HL 19: Focus Session: Strongly Correlated Quantum States in Moire Heterostructures (joint session TT/HL/MA)

In recent years, significant progress has been made in realizing and exploring correlated quantum states in multilayer moiré heterostructures of graphene or transition metal dichalcogenides. These achievements have been made possible by the high level of control and tunability of these systems. Striking phenomena have been demonstrated experimentally, including unconventional superconductivity, fractional quantum anomalous Hall states, Mott-Wigner states and density waves, as well as kinetic ferromagnetism. Moreover, recently novel spectroscopic experimental techniques have been developed which allow for new ways to explore the dynamical response of these exotic states. This focus session will discuss recent experimental advancements as well as theoretical developments in the field of strongly correlated moiré heterostructures.

Organizers: Dmitri K. Efetov (LMU München), Michael Knap (TU München)

Time: Tuesday 9:30–13:15 Location: H36

Topical Talk HL 19.1 Tue 9:30 H36

The Thermoelectric Effect and Its Natural Heavy Fermion Explanation in Twisted Bilayer and Trilayer Graphene — Dumitru Calugaru[1], Haoyu Hu[2], Rafael Luque Merino[3], Nicolas Regnault[4], Frank Koppens[3], Dmitri K. Efetov[5], and •Bogdan Andrei Bernevig[1] — [1]Dept of Physics, Princeton University, Princeton, USA — [2]DIPC, San Sebastián, Spain — [3]ICFO, Barcelona, Spain — [4]Laboratoire de Physique de l'ENS, Paris, France — [5]LMU Munich, Munich, Germany

We study the interacting transport properties of twisted bilayer graphene (TBG) using the topological heavy-fermion (THF) model, where TBG comprises localized, correlated f-electrons and itinerant, dispersive c-electrons. The Seebeck coefficient of TBG exhibits unconventional traits: negative values with sawtooth oscillations at positive fillings, contrasting typical band-theory expectations. This behavior arises from the dichotomy between heavy (short-lived, correlated f-electrons) and light (long-lived, dispersive c-electrons), with transport dominated by c-electrons due to their stronger dispersion and longer lifetimes. At positive integer fillings, c- (f-)electron bands govern the electron (hole) doping side, resulting in an overall negative Seebeck coefficient. Sawtooth oscillations occur near each integer filling due to gap openings. Our results underscore the importance of electron correlations and lifetime asymmetry, naturally captured by the THF model, in understanding TBG transport properties. These findings align with experiments on twisted bilayer and trilayer graphene and highlight the interplay of heavy and light carriers.

Topical Talk HL 19.2 Tue 10:00 H36

Angle-Tuned Chiral Phase Transition in Twisted Bilayer Graphene — •Laura Classen[1,2], Nikolaos Parthenios[1,2], Cheng Huang[3], Xu Zhang[3], Maksim Ulybyshev[4], Fakher Assaad[3], and Zi Yang Meng[4] — [1]Max Planck Institute for Solid State Research — [2]Technical University of Munich — [3]University of Hong Kong — [4]University of Wuerzburg

The twist angle constitutes an important control knob in twisted bilayer graphene that has become accessible in-situ. It effectively tunes between weakly interacting, decoupled graphene layers and strongly correlated electrons at a magic angle of around 1.1 degree. We propose that this facilitates the realisation of a chiral phase transition of Dirac fermions at charge neutrality in twisted bilayer graphene. We argue that the transition can be described by the Gross-Neveu-Yukawa model that couples Dirac fermions and an XY order parameter field. The quantum critical behavior of this effective model is consistent with quantum Monte Carlo simulations of the continuum model for twisted bilayer graphene.

Topical Talk HL 19.3 Tue 10:30 H36

Quantum Optics of Semiconductor Moire Materials — •Atac Imamoglu — Institute of Quantum Electronics, ETH Zurich

Moire superlattices in two dimensional semiconductors have enabled the observation of a wealth of phenomena driven by strong electronic correlations, ranging from Mott-Wigner states to fractional quantum anomalous Hall effect. In this talk, I will present experiments exploring quantum optical control of strongly correlated electrons.

15 min. break

Topical Talk HL 19.4 Tue 11:15 H36

Probing the Band Structures of Multilayer Graphene Using the Quantum Twisting Microscope — •Martin Lee[1,2], Ipsita Das[1,2], János Papp[1,2], Marc Currle[1], Jiazhuo Li[1,2], Mudit Bhatt[1,2], Jonah Herzog-Arbeitman[3], Jiabin Yu[3], Zhiyuan Zhou[3], Markus Becherer[4], Philipp Altpeter[1], Christian Obermayer[1], Heribert Lorenz[1], Kenji Watanabe[5], Takashi Taniguchi[5], Bogdan Andrei Bernevig[3,6,7], and Dmitri Efetov[1,2] — [1]Fakultät für Physik, Ludwig-Maximilians-Universität, München, Germany — [2]Munich Center for Quantum Science and Technology, München, Germany — [3]Department of Physics, Princeton University, Princeton, New Jersey, USA — [4]School of Computation Information and Technology, Technical University of Munich, Germany — [5]National Institute of Material Sciences, Tsukuba, Japan — [6]Donostia International Physics Center, Donostia-San Sebastian, Spain — [7]IKERBASQUE, Basque Foundation for Science, Bilbao, Spain

Understanding the band-structure is foundational in describing the behavior of electrons in crystalline systems. While the tight-binding model effectively captures the non-interacting band-structures in materials like graphene, it relies on analytically or numerically derived hopping parameters. In this talk, we present the development of a quantum twisting microscope (QTM), which allows the k-resolved tunneling spectroscopy between the electronic states at the 2D tip and the 2D sample by twisting in-situ. Our QTM measurements allow us to extract the hopping parameters that agree with theoretical predictions.

Topical Talk HL 19.5 Tue 11:45 H36

Gate-Tunable Bose-Fermi Mixture in a Strongly Correlated Moiré Bilayer Electron System — •Nathan Wilson[1], Amine Ben Mhenni[1], Wilhelm Kadow[2], Mikołaj Metelski[1], Adrian Paulus[1], Alain Dijkstra[1], Jonathan Finley[1], and Michael Knap[2] — [1]Walter Schottky Institute, TU Munich, Garching, Germany — [2]School of Natural Sciences, TU Munich, Garching, Germany

Quantum gases consisting of species with distinct quantum statistics, such as Bose-Fermi mixtures, can behave in a fundamentally different way than their unmixed constituents. This makes them an essential platform for studying emergent quantum many-body phenomena such as mediated interactions and unconventional pairing. Here, we realize an equilibrium Bose-Fermi mixture in a bilayer electron system implemented in a WS_2/WSe_2 moiré heterobilayer with strong Coulomb coupling to a nearby moiré -free WSe2 monolayer. Absent the fermionic component, the underlying bosonic phase manifests as a dipolar excitonic insulator. By injecting excess charges, we show that the bosonic phase forms a stable mixture with added electrons but abruptly collapses upon hole doping. We develop a microscopic model to explain the unusual asymmetric stability with respect to electron/hole doping. By monitoring excitonic resonances from both layers, we demonstrate stability of the phase over a wide range in the boson/fermion density phase space, in agreement with theoretical calculations. Our results further the understanding of phases stabilized in moiré bilayer electron systems and demonstrate their potential for exploring the exotic properties of equilibrium Bose-Fermi mixtures.

HL 19.6 Tue 12:15 H36

Theory for Optical Control of Correlated States in

Moiré Transition Metal Dichalcogenide Heterostructures — •Haoyang Tian and Urban Friedrich Peter Seifert — Institut für Theoretische Physik, Universität zu Köln, Zülpicher Str. 77a, 50937 Köln, Germany

In recent years, moiré transition metal dichalcogenide (TMD) heterostructures have emerged as highly versatile platforms for investigating phases and phenomena of strongly correlated electrons on emergent lattice scales. However, experimental characterization of the precise nature of some interaction-driven long-range ordered states and their excitations has remained a challenge. Given strong light-matter couplings and valley selection rules in TMD materials, ultrafast optical methods may constitute a promising avenue for probing and controlling these states and their collective modes. In this work, we develop a theoretical framework to describe coherent light-matter interactions in moiré TMD heterostructures, and model the system's steady-state and non-equilibrium dynamics during and after photoexcitation with a laser pulse. Thus obtained characteristic signatures of the system's dynamics may allow for new experimental insights.

HL 19.7 Tue 12:30 H36

Single-Particle Spectral Function of Fractional Quantum Anomalous Hall States — •Fabian Pichler[1,2], Wilhelm Kadow[1,2], Clemens Kuhlenkamp[3,1,2], and Michael Knap[1,2] — [1]Technical University of Munich, TUM School of Natural Sciences, Garching, Germany — [2]Munich Center for Quantum Science and Technology (MCQST), München, Germany — [3]Department of Physics, Harvard University, Cambridge, Massachusetts, USA

Fractional quantum Hall states are the most prominent example of states with topological order, hosting excitations with fractionalized charge. Recent experiments in twisted $MoTe_2$ and graphene-based heterostructures provide evidence of fractional quantum anomalous Hall (FQAH) states, which spontaneously break time-reversal symmetry and persist even without an external magnetic field. Understanding the unique properties of these states requires the characterization of their low-energy excitations. To that end, we construct a parton theory for the energy and momentum-resolved single-particle spectral function of FQAH states. We explicitly consider several experimentally observed filling fractions as well as a composite Fermi liquid in the half-filled Chern band. The parton description captures qualitatively our numerical exact diagonalization results. Additionally, we discuss how the finite bandwidth of the Chern band and the non-ideal quantum geometry affect the fractionalized excitations. Our work demonstrates that the energy and momentum-resolved electronic single-particle spectral function provides a valuable tool to characterize fractionalized excitations of FQAH states in moiré lattices.

HL 19.8 Tue 12:45 H36

Tuneability of Superconducting Properties in Transition Metal Dichalcogenide bilayers — •Michael Winter and Tim O. Wehling — I. Institut für Theoretische Physik, Universität Hamburg, Notkestraße 9-11, 22607 Hamburg

In recent years, rising interest sustained in van der Waals materials, particularly in transition metal dichalcogenides (TMDs or TMDCs). This work explores the potential for bilayer [hetero-]structuring in TMDs, which have garnered significant attention due to the discovery and prediction of exotic quantum phases, such as superconductivity and Mott insulating behaviour.

I present predictions derived from a minimal quantum lattice model, incorporating ab initio calculations based on plane-wave density functional theory (DFT), density functional perturbation theory (DFPT), and subsequent electron-phonon interaction calculations. The resulting model allows us to investigate the effects of different material combinations (e.g., MoS_2, $MoSe_2$, WS_2, WSe_2) and electron doping on superconductivity in such [hetero-]bilayer.

HL 19.9 Tue 13:00 H36

Proximity-Induced Spin-Triplet Superconducting Correlations in Transition Metal Dichalcogenides — •Florian Kayatz, Jorge Cayao, and Annica Black-Schaffer — Department of Physics and Astronomy, Uppsala University, Box 516, S-751 20 Uppsala, Sweden

The realization of spin-triplet Cooper pairs is a key ingredient for superconducting spintronics. One promising route to achieve this task is by exploiting the strong intrinsic spin-orbit coupling of transition metal dichalcogenides (TMDs). In this work, we consider a TMD layer coupled to a conventional spin-singlet s-wave superconductor and demonstrate the emergence of spin-triplet superconducting correlations. We find that these spin-triplet pair correlations form in the TMD as a proximity-induced effect but also appear in the superconductor as an inverse proximity effect and as a nonlocal phenomenon that exists between the TMD and superconductor. Furthermore, we relate these emergent superconducting correlations to experimentally observable features in the density of states and conductance.