pore. To suppress artifacts from periodic boundary conditions, a liquid-like phase was added to the edges of the simulation box and prevented unwanted boundary interactions with the quasicrystal.

The simulations included about 5 million particles—other crystal simulations typically have on the order of thousands of particles. On top of that challenge, the researchers had to run several hundred simulations on a supercomputer to understand the statistics of the dynamic system. “I think that’s why people generally don’t do this sort of simulation,” says Wang. “It’s not that it’s impossible. I think there’s just easier things to do with your time.”

The simulations quantified a series of parameters that describe the degree of order in the material structure. In the quasicrystal case, the calculated order parameters initially decreased after the growth front collided with and engulfed the pore. Then they increased over time and returned to their precollision values. The increase is consistent with quasicrystals’ capability of structural rearrangement. Once the common crystal encountered the pore, however, the order parameters decreased and never recovered.

Beyond validating theoretical models, the new simulation and experimental results suggest that quasicrystals could be incorporated into materials to make them tolerant of defects. The durability and low friction of quasicrystals have made them possible candidates for nonstick coatings and other surface treatments. Because of their unique structural properties and their capacity for growing defect-free, quasicrystals may have other potential applications too. Some research has examined their use as reinforcements in metal composites and polymer materials.[5] **PT**

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UPDATES

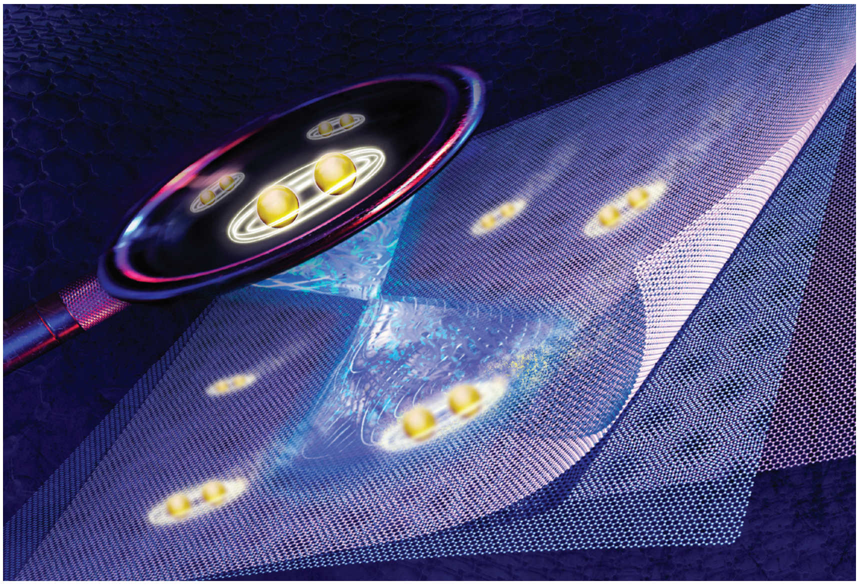
Energy scales of superconducting graphene come into focus

To get a handle on how a superconductor forms its electron pairs, researchers first need to know what it takes to rip them apart.

By Johanna L. Miller

It’s one of the most stubborn open questions of modern physics: What’s the mechanism of high-temperature superconductivity? All superconductors need some way of binding their electrons, which are fermions, into quasiparticles called Cooper pairs, which act as bosons. The low-temperature superconductivity in metals is well described by the Bardeen-Cooper-Schrieffer theory, which states that the pairs are held together by phonons. But in 1986, cuprate ceramics were discovered to superconduct at a much higher temperature via a different, unknown mechanism. Despite four decades of research and the discovery of many other unconventional superconducting materials, their mechanism remains a mystery.

So the condensed-matter physics community took note when, in 2018, superconductivity was found in magic-angle graphene: two or more layers of the atomically thin carbon material stacked with a relative twist of 1.1°. Its allure is in its tunability: With a single graphene device, researchers can explore regions of the superconducting phase diagram that otherwise would require the synthesis of several new materials. But despite that advantage, magic-angle graphene has until now resisted a basic measurement: the size of the hole in the density of states called the su-



When sheets of graphene are stacked at just the right angle, their electrons form Cooper pairs at low temperatures, and the material becomes a superconductor. (Illustration by Sampson Wilcox and Emily Theobald, RLE, MIT.)

perconducting gap, a measure of how much energy is needed to break apart a Cooper pair.

It's not that the density of states couldn't be measured. That could be done using tunneling spectroscopy, a technique related to scanning tunneling microscopy. The trouble lay in confirming that the gap being measured was really a superconducting gap. Other phases of matter—for example, insulators—also have gaps in their densities of states, and magic-angle graphene hosts a rich array of phases that all lie close to one another in parameter space and thus could be easily confused. (For details, see the 2024 *PT* feature article "Twisted bilayer graphene's gallery of phases," by B. Andrei Bernevig and Dmitri K. Efetov.)

Now Princeton University's Jeong Min Park, her former PhD adviser Pablo Jarillo-Herrero at MIT, and their colleagues have overcome that challenge. They've developed a way to simultaneously measure magic-angle graphene's density of states and its charge-transport properties so that they know whether the phase that they're probing is superconducting.[1] Their experimental device, sketched below, was intricate to construct. Several of the layers are atomically thin, the two graphene layers each have electrodes attached at several points, and the central layer of bulk hexagonal boron nitride has a precisely etched hole through which the adjoining layers must smoothly contact each other.

Magic-angle graphene superconducts at low temperatures, but probing the energetics of the superconducting state has been a challenge. With this multilayered device, researchers can simultaneously measure the charge transport and density of states of the elusive superconductor. (Figure adapted from ref. 1 by Freddie Pagani.)

With their device, the researchers discovered that magic-angle graphene's density of states features two distinct energy gaps: the superconducting gap, which disappears above the critical temperature, and another, higher-energy gap called a pseudogap, which persists at higher temperatures. That observation is not yet enough to clarify the Cooper-pairing mechanism of magic-angle graphene—or any other unconventional superconductor—but it does point to a possible similarity between them: Many other unconventional superconductors also feature pseudogaps that resemble the one seen in graphene. If magic-angle graphene's pairing mechanism can be discovered, it could lead to the design of new superconductors—maybe even ones that superconduct at room temperature and pressure. PT

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