in the soil[7]. However, such connections would probably come at a substantial cost in terms of tree-biomass reduction because of the need to divert sugars to fungal partners. The type and abundance of mycorrhizal symbioses vary with soil type and climate[8,9], so if fungal symbiosis is a major consideration in these scenarios, such factors would need to be considered in future implementations of the approach used by Zhang and colleagues.

There is a pressing need to understand the relationship between water availability and the drought tolerance and biomass of forests. It is necessary, therefore, to ask whether the types of change that the authors observed would be able to keep pace with climate changes that occur on longer timescales. For example, will the drought-tolerance capacity of today's saplings suffice for the conditions that these trees might encounter when they reach maturity? It's high time to knock on wood that it will, as well as to continue to investigate the mechanisms that affect forest ecosystems in a changing climate. ■

Sebastiaan Luyssaert *and* **J. Hans C. Cornelissen** *are in the Department of Ecological Science, Faculty of Science, VU Amsterdam, 1081 HV Amsterdam, the Netherlands.*
e-mails: s.luyssaert@vu.nl; j.h.c.cornelissen@vu.nl

1. Parmesan, C. & Yohe, G. *Nature* **421,** 37–42 (2003).
2. Zhang, T., Niinemets, Ü., Sheffield, J. & Lichstein, J. W. *Nature* **556,** 99–102 (2018).
3. Kunstler, G. *et al. Nature* **529,** 204–207 (2016).
4. Bechtold, W. A. & Patterson, P. L. *The Enhanced Forest Inventory and Analysis Program — National Sampling Design and Estimation Procedures.* Gen. Tech. Rep. SRS–80 (US Department of Agriculture Forest Service, 2005).
5. McDowell, N. G. & Allen, C. D. *Nature Clim. Change* **5,** 669–672 (2015).
6. Ruiz-Benito, P. *et al. Glob. Change Biol.* **23,** 4162–4176 (2017).
7. Smith, S. E. & Read, D. J. *Mycorrhizal Symbiosis* (Elsevier, 1997).
8. Phillips, R. P., Brzostek, E. & Midgley, M. G. *New Phytol.* **199,** 41–51 (2013).
9. Soudzilovskaia, N. A. *et al. Glob. Ecol. Biogeogr.* **24,** 371–382 (2015).

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CONDENSED-MATTER PHYSICS

Novel electronic states seen in graphene

A simple system made from two sheets of graphene has been converted from an insulator to a superconductor. The finding holds promise for opening up studies of an unconventional form of superconductivity. SEE ARTICLE P.43 & LETTER P.80

EUGENE J. MELE

In two papers in *Nature*, Cao *et al.*[1,2] report the discovery of new electronic ground states in twisted bilayer graphene — a pair of single-atom-thick sheets of carbon atoms, stacked with their honeycomb lattices rotated out of alignment. The authors interpret one of these states[2] (page 80) as a correlated Mott insulator, a non-conducting state produced by strong repulsive interactions between electrons. The other[1] (page 43) is a superconductor, a state of zero electrical resistance produced by effective attractive interactions between electrons. The insulator turns into the superconductor when a small number of charge carriers are added to the graphene. This connection between the states is unlikely to be a coincidence — as Sherlock Holmes might have commented, "the universe is rarely so lazy".

Cao *et al.* show that the stacking of graphene sheets allows access to a new family of materials with electronic behaviours that are exquisitely sensitive to the atomic alignment between the layers, which affects interlayer electron motion. This finding might surprise physicists, because electronic behaviour is usually dominated by whichever of the associated processes has the largest energy scale. But, in this case, there's a conundrum: the energy associated with electron motion between atoms within a layer is of the order of electronvolts, whereas the energy for electron motion between layers[3] is, at most, hundreds of millielectronvolts.

The resolution to this conundrum is a matter of symmetry. Well-prepared, single layers of graphene are highly ordered systems whose electronic properties are determined by a subtle symmetry, which is encoded in a solid-state version of the Dirac equation describing low-energy excitations. These excitations are sensitive to interlayer couplings that alter the symmetries of the stack.

Interactions between electrons in these excitations can produce forms of matter generically described as being strongly correlated. A well-reasoned strategy for discovering such forms of matter has been to restrict intralayer electron motion by applying a strong magnetic field[4]. This generates narrow electron energy bands (Landau levels) in which electron–electron repulsion can control the physics of the graphene bilayer.

Cao *et al.* have taken a simpler tack to discover strongly correlated states. They used the rotational misalignment of graphene sheets to tune twisted bilayer graphene into a regime in which interactions between electrons can dominate the electronic states of the system. Such rotational misalignment forces the electronic band structures in the two sheets out of alignment and enlarges the bilayer's unit cell (the smallest repeating unit of the crystal lattice) (Fig. 1a). For large rotations, the first

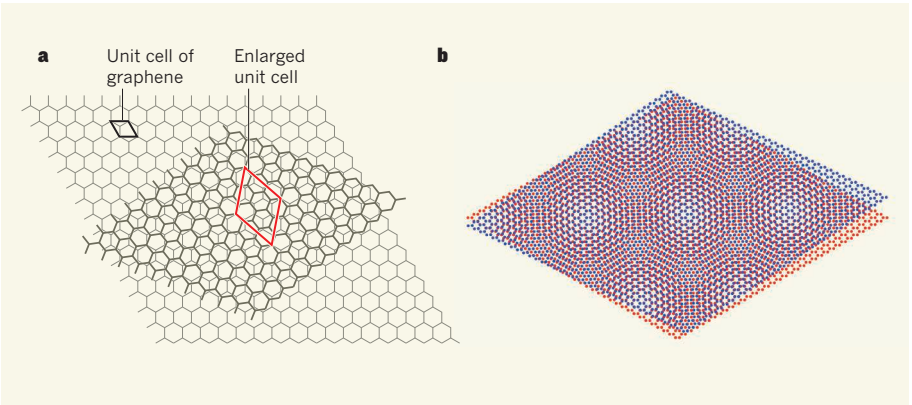

Figure 1 | The effects of rotation in twisted bilayer graphene. a, When a graphene bilayer is twisted so that the top sheet is rotated out of alignment with the lower sheet, the unit cell (the smallest repeating unit of the material's 2D lattice) becomes enlarged. For large rotations, the electronic band structures of the two graphene sheets are also rotated out of alignment (not shown). **b**, For small rotation angles, a 'moiré' pattern is produced in which the local stacking arrangement varies periodically. Cao *et al.*[1,2] have observed that, for rotation angles of less than 1.05°, regions in which the atoms are directly above each other (the lighter regions in the pattern) form narrow electron energy bands, in which electron 'correlation' effects are enhanced. This results in the generation of a non-conducting state[2] (a Mott insulator), which can be converted into a superconducting state[1] if charge carriers are added to the graphene system.

effect completely dominates, and electron motion between layers is suppressed by a kinematic barrier[5].

However, at very low rotation angles, a moiré pattern is produced by the misaligned lattices (Fig. 1b); the unit cell is greatly enlarged and so the effects of this come into play[6,7]. The misalignment of the band structure essentially disappears, and theory predicts that the low-energy electronic states are completely reconstructed[7]. Coupling between electrons in the different layers becomes strong, and new narrow bands emerge at certain 'magic' rotation angles below 1.05° when the bilayer system is close to charge neutrality. Electrons in these narrow bands are found mainly in regions of the moiré pattern in which the atoms are stacked directly above each other (the light regions in Fig. 1b). In these circumstances, the bilayer can be thought of as a synthetic, triangular lattice of weakly coupled quantum dots (tiny semiconductor particles that bind electronic states) with a residual tunnelling of electrons between them[6].

Cao *et al.* fabricated twisted bilayer graphene so that the sheets are rotated at magic angles, and accumulated or depleted charge carriers in the system to study how the charge-transport properties of the system depend on the filling of the energy bands. The authors observed[2] strong insulating behaviour when each unit cell of the synthetic lattice contained four charge carriers, a density that corresponds to complete filling of the bands. Intriguingly, they also find evidence for additional insulating states at lower densities in which the number of carriers per unit cell is an integer, but for which the narrow energy bands of the system are fractionally occupied. This suggests that the additional states are Mott insulating states, in which free motion of the carriers is prevented by their mutual repulsion, producing gridlock on the lattice. Mott insulators are a strongly correlated, non-conducting form of matter.

Even more intriguing is what happens when charge carriers are added to the Mott-insulator states associated with half-full unit cells of the synthetic lattice. The authors observe[1] that the system enters a state that has zero electrical resistance below a critical temperature of approximately 1.7 kelvin, in a phase change known as a Berezinskii–Kosterlitz–Thouless transition, thus forming a 2D superconductor. This transition temperature is remarkably high, given the very low carrier density achieved in these measurements (10^{11} charge carriers per square centimetre). The high transition temperature and the apparent connection to correlated insulating states invites comparison of this superconducting state to that of a family of 'unconventional' superconductors[8], which also have a close relationship with other strongly correlated electronic ground states. Twisted bilayer graphene might therefore be a useful experimental system in which to investigate the mechanism of unconventional superconductivity.

In the meantime, Cao and colleagues' discoveries will stimulate a wave of activity as scientists seek to unwind the microscopic basis for the reported striking phenomena. The findings also demonstrate the promise of using twisted bilayer graphene as a flexible and tunable platform in which correlated electronic phenomena can be readily observed, and possibly even engineered and exploited[9]. ■

Eugene J. Mele *is in the Department of Physics and Astronomy, University of Pennsylvania, Philadelphia, Pennsylvania 19104, USA.*
e-mail: mele@physics.upenn.edu

1. Cao, Y. *et al. Nature* **556,** 43–50 (2018).
2. Cao, Y. *et al. Nature* **556,** 80–84 (2018).
3. Castro Neto, A. H., Guinea, F., Peres, N. M. R., Novoselov, K. S. & Geim, A. K. *Rev. Mod. Phys.* **81,** 109 (2009).
4. Zibrov, A. A. *et al. Nature* **549,** 360–364 (2017).
5. Lopes dos Santos, J. M. B., Peres, N. M. R. & Castro Neto, A. H. *Phys. Rev. Lett.* **99,** 256802 (2007).
6. de Laissardière, G. T., Mayou, D. & Magaud, L. *Phys. Rev. B* **86,** 125413 (2012).
7. Bistritzer, R. & MacDonald, A. H. *Proc. Natl Acad. Sci. USA* **108,** 12233–12237 (2011).
8. Scalapino, D. J. *Rev. Mod. Phys.* **84,** 1383–1417 (2012).
9. Kim, K. *et al. Proc. Natl Acad. Sci. USA* **114,** 3364–3369 (2017).

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STRUCTURAL BIOLOGY

Two-pore channels open up

Two-pore channels span the membranes of acidic organelles inside cells. A structural and functional analysis reveals secrets about how these channels open to allow ions to pass across the membrane. SEE LETTER P.130

SANDIP PATEL

Two-pore channels (TPCs) are an ancient family of ion channels that are unusual because they are found, not at the cell surface, but spanning the membranes of acidic organelles such as endosomes and lysosomes. These organelles mediate biomolecule transport and breakdown, and serve as stores of calcium ions[1] (Ca^{2+}). TPCs are key for several organellar functions — releasing Ca^{2+} into the cytoplasm to control trafficking of material such as receptor proteins and viruses, for instance, and stabilizing junctions with other organelles[1,2]. They are increasingly being associated with disorders such as Parkinson's disease, and are therefore emerging as potential therapeutic targets[1]. Detailed structural information is scant, but advances in cryo-electron microscopy are revolutionizing our ability to study ion channels. On page 130, She *et al.*[3] use this technique to provide the first detailed view of an animal TPC.

Previous work[4,5] has reported the atomic structure of a plant TPC. This consists of two subunits, each containing two similar transmembrane domains (6-TMI and 6-TMII) connected by a large cytoplasmic linker. 6-TMI and 6-TMII are in turn each made up of six membrane-spanning regions, dubbed S1–S6. The pore through which ions flow is formed by S5 and S6 from each transmembrane domain in each subunit.

She *et al.* resolved the structure of mouse TPC1. Their results revealed that the overall folding of this channel is, as expected, like that of plant TPC. Nonetheless, there is a surprising degree of structural conservation between the linkers, given that animal and plant TPCs have very different amino-acid sequences in this region.

There are some structural differences, however. In plant TPC, the linker binds Ca^{2+} to help open the channel[4,5]. But Ca^{2+} binding by mouse TPC1 is unlikely, because amino acids essential for this interaction are missing. And the authors show that the carboxy-terminal domain of mouse TPC1, which is longer than the equivalent domain in plant TPC, forms a horseshoe-shaped arrangement of four helices that makes direct contact with the linker. This animal-specific feature probably serves to fine-tune channel activity.

Activation of animal TPCs is complex and multifaceted. These channels were originally identified[6,7] as the targets for a messenger molecule called NAADP, which releases Ca^{2+} from acidic organelles[8]. Subsequent work revealed[9] that TPCs are also activated by the lipid $PI(3,5)P_2$. In addition, TPC1 is regulated by changes in voltage across the organelle membrane[10,11]. She *et al.* demonstrated that both $PI(3,5)P_2$ and voltage changes are required to open TPC1; neither alone is sufficient (they did not examine NAADP). The authors then resolved structures of TPC1 in both the absence and presence of $PI(3,5)P_2$, giving insight into the structural transitions that occur during channel opening. This analysis produced two key findings.