Electronic correlations in bilayer-graphene superlattices

1. **Correlated insulator behaviour at half filling in magic-angle graphene superlattices**
   Authors: Yuan Cao, Valla Fatemi, Shiang Fang, Kenji Watanabe, Takashi Taniguchi, Efthimios Kaxiras, and Pablo Jarillo-Herrero
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2. **Unconventional superconductivity in magic-angle graphene superlattices**
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Recommended with a Commentary by Joerg Schmalian, Karlsruhe Institute of Technology

Twisting two periodic lattices against each other at a small angle gives rise to large-scale interference-like motives, so called moiré pattern. Twisting a graphene layer against a boron-nitride layer has been investigated in the recent past and gives rise to such pattern and a concomitant Hofstadter's butterfly spectrum in a magnetic field[1]. The physical behavior that emerges if one twists two single-layer graphene sheets against each other turns out to be even richer. The precise manipulation and twist of two graphene sheets was accomplished by Cao *et al.* in the above papers. Near a *magic* twist angle θ of about one degree a narrow band is expected to form from Wannier states of the large supercell[2, 3]. Cao *et al.* prepared such samples and identified correlated insulating, metallic, and superconducting states, depending on temperature and carrier concentration. In the context of correlated electron systems, the achieved ability to tune and manipulate a material is truly unique. The twist angle determines the electronic structure. The charge carrier concentration can be varied via a gate voltage over regimes that correspond to several carriers per unit cell.

The moiré patterns of the reported twist angles $\theta = 1.05^\circ$ and $\theta = 1.16^\circ$ have a lattice constant $a = a_0/\left(2\sin\left(\theta/2\right)\right)$ of about 50 times that of graphene, where $a_0 \approx 2.46\,\text{Å}$. This corresponds to approximately 8×10^3 carbon atoms per unit cell. Given indications for sample inhomogeneities, this makes the observations of low-T metallic charge transport impressive. Remember, closely-related quasicrystals display electron localization with a powerlaw-divergence of the resistivity[4]. Depending on the gate voltage, the carrier concentration was varied between $\pm 4n_0$ relative to the charge neutrality point of graphene, see

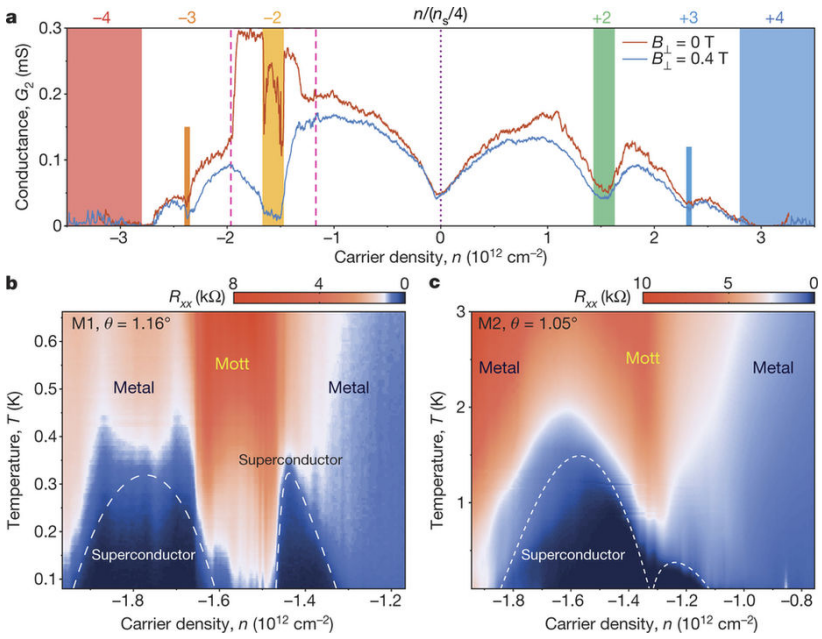

Figure 1: Fig.2 of the second paper by Cao *et al.*. **a**: Conductance for twist angle $\theta = 1.16°$ at zero magnetic field (red) and for $B_\perp = 0.4\,\mathrm{T}$ (blue). $n_0 = n_s/4$ is the electron density per unit cell. **b** and **c**: Resistance for different carrier concentration and T near $n = -2n_0$.

Fig. 1. Here, $n_0 = \frac{2}{\sqrt{3}a^2}$ corresponds to one electron per unit cell of the superlattice. For $\theta = 1.06°$ this yields $n_0 \approx 6.41 \times 10^{11}\mathrm{cm}^{-2}$.

Correlated insulators: For $n = \pm 4n_0$ a suppression of the conductivity is consistent with band-insulating behavior. In addition, activated transport with $d\rho/dT < 0$ for an intermediate temperature regime was observed at commensurate fillings $n = \pm 2n_0$ and less pronounced for $n = \pm 3n_0$. This behavior requires many-body interactions. Estimates of the matrix elements of the electron-electron Coulomb interaction show that they are comparable to the bandwidth. The precise nature of the insulating state is still unclear. The activation energy $E_\mathrm{g} \approx 0.3\,\mathrm{meV}$ of the resistivity is close to the temperature $T^* \approx 4\,\mathrm{K}$ above which metallic behavior sets in rather suddenly. Such behavior could be the result of a density-wave instability. Whether it is consistent with a Mott insulating state without additional symmetry breaking near T^* remains to be explored. At zero magnetic field, the insulator at half filling is in fact a metal ($\frac{d\rho}{dT} > 0$) for $T < 1\mathrm{K}$, but becomes truly insulating for a magnetic field $B_\perp = 0.4\mathrm{T}$ perpendicular to the planes. This hints at sample inhomogeneities, where superconducting regions short circuit the low-temperature transport. Increasing further the magnetic field up to $B_\perp = 8\mathrm{T}$ suppresses the activation energy and destroys the insulator. For moments of the order of a Bohr magneton, this field corresponds to energies comparable to the charge gap E_g and to T^* . The absence of sharp features in the resistance could suggest that no true symmetry breaking takes place. However, inhomogeneities of a random-field type can easily wash out a sharp transition of a discrete order parameter.

Slightly reducing the electron concentration from the $n = -2n_0$ insulator leads to a state with small Fermi surface volume, obtained via magneto-oscillation measurements, that grows linearly in x, where $x = -2n_0 - n$. At the same time the degeneracy of Landau levels

changes from the value four, observed elsewhere in the phase diagram (valley and spin), to two. Thus, the insulator breaks a symmetry that is related to these two quantum numbers. A small Fermi surface has only been observed for hope doping. Whether it is limited to a very narrow regime of electron doping or the system phase separates remains to be seen.

Superconductor: Superconductivity was observed near the insulator at $n = -2n_0$, see Fig. 1. So far, no superconductivity was observed near $n = +2n_0$, i.e. on the "other side" of the charge neutrality point of graphen. With the mentioned strong asymmetry w.r.t. electron and hole doping relative to $n = -2n_0$, it is curious that superconductivity occurs on both sides, albeit over a narrower density range on the electron-doped side. No superconductivity was observed once a large Fermi surfaces emerges. Transition temperatures up to $T_c = 1.7\,\mathrm{K}$ for hole doping are surprisingly large for a system with an estimated band width of a few millivolts. If one could scale this up to the band width of mercury, the first superconductor to be discovered, it would amount to a transition temperature above $10^4\,\mathrm{K}$. For an in-plane magnetic field, the superconductivity is Pauli-limited, as expected for singlet pairing. From the upper-critical field perpendicular to the plane, a superconducting coherence length of 52nm was estimated, only about five lattice constants of the superlattice! Finally, Cao *et al.* interpret oscillations of the current with $B_\perp$ in terms of Josephson-junction-array interferences. This implies spatial homogeneities that are correlated in space, an observation that clearly deserves further attention.

From a the point of view of the charge-density distribution, the superlattice forms a triangular lattice near those regions where carbon atoms of the same sub-lattices are right on top of each other. However, from a symmetry point of view the appropriate low-energy model is a two-orbital hexagonal lattice[5, 6]. The former should be relevant for local, energetic arguments[7, 8] while the latter must be important if one wants to identify the broken symmetries near commensurate fillings. Those could then be tied to the mechanism for superconductivity.

Whether magic-angle twisted bilayer graphene will offer a blue print to solve the hight-T_c problem remains to be seen. There are close analogies and clear differences between the two systems. Nevertheless, the similarity in the phase diagrams does suggest a universal set of principles for unconventional superconductivity, valid for systems with different lattice symmetry and orbital degeneracy. Even if it turns out that cuprates and twisted bilayer graphene are fundamentally different, it would hardly make this discovery less interesting. A key novelty of the work by Cao *et al.* is the achieved control over the material. The relevant degrees of freedom are determined by a comparatively unostentatious chemistry. Thus, the low-energy model is much better defined, making it harder to "re-adjust" theories. One can therefore be optimistic that the community will soon be able to understand this fascinating synthetic quantum material.

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