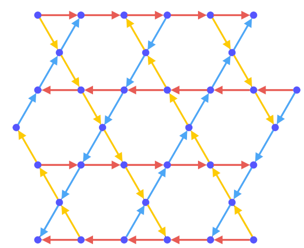
Master Thesis Projects 2024

Theory of Quantum Matter, Prof. Titus Neupert

INTERPLAY OF SUPERCONDUCTIVITY AND LOOP-CURRENT ORDER



The family of Kagome metals AV_3Sb_5 with A = K, Rb, Cs has attracted a lot of attention in the last few years for the host of exotic ordered phases its members exhibit. In particular, all three members enter a charge density wave phase—a phase where charge redistributes thereby increasing the unit cell of the lattice—at T_{CO} ~ 100 K and below T_c ~ 2 K they become superconducting. From a theoretical perspective, the Kagome lattice of vanadium (V) atoms allows for a multitude of intriguing charge orders, some with loop currents inducing flux pattern in the plane. Such flux orders would indeed be consistent with some experimental indications of time-reversal-symmetry breaking. However, at present neither the exact form of the charge order below T_{CO} nor the nature of the superconducting state are known.

The goal of this project is to study the interplay of loop-current order and superconductivity. Specifically, we want to understand the microscopic origin of possible couplings between the different phases. In the process, we gain a better understanding of currently available experiments and hope to be able to propose new experimental probes for the different combinations of ordering.

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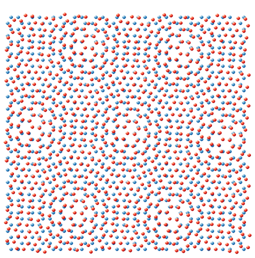
Keywords: (un)conventional superconductivity, symmetry arguments (aka group theory), effective models

CORRELATED PHASES IN TWISTED BILAYER GRAPHENE



Twisted bilayer graphene is an iconic system that has drawn a lot of interest due to the presence of flat bands. Flat bands mean the kinetic energy is suppressed compared to the interaction energy and therefore this provides the ideal place to look for strongly correlated phases. Examples of such exotic phases are quantum Hall phases, where the electrons are strongly entangled. Experiments this year have demonstrated that strain is crucial for understanding the states in twisted bilayer graphene. Encouraged by this, this project will aim to perform the first exact diagonalization study of twisted bilayer graphene with strain. We expect to recover the states that were observed in the experiments and can compare our results to these measurements. This project is suited for a student who has a keen interest in learning and applying a new numerical technique (exact diagonalization). Prior experience with python is an advantage.

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Keywords: twisted bilayer graphene, numerical methods

APPROXIMATE HILBERT SPACE FRAGMENTATION IN TRANSMON CHAINS

The phenomenon of many-body localization plays a key role in the operation of superconducting transmon based quantum processors, such as those being developed by IBM and Google. The behavior of computational states, as the system transitions from a localized to a chaotic phase, is an interesting problem to explore. The goal of this project is to study potential Hilbert space fragmentation in a disordered transmon chain using graph theoretic clustering approaches.
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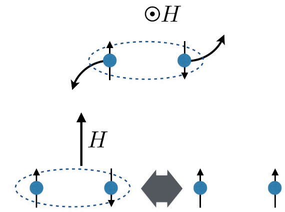
Keywords: many-body localization, Hilbert space fragmentation, graph theory

MICROSCOPIC INVESTIGATION OF THE UPPER CRITICAL FIELD OF A SUPERCONDUCTOR

The coupling of an external magnetic field to the electrons in a material may destroy the superconducting state through Zeeman coupling or the coupling to the electrons' orbital motion. The latter coupling, often the relevant contribution, can be introduced through minimal coupling or, on the level of a tight-binding description, through Peierl's substitution and will gradually decrease the transition temperature. The question arises at which critical field H_{c2} a material's critical temperature reaches zero. This critical field is of interest both from an applied as well as from a fundamental perspective—the magnitude of H_{c2} and the shape of the transition line can give insights into the microscopic details of the superconducting order parameter.

The starting point of this project is a tight-binding Hamiltonian on a square lattice including a pairing-interaction term. Both analytical and numerical approaches will be required to arrive at and eventually solve a self-consistency equation for the order parameter and consequently, the critical temperature. In a further step, multiple orbitals or different couplings to the magnetic field, for example Zeeman coupling, can be included. Such complications will be crucial to understand the magnetic field–temperature phase diagram of superconductors of current interest, like the Kagome superconductors, Sr_2RuO_4, or $CeRh_2As_2$. Ultimately, we want to work towards crafting a numerical tool to find the upper critical field for arbitrary functional forms of the order parameter and complicated band structures.



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Keywords: unconventional superconductivity, effective modeling, numerical methods