

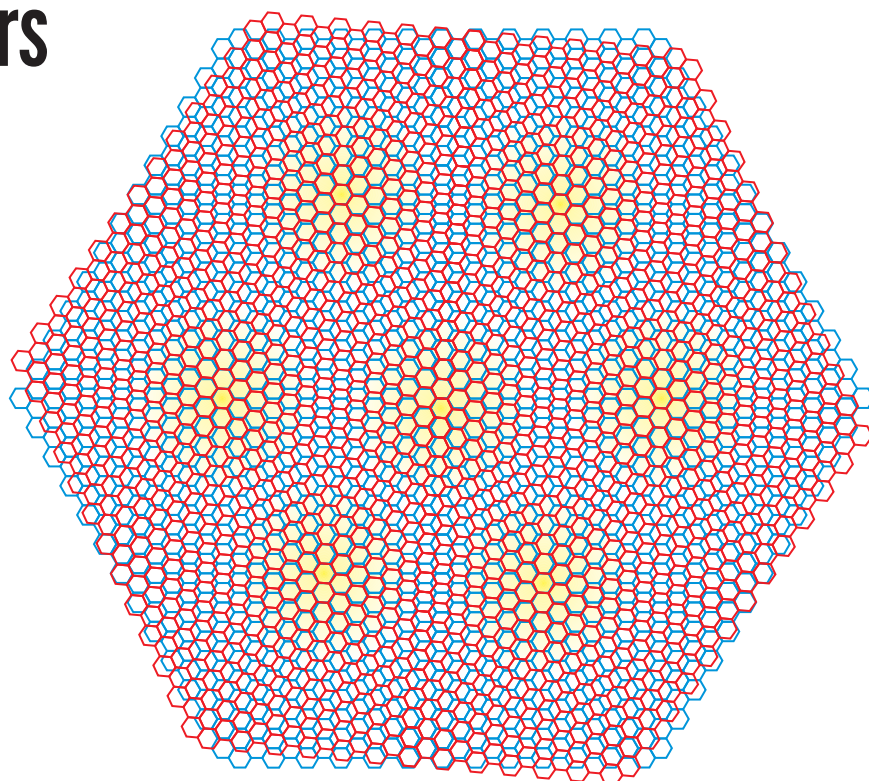
Unconventional superconductivity discovered in graphene bilayers

When two carbon sheets are misaligned by a mere degree, striking changes result.

Much of the appeal of the two-dimensional materials zoo—which includes graphene, hexagonal boron nitride, molybdenum disulfide, and many others—lies in the multitude of ways the atomically thin sheets can be stacked and combined to create heterostructures with novel properties. (See the article by Pulickel Ajayan, Philip Kim, and Kaustav Banerjee, *PHYSICS TODAY*, September 2016, page 38.) New structures can be created not only by stacking different materials but also by arranging the same materials in different ways and, in particular, by introducing a relative twist between successive layers.

When two periodic lattices, atomic or otherwise, are overlaid and slightly offset, they can interfere to create a moiré pattern, named after a type of silken fabric whose construction gives it a rippled appearance. As figure 1 demonstrates, a moiré pattern has spatial structure on a larger scale than either lattice alone, and that quasiperiodicity can have interesting physical consequences. For example, the spatial modulation in the moiré pattern between sheets of graphene and hexagonal boron nitride can produce a fractal energy spectrum called Hofstadter's butterfly.¹

Now MIT's Pablo Jarillo-Herrero, his student Yuan Cao, and their colleagues have shown that the twist angle between two sheets of graphene can be exploited to even more dramatic effect: At a magic angle of approximately 1.1° , the two-layer stack becomes a superconductor.² Furthermore, superconducting twisted bilayer graphene bears a strong resemblance to the cuprates and other materials that superconduct at temperatures near 100 K or even higher. Although the graphene bilayers don't have critical temperatures anywhere near that high,



they constitute an enticing new platform for studying unconventional superconductivity that may yield new insights into the elusive phenomenon.

Strong coupling

Monolayer graphene gets many of its interesting properties from its unusual band structure. The valence and conduction bands meet in conical valleys, meaning that charge carriers have kinetic energy directly proportional to their momentum, just like photons and other relativistic particles do (see the article by Andre Geim and Allan MacDonald, *PHYSICS TODAY*, August 2007, page 35).

The same quasi-relativistic behavior is present in bilayer graphene with a twist angle of more than a few degrees. At those large angles, the sheets decouple and behave like independent monolayers. On the other hand, in ordinary bilayer graphene—with a twist angle of zero, at which the sheets are stacked just as they are in bulk graphite—the valleys are parabolic, energy is proportional to momentum squared, and charge

FIGURE 1. THE MOIRÉ PATTERN between two honeycomb lattices is quasiperiodic over a much larger scale than either lattice itself. Highlighted in yellow are the repeating regions where the hexagons in the two sheets nearly align.

carriers act like the massive particles that they are.

At some small twist angle, then, there must be a transition between those two qualitatively different band structures, and several papers³ have hinted that in that crossover regime, the energy-momentum dispersion actually flattens out, so all electrons, regardless of momentum, have the same energy. Looked at another way, the density of states as a function of energy diverges. That so-called band flattening is typical of strongly correlated phases of matter, such as the electron fluid in a high-temperature cuprate superconductor.

Strongly correlated systems, which also include other quantum phases of matter, quark-gluon plasmas, and neutron stars, are notoriously difficult to

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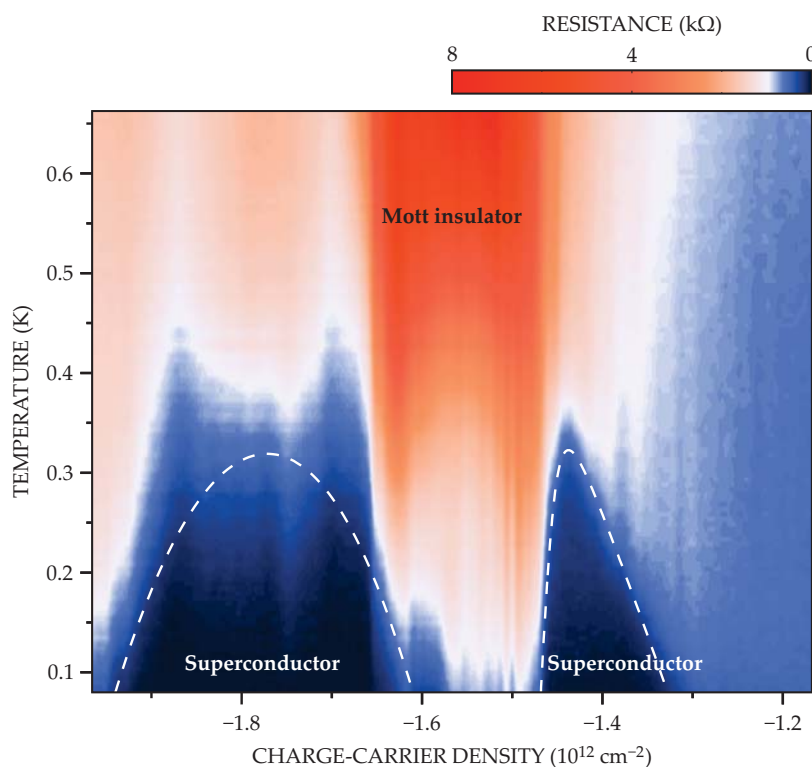


FIGURE 2. PHASE DIAGRAM of a graphene bilayer with a twist angle of 1.16° . A Mott insulating phase is flanked by two dome-shaped superconducting phases, reminiscent of the electron- and hole-doped phases of a high-temperature superconductor. The critical temperature, here just 0.3 K, can be increased to 1.7 K by changing the twist angle to 1.05° . (Adapted from ref. 2.)

understand, because the states of their constituent particles can't be mathematically separated. Moreover, twisted bilayer graphene poses its own theoretical challenges. Standard computational methods for simulating electrons in a solid require that the system be periodic. But except at a discrete set of twist angles, moiré patterns are only quasiperiodic: Similar-looking regions appear at regular intervals, but the structure never exactly repeats. As a result, it was unclear just how band flattening would manifest itself in twisted bilayer graphene, or even at what twist angle it would occur.

Jarillo-Herrero and colleagues were studying twisted bilayer graphene experimentally when in 2016 they started to see hints of strong-coupling behavior at twist angles less than 2° .⁴ They became aware of a paper published five years earlier in which Rafi Bistritzer and Allan MacDonald formulated a continuum model of the quasiperiodic structures and predicted singular electronic behavior at not just one but a series of twist angles.⁵ The largest of those, and the one

with the most severe band flattening, was 1.05° .

Thereafter, the MIT experimenters focused on twists near that magic angle. To ensure the sheets had good electronic quality, they sandwiched their graphene bilayer between thin flakes of insulating boron nitride. With a gate electrode, they adjusted the material's charge-carrier density. Source and drain electrodes passed a current along the plane of the sheet, allowing measurements of its resistance.

The first hint that something unusual was going on came when they tuned the carrier density to about 1.5×10^{12} electrons per square centimeter and the conductivity dropped to zero.⁶ The graphene bilayer became an insulator, but there was no gap in the density of states to account for the observed behavior. The researchers deduced that they were seeing a correlated insulator, in which strong correlations between charge carriers prevent them from moving around, despite an abundance of available states.

Because a Mott insulating phase, a type

of correlated state, also shows up in the phase diagrams of some unconventional superconductors, Jarillo-Herrero and colleagues suspected that the unexpected insulating behavior was just the tip of the iceberg. To see what other surprises lay in store, they needed to refabricate their devices with six in-plane electrodes, not just two, and make their electrical measurements in a dilution refrigerator that could cool to 0.1 K. After several months of work, they had their results, as shown in figure 2: At carrier densities just above and below the insulating swath lay two dome-shaped superconducting phases, much like the electron- and hole-doped superconducting phases seen in the cuprates. The correlated insulator work was still under review for publication at that point, and Jarillo-Herrero arranged to have the superconductivity results published at the same time.

Dial a superconductor

At first glance, twisted bilayer graphene might look unimpressive as a superconductor. Its critical temperature T_c is on the order of just 1 K. The sample that was probed in figure 2, with a twist angle of

1.16°, had a somewhat lower T_c . But even at twist angles closer to the predicted magic angle 1.05°, the researchers observed critical temperatures no higher than 1.7 K—about the same as that of aluminum, one of the long-known conventional superconductors that's well described by Bardeen-Cooper-Schrieffer (BCS) theory.

But T_c doesn't tell the whole story. Aluminum's charge-carrier density is 10 000 times that of twisted bilayer graphene. That's important, because carrier density represents a limit on how many electrons can pair up and condense into a superfluid. The lower the carrier density, the harder it is for the phonon-mediated pairing mechanism of the BCS theory to work. In fact, the true measure of a superconductor is better quantified by the ratio of T_c to carrier density. Looked at that way, twisted bilayer graphene is right in line with the most strongly correlated superconductors known: In terms of its electronic properties, it has more in common with high- T_c materials than with aluminum and its BCS cousins.

But graphene has a big experimental

advantage over other unconventional superconductors: Tuning its carrier doping is as simple as adjusting the voltage on the gate electrode, so all parts of the phase diagram can be explored with a single device. In cuprate superconductors, on the other hand, superconductivity lives in the CuO_2 planes, which are doped with electrons or holes by the atoms above and below. Adjusting the doping therefore requires making an entirely new material with slightly different chemical composition. At best, that's tedious and challenging; at worst, it can be impossible.

For example, yttrium barium copper oxide (YBCO) can be doped with holes by adjusting the material's oxygen content—indeed, hole-doped YBCO was the first material to superconduct at liquid-nitrogen temperatures—but it doesn't lend itself to doping with electrons. Other cuprates allow electron doping but not hole doping. Twisted bilayer graphene admits the equivalent of both, continuously and easily.

Furthermore, it's possible to tune the band structure itself by making new bilayers with slightly different twist

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angles. To do the same with the cuprates requires not just tweaking the chemical composition but completely changing it—from YBCO to bismuth strontium calcium copper oxide, say—and it's not always clear what effects those complex chemical changes might have. Twisted bilayer graphene supports superconductivity over a range of at least 0.11° , maybe more, and Jarillo-Herrero and colleagues have already shown that tuning the twist angle changes not only T_c but also the structure of the phase diagram. Explor-

ing the effect further could help to show just how material structure, density of states, and superconductivity are all connected. Ultimately, that approach may reveal the mechanism of high- T_c pairing and how to design materials with even higher T_c .

"The ability to dial the electronic band structure with a simple twist is an incredibly powerful new tool," explains Eva Andrei of Rutgers University. "Until now, all superconductor discoveries were the result of serendipity or painstaking

chemical synthesis. Twisted bilayer graphene strips away all the complications imposed by the chemistry of the high- T_c superconductors. This could be a huge step toward solving this 30-year-old puzzle."

A matter of scale

In some ways, twisted bilayer graphene brings to mind the ultracold gaseous systems some groups are using to try to unlock the secrets of high-temperature superconductivity. (See PHYSICS TODAY, August 2017, page 17.) Atoms in an array of optical traps are thought to mimic the electrons in a superconducting solid, and their configurations can be directly imaged with a quantum gas microscope. The significant downside is that experimenters are still struggling to reach the extremely low temperatures—below a nanokelvin—that they suspect will produce the analogue of superconductivity.

Twisted bilayer graphene is intermediate between optical lattices and crystalline superconductors in at least two ways. Its critical energy scale is below 100 K but well above 1 nK. And its length scale—as measured by the distance between the regions marked in yellow in figure 1 where hexagons in the two layers line up—is about 13 nm, bigger than the cuprate interatomic spacing but smaller than the micron-scale distance between the wells of an optical trap.

The size scale of the moiré pattern isn't incidental. The carrier density that produces the Mott insulating phase, $1.5 \times 10^{12} \text{ cm}^{-2}$, corresponds to exactly two carriers per moiré unit cell. And simulations show that the charge density is strongly concentrated in the regions of lattice alignment, just like the atoms in the cold-gas experiments are confined to their optical traps. Graphene superconductivity, therefore, seems to have something to do with electron correlations on a 13 nm scale. That's too small to image optically, but other technologies, such as nanoSQUIDS, could make it possible to directly probe the superconducting electronic state.

Graphene is just one of an ever-growing family of 2D materials, each with its own distinct flavor. There are 2D semiconductors, 2D ferromagnets (that Jarillo-Herrero helped to discover; see PHYSICS TODAY, July 2017, page 16), 2D materials

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with high spin-orbit coupling, and so on. Each of them could, conceivably, be brought into the strong-coupling regime by finding the right twist angle, and there's no telling what surprising properties they could show. Says Jarillo-Herrero, "It may take a while before we can make high-quality devices"—graphene is exceptional in its propensity to form

large, defect-free crystals—"but this might be a whole new field of magic-angle superlattices."

Johanna Miller

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Jupiter's wind bands have deep roots

Gravity measurements by NASA's *Juno* spacecraft resolve a long-standing debate about the structure of gas giants.

All four of our solar system's gas giants sport stripes. Jupiter's bands, the most prominent, offer even amateur astronomers a stunning view of the planet's complex atmospheric dynamics. Planetary scientists are especially intrigued by the areas between the stripes, where east-west winds whip clouds around the planet at up to 150 m/s.

For decades researchers have debated the depth of Jupiter's jet streams, or zonal jets. Some argued that the winds persist only tens or hundreds of kilometers beneath the visible cloud layer. In their view, Jupiter was a giant, uniformly rotating body topped with a razor-thin tier of atmospheric action. Others maintained that the jets stretch much deeper as part of a rich, complex atmosphere, perhaps sustained by heat from the Jovian interior.

Now, a year and a half after settling into orbit around Jupiter, NASA's *Juno* spacecraft has resolved the debate.¹ Precise gravimetry measurements reveal that Jupiter's winds stretch relatively deep into the planet, plunging up to 3000 km beneath the colorful cloud tops.² Beyond that depth, Jupiter's magnetic field takes over and forces the pressurized, conductive hydrogen in the interior to rotate uniformly.³ The results solve an important puzzle about Jupiter's structure and could provide a blueprint for profiling other gas worlds in and beyond the solar system.

Odds and evens

The air in Jupiter's light-colored stripes is at relatively high pressure; the dark stripes are regions of low pressure.



NASA/JPL-CALTECH/SWRI/MSSS/GERALD EICHSTÄDT/SEÁN DORAN

Those pressure differences, combined with Jupiter's rotation, cause the roughly two dozen zonal jets to alternate easterly and westerly directions. The jets are not just mirror images of each other. Jets in the northern hemisphere tend to be stronger, particularly in the vicinity of 24° N latitude, where the planet's fiercest cloud-top winds have been recorded. The southern hemisphere is a bit calmer, perhaps contributing to the presence of most of the famous long-lived Jovian storms, including the String of Pearls cluster shown in figure 1 and the Great Red Spot.

For theorists trying to determine the mechanism that drives the zonal jets, the

FIGURE 1. JUPITER'S ACTIVE ATMOSPHERE, in an enhanced-color image from NASA's *Juno* spacecraft. The planet's bands of dark and light clouds support powerful zonal winds and long-lived storms like those in the so-called String of Pearls (white ovals).

hemispheric asymmetry rules out the simplest models, which makes the question of depth all the more important to answer. Fortunately, the north-south differences also open up a means of determining the jet streams' vertical reach. Winds that stretch deep into the planet would presumably transport a significant amount of mass. And because the winds blow differently in the north than in the