Local probes and superconductivity in magic angle twisted bilayer and trilayer graphene.

1. **Evidence for unconventional superconductivity in twisted bilayer graphene**
   Authors: Myungchul Oh, Kevin P. Nuckolls, Dillon Wong, Ryan L. Lee, Xiaomeng Liu, Kenji Watanabe, Takashi Taniguchi, Ali Yazdani
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2. **Evidence for unconventional superconductivity in twisted trilayer graphene**
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Recommended with a Commentary by Francisco Guinea, Imdea Nanoscience, Madrid, Spain, and Donostia International Physics Center, San Sebastian, Spain

1 Introduction. Scanning tunneling microscopy (STM) experiments on magic angle twisted bilayer graphene.

Evidence for a rich and very intriguing and interesting phase diagram in magic angle twisted bilayer was first obtained from electronic transport experiments[1, 2]. On the other hand, a variety of local probes, scanning tunneling microscopy (STM), atomic force microscopy (AFM), ... are a basic tool in experimental condensed matter physics. The early transport experiments were carried out on graphene bilayers encapsulated on both sides by hexagonal boron nitride stacks. This set up provides a very clean and defect free environment, although it is not suitable for STM experiments. Nevertheless, a number of observations[3, 4, 5, 6] offered a wealth of information on the geometry and the electronic density of states of magic angle graphene. STM has also allowed to study in detail the way strains interfere with the twist angle and modify locally the moiré unit cell[7]. Local probes other than STM have provided important information on the spatial distribution of twist angles[8], or on inhomogeneities of topological features of the band structure[9]. The STM has also been applied to the study of possible correlated phases in twisted bilayer graphene[10, 11, 12].

2 STM as a tool to observe the superconducting order parameter.

The work which is the subject of this commentary[13, 14] deals with STM studies of the superconducting phase of the moiré system. Low temperature STM measurements in non encapsulated samples give convincing evidence of the existence of a superconducting gap in the range of electron densities where transport experiments show superconductivity. Junctions between normal metals and superconductors, or between different superconductors can provide valuable information on the superconducting state of the electrodes. Moreover, STM experiments allow for two complementary regimes: i) when the STM tip is far from the sample being studied, the so called tunneling regime, the dI/dV spectra of the junction is proportional to the local density of states of the substrate, ii) if the tip is near the sample, transport across the junction is due to a few, or even one, well connected channels, and Andreev reflection, that is, the transformation of an incoming electron into an outgoing hole, becomes possible at voltages below the superconducting gap. Hence, both regimes offer information on the nature of the superconducting phase of the substrate.

Ref.[13] shows spectroscopy data obtained both in the tunneling and in the contact regimes. Both results include features which differ significantly from those expected in an s-wave, constant gap superconductor. The tunneling data, which should describe the density of states of the superconductor, does not show a well defined gap over a finite range of energies, but rather a depressed density of states which seems to vanish at the Fermi energy. This result suggests a nodal gap, which goes to zero only at a discrete set of points of the Fermi surface. Experiments in the contact regime give a significant increase of the junction conductance near the Fermi energy, suggesting the existence of Andreev scattering within the superconducting gap. In addition, the ratio between the values of the gap and $k_B T_c$, where T_c is the critical temperature, is much smaller in the contact regime than in the tunneling regime, a finding which seems difficult to explain within the framework of a constant gap and s-wave pairing.

Ref.[14] also presents dI/dV curves in the contact and tunneling regimes, although for a superconducting trilayer sample. Results for the tunneling regime show two different behaviors: i) near a filling of $\nu = -2$ a U shaped gap is observed, while for $-3 \lesssim \nu \lesssim 2.2$ the spectrum seems more consistent wth a V shaped gap. Ref.[14] also reports, in the tunneling regime dip-hump features beyond the superconducting gap. In the contact regime, ref.[14] reports a peak at the Fermi energy, which suggests Andreev scattering within the superconducting gap. Unlike in[13], the ratio between the superconducting gap and the value of $k_B T_c$ observed in[14] is comparable to estimates based on transport measurements.

3 Discussion.

The results mentioned above shed light on the nature of the superconducting order parameter, altough they can be interpreted in different ways. The Fermi surface of twisted bilayer graphene, as in monolayer graphene and in graphite, must have, at least, two pockets, one per valley (unless the system is valley polarized). The existence of nodal superconductivity would imply that not only that the order parameter changes sign at different regions of the

Fermi surface, but that there is a change of sign within each valley. In addition, the different gap shapes reported in[14] suggest that a transition between different superconducting phases takes place as the band filling changes. The V shaped superconducting gap reported in[13] and in[14] can be consistent with $p-$ and $d-$wave order parameters around closed Fermi surface pockets in each valley. Ref.[14] suggests that the phase with an U shaped gap could be a strongly coupled superconductor, best described as a Bose-Einstein condensate. This point has been related to the observed subgap Andreev scattering using models presented in[15].

Subgap Andreev scattering is forbidden in a superconductor where the gap around the Fermi surface averages out to zero, if the tip is assumed to inject electron waves described by an equal amplitude superposition of all momenta. Such electron wave is transformed within the superconductor into and odd superposition of hole plane waves, which interfere destructively when they are reflected into the tip, see[16, 17]. In a superconductor where the order parameter changes sign between valleys, however, the tip can act as a pair breaking defect which induces intervalley scattering. This process leads to subgap Andreev states, which mediate Andreev scattering[13, 17]. The existence of these subgap states could explain the observed discrepancy between the ratio of the gap to the critical temperature and BCS theory.

The humps in the spectra above the superconducting gap have previously been interpreted in several types of superconductors as signatures of the excitations which mediate the pairing[18], or the effect of other superconducting phases[19], the "Leggett mode"[20]. It is interesting to note that different (ARPES) experiments performed by a collaboration which includes the team in[13] have reported "replica" bands in twisted bilayer graphene[21]. The positions of these bands are consistent with the transverse optical mode of graphene at the K point. The existence of these bands suggest a strong coupling between electrons and these TO phonons, which could lead to pairing[22]. The possibility of pairing due to optical phonons was discussed shortly after the discovery of twisted bilayer graphene[23]. The coupling between TO phonons and electrons leads to interesting instabilities[24, 25, 26], and the phonon band itself gets significantly flattened in a twisted bilayer[27].

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