PhD THESIS DEFENSE: Theoretical models for quantum simulators of novel materials and devices

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Over the past three decades, optically trapped ultra-cold atoms have served as a versatile platform for controlled exploration of numerous condensed matter phenomena. The successful fabrication of magic angle twisted bi-layer graphene (MATBG) has introduced a for condensed matter physicists, while concurrently posing a novel challenge for the quantum simulation community. This thesis is devoted to addressing this problem, focusing mainly on the simulation of MATBG structures using ultra-cold atoms within its initial three chapters.
To overcome the issue of unit cell expansion resulting from rotation misalignment, in the first chapter we propose the concept of "twist-less twistronicsi¿½ (twistronics, a term coined fr m twist and electronics). This innovative notion involves replacing the physical rotation of o

e layer with a light-modulated hopping amplitude between the layers. Enabled by t
e architecture of ultra-cold atoms, this approach yields quasi-flat bands, a pivotal ingredie
t for collective phenomena observed in Magic-Angle Twisted Bilayer Graphene (MATBG
, achieved at significantly reduced unit cell size
. The opening chapter also presents a suitable experimental set-up. Moreover, it provides
a comprehensive theoretical framework, including tight-binding calculations and effecti
e models derived from perturbative analysis. The second chapter delves into the topologic
l properties of an analogous system, emphasizing the energy separation between t
e quasi-flat bands and the resulting spectrum. We demonstrate Quantum Anomalous Ha
l Effect across diverse parameter regimes, accompanied by an exhaustive phase diagram wi
h respect to tunable parameter
. In the third chapter, we extend our investigation to encompass onsite, density-densi
y attractive interactions between lattice atoms. Employing the Hartree-Fock-Bogoliub
v mean-field approximation, we consider all feasible interaction channels within/betwe
n layers and spins. This chapter aims to elucidate the relationship between band flattening,
a fully controlled parameter in our system, and the emergence/size of a superconductive ga
. Notably, we uncover a substantial enhancement in the critical (Kosterlitz-Thoules
) temperature within the quasi-flat band regime at quarter filling, along with a comprehensi
e diagram illustrating superconducting order parameters corresponding to each interacti
n channe
. The fourth chapter marks a departure from condensed matter simulations, delving in
o "special purpose quantum computing" within the context of quantum batteries. The
e devices, analogous to their classical counterparts, store and release energy on demand,
a process inherently governed by the battery Hamiltonian. Our work establishes a nov
l framework for assessing quantum battery performance and setting fundamental bounds
n two key attributes: power and capacity. We investigate the essential Hamiltonian terms of
a for achieving quantum speed-up in battery chargin
. The last, fifth chapter describes the theoretical tools, that have been used to support the fir
t experimental realisation of the Extended Bose Hubbard model with dipolar excitons.
e discuss the parameters of interests and important observables, such as a structure factor a
d discuss both the exact diagonalization and mean-field methods, which were necessary
o verify the observation of strongly correlated phases at half and unit fillin

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