PhD THESIS DEFENSE: Controlling interactions in quantum materials: from a microscopic description to quantum simulation

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The last decades have witnessed impressive technical advances in all the fields of quantum science, including solid-state systems or atomic, molecular, and optical physics, allowing one to control materials at the microscopic scale with a high degree of precision. This development opens the road for the investigation of complex many-body phenomena in quantum materials, which cannot be easily inferred from the behavior of their individual constituents. Indeed, interactions in quantum many-body systems can lead to richer physics compared to the noninteracting case, as they are deeply connected with spontaneous symmetry breaking, quantum correlations, i.e., entanglement, and some collective behaviors.

On the one hand, in some cases, the motivation to study such interacting systems is the possibility to synthesize them in the lab, such as for instance with cold atoms in optical lattices. The latter platform can be used as a quantum simulator of systems that were regarded just as toy models in the last century, as it is the case of topological insulators: materials characterized by a global topological invariant leading to protected surface modes. While so far experiments have concentrated their efforts on engineering noninteracting topological insulators, state-of-the art techniques can also be used to study the role of interactions in these systems.

In this context, the first goal of this thesis is to investigate novel effects i interaction-induced topological insulators. In the one-dimensional case, we reveal th topological nature of fermionic chains with frustrated interactions, which could be realize with dipolar quantum gases. For the two-dimensional case, we focus on topological Mot insulators, for which we propose an experimental scheme based on Rydberg-dressed atoms Furthermore, we show that these systems can exhibit rich spatial features intertwined wit their topological protection, owing to the interacting nature of the phase

On the other hand, there are some paradigmatic cases, as in high-Tc superconductors, wher exotic experimental results clearly point towards the need of finding a microscopic model i a many-body interacting framework. In the particular case of high-Tc superconductors, thei complex composition and unknown exact form of intrinsic interactions make it challenging t characterize their rich phase diagram: such materials not only host a high-T superconducting phase, but also other exotic phases, such as the strange metal o pseudogap phases. In this regard, the second goal of this thesis is to gain physical insight o the pseudogap phase of cuprate high-Tc superconductors. To this aim, we numerically stud the effect of interactions between electrons and bond phonons within a particula Hamiltonian modeling of the system. We show that, by properly accounting for the subtl interplay between electron-electron and electron-phonon interactions, one can indee numerically reproduce the main experimental features of the pseudogap phase

Finally, the study of collective interaction-induced effects is also needed to analyze th quantum advantage theoretically claimed for some systems. In particular, many-bod interactions and entanglement are sometimes regarded as a resource for quantu thermodynamic machines: devices that perform tasks related to refrigeration, heat-to-wor conversion, or energy storage. On this basis, the third goal of this thesis is to stud fundamental bounds imposed by quantum mechanics to collective charging effects i systems for energy storage, called quantum batteries

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