



## Congratulations to New ICFO PhD Graduate

Dr. Ipsita Das graduated with a thesis entitled 'Investigation of the Interaction Driven Quantum Phases in Magic-Angle Twisted Bilayer Graphene'

May 24, 2023

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We congratulate Dr. Ipsita Das who defended her thesis today in ICFO's Auditorium. Dr. Das obtained her MSc in Physics from the Jadavpur University in India. She joined the Low-dimensional quantum materials research group at ICFO led by Prof. Dr. Dmitri Efetov as a PhD student. Dr. Das' thesis entitled 'Investigation of the Interaction Driven Quantum Phases in Magic-Angle Twisted Bilayer Graphene' was supervised by Prof. Dr. Dmitri Efetov.

### **ABSTRACT:**

The discovery of two dimensional materials opened a unique pathway to study the electronic properties of quantum materials which are otherwise absent in bulk systems. Soon after the discovery of graphene (2004), a plethora of 2D materials were found with various diverse

properties such as, metals, insulators, semiconductors, superconductors, magnets etc. These materials can be assembled by using the van der Waals (vdW) force, which greatly extends the possibilities of studying new phenomena. Initially vdW heterostructures have been made by vertically stacking different layers. However, twist angle plays an interesting tuning knob to engineer the electronic properties of the 2D heterostructures. Following long standing theoretical predictions, people have observed exotic quantum phenomena in twisted bilayer graphene in 2018.

In this thesis, we have studied the electronic properties of magic angle twisted bilayer graphene (MATBG), which consists of two graphene layers rotated by an angle  $\theta = 1.1^\circ$ . It has been experimentally shown that MATBG possesses flat electronic bands in the low energy scale, which hosts multiple correlated phenomena such as correlated insulators, superconductivity, magnetism etc

We studied different phases of MATBG in the presence of a magnetic field to reveal the zero-field ground state of the system. In the presence of a small magnetic field ( $B < 3$  T), the Hall conductance of MATBG shows quantisation with the Chern numbers  $C = \pm 1, \pm 2, \pm 3$  and  $\pm 4$  which nucleate from different integer fillings of the moire bands,  $\nu = \pm 3, \pm 2, \nu$

1 and 0 respectively. These phases can be interpreted as spin and valley polarized many body Chern insulators. The exact sequence and correspondence of the Chern numbers and filling factors suggest that these states are directly driven by electronic interaction, which specifically break the time-reversal symmetry in the

system. We have also studied the evolution of the phase space of MATBG in high magnetic field and explored the Hofstadter spectrum. Due to the large moire unit cell area, MATBG reaches one full flux quantum ( $\Phi_0$ ) per moire unit cell close to 30 T. We studied a detailed magneto-transport behaviour of MATBG upto  $B = 31$  T. At  $\nu_0$ , reentrant correlated insulators are observed at  $\nu = +2, +3$ . Interaction driven Fermi surface reconstruction is also observed at other fillings of the band which are identified by the emergence of a new set of Landau level

(LLs). We further studied the higher energy dispersive bands in the presence of a magnetic field. The analysis of the LL crossings in the Rashba-like dispersive bands enables a parameter free comparison to a newly derived magic series of level crossings in a magnetic field and provides constraints on the parameters of the Bistritzer-MacDonald Hamiltonian. For the first time, this allows us to experimentally verify the band structure of

MATBG. In the next section of this thesis, we have studied the effect of Coulomb screening on the ground state of the quantum phases such as correlated insulator and superconductor. The coexistence of these two states prompts intriguing questions about their relationships. We have directly tuned the electronic correlations by changing the separation between the graphene and a metallic screening layer. Correlated insulators are suppressed when the separations are smaller than the typical Wannier orbital size ( $\sim 15$  nm) and also in devices with twist angles slightly away from magic angle ( $\theta = 1.1^\circ \pm 0.05^\circ$ ). Upon extinction

ion of the insulating orders, the vacated phase space is taken over by the superconductors. Finally, we study the temperature dependence of the resistance and unveil a strange metal phase up to a very low temperature  $T = 40$  mK. We thus have experimentally demonstrated the effect of several external parameters (magnetic field, screening, temperature etc.) on the ground state of MATBG and how they alter the microscopic mechanism of different correlated phenomena in

**Thesis Committee:**

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