SUPERCONDUCTIVITY

Magic, symmetry, and twisted matter

Alternating magic-angle twist induces unconventional superconductivity

By **Ali Yazdani**

The discovery in 2018 of superconductivity when two layers of graphene are stacked on top of each other at a "magic angle" has opened a new paradigm for studying electronic phenomena (*1*). Now, a pair of studies, one on page 1133 of this issue by Hao *et al.* (*2*) and the other by Park *et al.* (*3*), take the twisting magic trick one step further. More robust and tunable superconductivity was realized in three-layer stacks of graphene arranged at an alternating magic twist angle that is a factor of $\sqrt{2}$ greater than the magic angle for bilayers. The authors also present evidence that superconductivity in twisted graphene is not caused by the conventional weak-coupling Bardeen-Cooper-Schrieffer (BCS) electron-pairing mechanism. The mechanism of pairing remains unknown, but the experiments suggest that the electrons form tightly bound pairs at temperatures above those at which superconductivity is macroscopically detected.

Early theoretical work predicted that the moiré superlattice created by stacking two twisted layers of graphene, at a magic angle of ~1°, creates electronic bands with vanishing bandwidths (*4*, *5*). The quenched kinetic energy of electrons occupying such flat bands creates strong interactions and would make magic angle–twisted bilayer graphene (TBG) a spectacular platform for collective phenomena. for sighting new quantum phases (*6*) including unexpected interaction-driven topological insulators (*7*).

Although steady progress is being made in understanding TBG, the mechanism and nature of its superconducting phase remains a mystery. It is tempting to think in terms of a simple weak-coupling BCS scenario in which a large density of states of a nearly flat band can enhance superconductivity. However, superconductivity occurs in the presence of strong Coulomb interactions that are comparable with or larger than the bandwidth of TBG in the noninteracting limit (*8*), and other flat-band moiré systems do not show reliable signs of superconductivity, despite exhibiting other strongly correlated behavior.

Twisting three-layer graphene was predicted to possess flat bands if it was constructed with a curious alternating magic twist angle $\sqrt{2}$ greater than that of the bilayer system (*9*). This trilayer differs from the bilayer in several respects. For example, its flat bands coexist with dispersing Dirac bands, and a perpendicular displacement field can be used to tune its band structure (see the figure). The two experimental studies fabricated trilayer near the predicted greater alternating magic angle and explored trilayer properties as a function of carrier density and perpendicular displacement field.

The presence of the Dirac bands circumvents the formation of correlated insulating states, which also slightly screens the interaction between electrons in the flat band of the trilayer. However, the interactions within the trilayer flat bands give rise to cascades of transitions at several of the integer filling (ν) of carriers per moiré unit cell of its flat bands, similar to those observed in TBG (*10*, *11*). These transitions signal the propensity for flavor (spin or valley isospin) symmetry–breaking, near-integer fillings, including at $\nu = \pm 2$, from which superconductivity emerges upon doping. The trilayer appears at a superconducting transition temperature (T_c) of 2 K (twice that of the bilayer) system. The cause of this enhancement is unclear, but the moiré superlattice constant is smaller in the trilayer, which would increase the Coulomb-interaction scale at the same electron density

Several experimental findings in the magic trilayer signal unconventional superconductivity. The superconducting coherence length is about the same as the interparticle distance, and T_c increases almost linearly with doping. The ratio of T_c to the Fermi temperature is also large (0.1). The superconducting state appears to be in the strong-coupling regime and likely driven by Bose condensation of tightly bound Cooper pairs and limited by their density. Pairing might occur at temperatures much higher than when the zero-resistance state is detected.

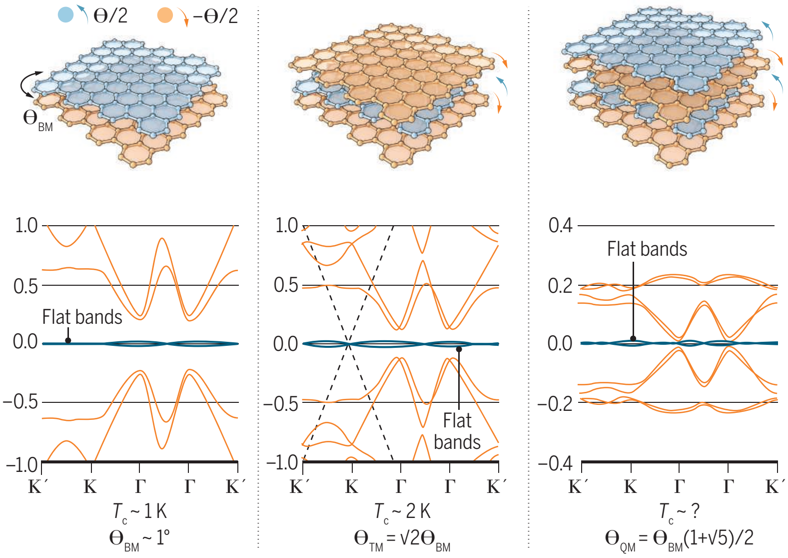
Tuning the trilayer's band structure allows experimental determination of the role of enhanced density of states at the van Hove singularity (vHS) of the flat bands in superconductivity. The new studies monitored the Hall conductivity as a function of doping and displacement field. When the vHS

Alternating twists

Superconductivity in twisted graphene layers arises from flat-band structures near zero energy.

Magic angles
The structures of graphene bilayer, alternating trilayer, and quadrilayers constructed at a hierarchy of respective magic angles Θ_{BM}, Θ_{TM}, and Θ_{QM}.

Flat bands
The theoretical energy-momentum bands are very flat near the Fermi level. Electrons in such flat bands experience strong interactions. Near half filling, bilayers and trilayers superconduct at below their transition temperature T_c. Calculations also predict flat bands in the alternating quadrilayers. K, K′, and Γ are symmetry points.



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is tuned to the chemical potential, T_c in the trilayer is suppressed, opposite of what is expected from the simple BCS weak-coupling mechanism. Superconductivity appears to be strongly tied to flavor-polarized states, which are beginning to be understood in the bilayer [for example, (*12*)]. Topological excitations of these states may be responsible for the pairing mechanism (*13*), but the breakdown of weak coupling does not mean phonons are not involved. Some calculations show that in a fully flat band, electrons cannot pair on their own (*14*).

The presence of superconductivity in bilayer and alternating trilayer systems, and its absence in the other flat band system, suggests the importance of spatial-time $C_{2z}T$ symmetry for the emergence of superconductivity. The discovery of superconductivity in this trilayer raises the possibility that the stacking of multilayers of graphene respecting certain symmetry at other magic angles will uncover more and hopefully greater-T_c twisted superconductors. The theory that predicted the $\sqrt{2}$ ratio for trilayer also identified a hierarchy of magic angles for multilayers with alternating layers (*8*). The prediction for quadrilayers with alternating magic angle larger than the bilayer by the golden ratio is that they would have flat bands without dispersing Dirac bands because they have an even number of layers (see the figure).

An unspoken rule in the hunt for new superconductors attributed to early Bell Lab pioneer Bernd Matthias (*15*) is to "never listen to the theorists." However, maybe the signs of symmetry and the elegance of special ratios need to be heeded. Finding superconductivity in twisted matter with a prescribed symmetry related by the golden ratio of twist angles would be pure magic. ■

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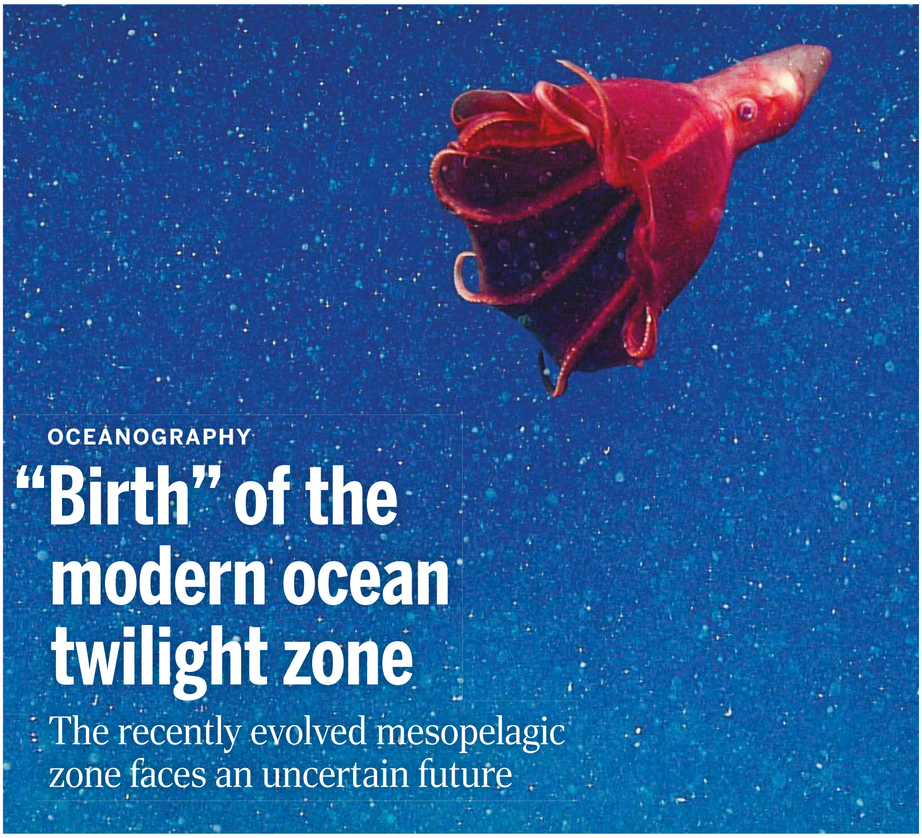

OCEANOGRAPHY

"Birth" of the modern ocean twilight zone

The recently evolved mesopelagic zone faces an uncertain future

An octopus moves through the "marine snow" of organic matter at 400-m depth in the North Atlantic Ocean.

By **Laurent Bopp**

The ocean "twilight zone," where sunlight hardly penetrates, is located at depths of 200 to 1000 m from the sea surface. Inhabited by iconic species such as lantern fish and giant squid, it has stimulated our collective imagination for generations. To this day it remains largely unexplored and has revealed few of its secrets. Also known as the mesopelagic, this zone occupies 20% of the volume of the world's oceans. It plays a key role in the global carbon cycle (*1*, *2*) and may contain both biomass and biodiversity that have been largely underestimated (*3*, *4*). On page 1148 of this issue, Boscolo-Gallazzo *et al.* (*5*) provide evidence that the establishment of the modern twilight zone is, on planetary time scales, a relatively recent phenomenon that has taken place gradually over the past 15 million years.

Using an approach that couples ocean biogeochemical simulations and a compilation of sedimentary isotopic data, Boscolo-Gallazzo *et al.* show the role of the gradual cooling of the climate system (by 4° to 6°C for the global surface ocean) in establishing the modern twilight zone. This global decrease in temperature has reduced the decomposition of organic matter that is formed by upper-ocean ecosystems and then sinks to depth. As such, the export of organic carbon to the deeper ocean has become more efficient and has increased the amount of food available to mesopelagic ecosystems. These long-term paleoclimatic changes are likely responsible for the establishment of relatively new deep ecological niches and the modern twilight zone.

The role of the twilight zone in the ocean carbon cycle has been recognized for more than 30 years, with the identification of the importance of the biological carbon pump in transporting carbon out of the ocean's surface layers (*1*). Indeed, it is in the twilight zone that most of the organic carbon that is exported from the surface ocean is remineralized back to carbon dioxide through a series of biological, physical, and chemical processes that are not yet well understood. However, what is known is that this input of organic matter is critical to the survival of most organisms living at these depths and to the ecosystems they inhabit. Hence, although a few billion tons of carbon leave the surface ocean every

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