconductivity. They should also look for direct evidence of zero-energy states in vortex cores, which would signal the presence of Majorana zero modes. The understanding gained from such studies could help physicists to develop promising platforms for topological quantum computation.

Yi-Ting Hsu is in the Department of Physics, University of Notre Dame, Notre Dame, Indiana 46556, USA.
e-mail: yhsu2@nd.edu

1. Cao, Y., Park, J. M., Watanabe, K., Taniguchi, T. & Jarillo-Herrero, P. *Nature* **595**, 526–531 (2021).
2. Read, N. & Green, D. *Phys. Rev. B* **61**, 10267 (2000).
3. Kitaev, A. Y. *Ann. Phys.* **303**, 2–30 (2003).
4. Nayak, C., Simon, S. H., Stern, A., Freedman, M. & Sarma, S. D. *Rev. Mod. Phys.* **80**, 1083–1159 (2008).
5. Cao, Y. *et al. Nature* **556**, 43–50 (2018).
6. Cao, Y. *et al. Nature* **556**, 80–84 (2018).
7. Park, J. M., Cao, Y., Watanabe, K., Taniguchi, T. & Jarillo-Herrero, P. *Nature* **590**, 249–255 (2021).
8. Hao, Z. *et al. Science* **371**, 1133–1138 (2021).
9. Lévy, F., Sheikin, I., Grenier, B. & Huxley, A. D. *Science* **309**, 1343–1346 (2005).
10. Ran, S. *et al. Nature Phys.* **15**, 1250–1254 (2019).
11. Leggett, A. J. *Rev. Mod. Phys.* **47**, 331–414 (1975).

The author declares no competing interests.

Optical physics

A step closer to compact X-ray lasers

Luca Giannessi

Light sources known as free-electron lasers can produce intense X-ray radiation for a wide range of applications. The process usually needs huge particle accelerators, but an experiment shows how to overcome this limitation. **See p.516**

The advent of new tools for investigating our world has always led to discoveries. Light sources called free-electron lasers (FELs) are examples of such tools. FELs can produce radiation in a broad array of wavelengths, including the extreme-ultraviolet[1] and X-ray[2] ranges, and can generate ultrashort pulses, at femtosecond[3] (10^{-15} s) or even attosecond[4] (10^{-18} s) timescales. At these spatial and temporal scales, there is little difference between biology, chemistry and physics, and FELs have revolutionized all three disciplines. FELs have enabled matter to be frozen in place and observed at the microscopic level, allowing scientists to resolve the motion of atoms or electrons, control chemical reactions and follow the dynamics of chemical bonds or energy-transfer processes. On page 516, Wang *et al.*[5] report a milestone in the development of compact X-ray FELs.

FELs generate radiation from a high-energy electron beam traversing an undulator, a long array of magnets of alternating polarity (Fig. 1). The undulator causes the electrons to oscillate transversely, and the oscillating beam emits light at a wavelength proportional to the spatial period of the oscillation divided by the square of the beam energy. Therefore, the beam energy is one of the main parameters used to tune the output wavelength of the FEL light.

Energy is efficiently transferred from the electron beam to the laser light if the beam has a high-enough current and is sufficiently monochromatic — that is, if the electrons have similar energies, follow similar trajectories and emit light with similar properties. When such a high-brightness beam interacts with the electromagnetic field of the light generated inside the undulator, the beam transfers part of its kinetic energy to the laser light. As a result, the light is amplified by several orders of magnitude while propagating through the undulator. FELs therefore require high-energy and high-brightness electron beams to generate intense laser light at short wavelengths, such as extreme-ultraviolet or X-ray wavelengths.

Electron beams are normally accelerated by injecting the electrons into a long sequence of hollow metal structures called resonant cavities, where the particles progressively gain energy by 'surfing' an electromagnetic wave. The final energy depends on the amplitude of the wave (that is, the strength of the accelerating field) and the length of the accelerator. Present technology limits the field strength in accelerating cavities to a few tens of megavolts per metre. Therefore, an accelerator several hundred metres to a few kilometres in length is required to reach the beam energy of several gigaelectronvolts (GeV) needed by an X-ray FEL. High-energy electron beams therefore tend to be available only at large accelerator facilities, limiting the number of scientists who can access FELs or advanced investigation tools needing high-energy electrons.

This restriction is one of the motivations behind the search for alternative ways of producing strong accelerating fields to reduce the footprint and costs associated with accelerators. One promising idea involves exciting an electromagnetic wave in a plasma — an ionized gas — using the high power density of optical lasers[6]. Accelerating fields that are thousands of times stronger than those in conventional accelerating cavities can be generated in a plasma. With such fields, the electron-beam energy required by an X-ray FEL could be reached in a few tens of

Correction

In this article, the magic-angle twisted trilayer graphene shown in Figure 1 was incorrect. This has now been corrected.