PhD thesis proposal

Subject : Topology and symmetry breaking in flat bands
Group : Laboratoire de Physique et Modélisation des Milieux Condensés (LPMMC UGA/CNRS)
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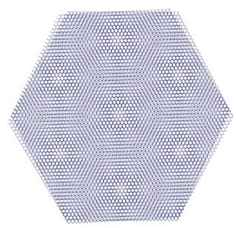
Context : topological flat bands Band theory tells us a lot about the macroscopic properties of materials, from insulating to metallic behavior. Yet, when a band is flat (i.e. it consists of many degenerate eigenstates), and partially filled, interactions play an essential role and the approximation of independent electrons is not a helpful starting point. When the flat band is additionally topological, this can lead to especially exotic phases, such as the fractional quantum Hall (FQH) effect, whose excitations have a fractional statistics intermediate between boson and fermions. Other phases, such as charge density waves, and metals are possible as well [1]. Knowing which microscopic model leads to which many-body phase is a central goal in quantum matter.

PhD project This PhD aims to establish a direct connection between single-particle attributes and many-body phases in flat topological bands. The first example of a topological flat band is the Landau level, obtained when a 2D electron gas is subjected to a large transverse magnetic field. It belongs to a large family of topological flat bands, sharing the same energetic and topological properties, but distinguished by their quantum geometry, a property of the band's single-particle wave functions. Within this family, some bands (including the Landau level) are deemed 'ideal': they have a symmetry, which makes it possible to write down exact many-body wave functions analytically [2, 3]. In particular, ideal bands admit fractional quantum Hall (FQH) states as their exact ground state. In spite of this powerful property, the ground state is not necessarily gapped. We will investigate how the quantum geometry of ideal bands determines the FQH gap. To understand the phase transition between FQH and competing (symmetry broken or metallic) phases, we will show how to close this gap. We will use the ideal band concept to understand what determines several other phenomena occuring in topological flat bands [4, 5], such as ferromagnetism, skyrmion transport, or exciton condensation. Whenever possible, we will apply our findings to relevant 2D materials (especially in the context of moiré materials), and compare them with experimental results [6].

Methods
analytical (holomorphic wave functions, projection of interactions onto a degenerate subspace)
numerical (exact diagonalization, diagonalization of non-interacting continuum models)

References

1. Fractional Quantum Hall Physics in Topological Flat Bands, Parameswaran, Roy, Sondhi, CRP 2013
2. Ledwith, Tarnopolsky, Khalaf, Vishwanath Phys. Rev. Research 2020
3. Wang, Cano, Millis, Liu, Yang Phys. Rev. Lett. 2021
4. Ferromagnetism in narrow bands of moiré superlattices, Repellin, Dong, Zhang, Senthil, Phys. Rev. Lett. 2020
5. Chern bands of twisted bilayer graphene: Fractional Chern insulators and spin phase transition, Repellin, Senthil, Phys. Rev. Research 2020
6. Fractional Chern insulators in magic-angle twisted bilayer graphene, Y. Xie et al Nature 2021
7. Tarnopolsky, Kruchkov, and Vishwanath, Phys. Rev. Lett. 2019



Twisted bilayer graphene, at magic rotation angle 1.1°, once aligned with its substrate, is an example of a topological flat band.
A small adjustment of its model results in an ideal band [7].