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Possible nodal superconducting pairing in magic angle twisted graphene layers

1. **Superfluid stiffness of twisted multilayer graphene superconductors**
   Authors: Abhishek Banerjee, Zeyu Hao, Mary Kreidel, Patrick Ledwith, Isabelle Phinney, Jeong Min Park, Andrew M. Zimmerman, Kenji Watanabe, Takashi Taniguchi, Robert M Westervelt, Pablo Jarillo-Herrero, Pavel A. Volkov, Ashvin Vishwanath, Kin Chung Fong, Philip Kim
   Nature, volume 638, pages 93–98 (2025)

2. **Simultaneous transport and tunneling spectroscopy of moiré graphene: Distinct observation of the superconducting gap and signatures of nodal superconductivity**
   Authors: Jeong Min Park, Shuwen Sun, Kenji Watanabe, Takashi Taniguchi, Pablo Jarillo-Herrero
   https://arxiv.org/abs/2503.16410

Recommended with a Commentary by T. Senthil, Massachusetts Institute of Technology

Since the discovery of strong correlation physics and superconductivity in magic angle twisted bilayer graphene in 2018, tremendous attention has been lavished on two dimensional moire materials [1]. A number of other phenomena have been discovered including, for example, ferromagnetism, and the (fractional) quantum anomalous Hall effect.

Superconductivity itself is by now a common phenomenon in moire, and non-moire, two dimensional materials. In this commentary I will however focus on superconductivity in magic angle twisted bilayer graphene (MATBG) and its close cousin, magic angle mirror symmetric twisted trilayer graphene (MATTG). These are the best studied superconducting 2d materials thus far. I will describe recent experiments suggesting that the pairing in these systems is such that there are gapless nodal quasiparticles, similar to what happens in the cuprate high-Tc superconductors.

MATBG consists of two layers of graphene twisted to a `magic angle' of about 1.10 deg when the electronic bands become very narrow. The strongest superconductivity occurs at an electron filling ν between -2 and -3 per moire unit cell. MATTG consists of three layers of graphene that are alternately twisted so that the top and bottom layers are aligned with each other while the middle layer is twisted by an angle $\pm\theta$ relative to them. This system too exhibits nearly flat bands at a magic angle $\theta \approx 1.5$ deg. Theoretically, in an ideal device, there is a mirror symmetry that reflects about the middle layer. Then the free electron band structure can be decomposed into mirror-even and mirror-odd sectors. The former is essentially the same as the nearly flat band in MATBG, while the latter has a dispersing Dirac band touching and is essentially the same as the bands of monolayer graphene[2]. The phenomenology of MATTG is broadly similar to MATBG, and it is useful to consider them in parallel.

A previous hint that the pairing in MATBG and MATTG may be nodal came through STM studies[3,4] that found a V-shaped tunneling conductance as a function of bias voltage in a range of dopings, However interpretation of these STM results is subtle, and involves a modeling of the tip when it is pushed deep into the sample which introduces several uncertainties [5,6,7,8]. For a recent theoretical discussion of some relevant issues, please see Ref. [8] which makes a strong case for unconventional pairing.

The highlighted papers offer other evidence supporting the possibility of nodal pairing. The first paper studies the temperature (T) and current (I) dependence of the superfluid phase stiffness ρ_s of MATTG (see also Ref . [9] for a measurement of ρ_s in MATBG). The energy of a superconducting system associated with a phase gradient $\vec{\nabla}\phi$ is given by

$$E = \int d^2x \, \frac{\rho_s}{2} \left(\vec{\nabla}\phi \right)^2$$

Re-expressed in terms of the current density $\vec{j} = \rho_s \vec{\nabla}\phi$, we get

$$E = \int d^2x \, \frac{(\vec{j})^2}{2\rho_s}$$

Thus there is an inductive contribution (known as the kinetic inductance) to the total energy that depends on ρ_s. By measuring the resonance frequency of a microwave resonator that includes the superconducting sample, the kinetic inductance and hence ρ_s can be obtained after a (delicate) subtraction of the geometric inductance of the rest of the circuit.

A key observation of Banerjee et al is that ρ_s has a linear temperature dependent decrease through out the doping range of superconducting MATTG. This is exactly what is expected in a nodal superconductor due to the linear density of quasiparticle states. (Ref. [9], which studied MATBG, also found a power law - though not a clear-cut linear - temperature dependence of ρ_s at low T, which could possibly be attributed to smearing of nodes due to disorder effects). Furthermore Banerjee et al also observed that ρ_s depends linearly on the measurement current itself provided it is large enough to overcome thermal smearing of the node - a phenomenon known as the nonlinear Meissner effect that is also expected in a nodal superconductor.

The second highlighted paper by Park et al builds a novel sandwich consisting of two MATTG devices separated by a thin layer of hexagonal Boron-Nitride (hBN). This hBN layer has a hole in the middle that allows electrons to tunnel between the two MATTG devices. Further both the top and bottom MATTGs are separately contacted so that their electrical transport can be separately studied. Top and bottom gates enable tuning the electron densities of each device and controlling the interlayer bias voltage. With this set-up, the authors are able to simultaneously measure, for the first time, both transport and tunneling of the same device.

When the top MATTG is in its superconducting state while the bottom one is held normal, a V-shaped tunneling conductance (as a function of the interlayer bias voltage) is observed. Further, the zero bias tunneling conductance is a linear function of T. Both these features are indicative of the linear density of quasiparticle states expected in a nodal superconductor.

Taken together the results in the highlighted papers strengthen the case for nodal pairing in MATTG (and by association in MATBG) that add to the suggestion from the early STM experiments. Further indirect theoretical support[5] for nodal pairing comes from a Ginzburg-Landau analysis that argues that the nematicity observed[10] in the MATBG superconductor requires nodal pairing.

Both highlighted papers contain a wealth of other information pertinent to other questions about these superconductors. For instance the flavor structure (i.e, the spin-valley quantum numbers of the pairing order parameter) is probed by Park et al through measurements of the tunneling conductance in a magnetic field. This paper also reports two distinct gaps which are both correlated with the superconducting Tc (measured through transport in the same set-up) but with different temperature and bias dependences. In their paper Banerjee et al also study the doping dependence of the ground state ρ_s and see that it tracks the superconducting Tc through out the doping range (see also Ref. [11]). Unravelling the information in all these measurements and their implications for the origin of superconductivity in MATBG and MATTG will be an interesting exercise for the future.

A few final remarks on superconductivity in MATBG/MATTG and in other moire and non-moire 2d materials are appropriate. First, despite wide variations in the details of devices, both superconductivity and correlated insulators are robustly observed in MATBG/MATTG in the vast majority of reported results. Device-to-device variations apparently affect the maximum Tc or other energy scales but not the occurrence of superconductivity itself. Second, there is no a priori reason to think that the superconductivity observed in moire-less rhombohedral graphene or in the Transition Metal Dichalcogenide (TMD) moire systems is the same as that in MATBG/MATTG. In the latter, the normal state out of which the superconductivity emerges has a low density of charge carriers as evidenced by Hall effect measurements. In MATBG this is directly a result of proximity to the correlated insulator at $|\nu| = 2$. Moire-less rhombohedral graphene has no such insulator `eating away' most of the potentially available mobile electrons. The moire TMD systems have strong spin-valley locking coming from spin-orbit coupling and other features not present in MATBG/MATTG. Thus the evidence for nodal pairing in MATBG/MATTG discussed in this commentary should not be viewed as saying anything on these other superconductors.

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