



Congratulations to New ICFO PhD Graduate

Dr Sergi Julia Farre graduated with a thesis entitled *Controlling interactions in quantum materials: from a microscopic description to quantum simulation*

June 28, 2022

We congratulate Dr Sergi Julia Farre who defended his thesis today in ICFO's auditorium. Dr Julia Farre obtained his MSc degree in Physics from the University of Innsbruck, in Austria. He joined the Quantum Optics Theory research group at ICFO led by ICREA Prof at ICFO Dr Maciej Lewenstein as a PhD student. Dr Julia Farre thesis entitled *Controlling interactions in quantum materials: from a microscopic description to quantum simulation* was supervised by ICREA Prof Dr Maciej Lewenstein

ABSTRACT:

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 in interaction-induced topological insulators. In the one-dimensional case, we reveal the topological nature of fermionic chains with frustrated interactions, which could be realized with dipolar quantum gases. For the two-dimensional case, we focus on topological Mott 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 with their topological protection, owing to the interacting nature of the phase.

On the other hand, there are some paradigmatic cases, as in high- T_c superconductors, where exotic experimental results clearly point towards the need of finding a microscopic model in a many-body interacting framework. In the particular case of high- T_c superconductors, their complex composition and unknown exact form of intrinsic interactions make it challenging to 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 or pseudogap phases. In this regard, the second goal of this thesis is to gain physical insight on the pseudogap phase of cuprate high- T_c superconductors. To this aim, we numerically study the effect of interactions between electrons and bond phonons within a particular Hamiltonian modeling of the system. We show that, by properly accounting for the subtle interplay between electron-electron and electron-phonon interactions, one can indeed numerically reproduce the main experimental features of the pseudogap phase.

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

systems for energy storage, called quantum batteries

Thesis Committee:

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