Polariton and circuit QED lattices: solid-state platforms for quantum simulations of correlated and topological states — PhD project-area description

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Ever since the original proposal for the idea of quantum simulations, the search for suitable physical platforms and their improvement has been one of the most active and successful branches of Quantum Technologies. Proposed platforms range from cold atoms and ions, nuclear and electronic spin, superconducting circuits, electrons on liquid helium to photonic systems. The applications are wide-ranging and aimed at understanding the most difficult condensed matter problems: Hubbard and spin models, quantum phase transitions, disordered and frustrated systems, spin glasses, superconductivity, topological order and open quantum systems as well as questions in high-energy, nuclear physics and cosmology. Although some effects have already been demonstrated, there are several obstacles tampering a smooth evolution of this field such as difficulty to dissipate energy (or remove entropy) in order to reach a ground state for low-energy problems (cold atoms), scalability, disorder, access to information etc...

The aim of our research in collaboration with leading experimental groups (Sheffield, Paris, Berlin and Bar Ilan) is to explore the recently emerged solid-state platforms, that of polariton lattices[1] (see Fig. 1) and superconducting qubits[2], and to optimise them for the holly grails of quantum simulations: **correlated regime** and **topological protection**.

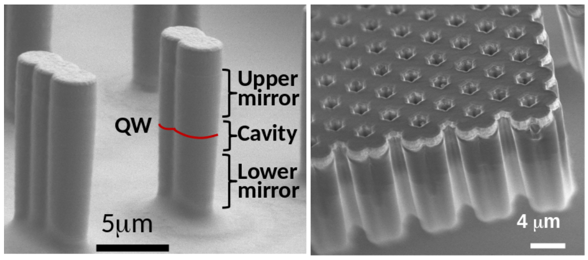

FIG. 1: Left: Two and three coupled micropillars. Right: honeycomb lattice of micropillars.

Superconducting qubits and circuit-QED architectures, with their scalability to arrays and lattices, versatility (e.g. engineering different Hamiltonians) and high level of control, are an ideal platform to explore the physics of driven-dissipative but correlated spin-boson systems, and their potential for quantum technologies. The fabrication of large lattices went under way with a range of geometries, even those that do not exist in nature (e.g. hyperbolic lattices leading to curved space[2]). Microcavity polaritons are mixed light-matter quasiparticles with extraordinary nonlinear properties. Due to their very light effective mass, of the order of 10^{-5} of an electron mass, quantum effects can persist to higher, even room temperatures. Photon polarisation gives rise to new types of spin-orbit coupling effects when combined with lattice geometries. Additionally, either by using their nonlinear character, or their sensitivity to magnetic fields, polaritons in a lattice could give rise to chiral edge states with topologically protected transport [3]. Spatially resolved measurements are possible with a single site resolution which enables to study hidden orders. The theoretical methods such as Matrix-Product States or DMRG are only in the process of being generalised to non-equilibrium driven/dissipative systems. So polariton lattices, which can be easily studied in a condition of dissipative-driven steady-state, can be used as simulator of non-equilibrium phase transitions to compare with outcomes from such methods, and help to develop them.

The aim of a PhD project is to develop techniques to study correlated and topological effects in conditions of drive, dissipation and non-equilibrium in collaboration with experimental groups following one or more of the below:

- Extension of stochastic phase space methods developed for driven-dissipative bosonic systems [4] to account for **strong correlations and entanglement** (application to polariton lattices);
- Development of stochastic phase space methods for **driven-dissipative spin** systems and their extension to account for **strong correlations** (application to circuit QED lattices);
- Study correlation between two (or a few) lattice sites using exact quantum optics methods (Master equations, quantum jumps and stochastic Schroedinger eqns);
- Analytical methods: mean-field approximation, Keldysh Field theory, Renormalisation Group;
- Development of **tensor network** methods for **driven-dissipative** systems.

a. Systems to look at:

- **Polariton Lattices:** phase transitions and topological defects in weak lattices of Surface Acoustic Waves (SAW), exotic quantum correlations in chains and lattices of polariton micro-pillars;
- **Circuit QED lattices:** collective effects in many-spin-cavity systems and lattices, symmetry protected topological states in spin systems with short and long range interactions.

b. Phenomena to explore:

The non-equilibrium phase transitions, orders, critical properties, topological defects, non-trivial topological states in driven-dissipative but strongly interacting polariton (bosonic) and circuit QED (spin-boson) lattices.

To study the formation and the propagation of entanglement, examine its robustness to dissipation, and design settings to optimise the quantum correlations and entanglement in open systems using small chains of polariton micro-pillars and of superconducting qubits.

[1] Exciton-polaritons in lattices: A non-linear photonic simulator A. Amo and J. Bloch, *C. R. Physique* 17 (2016) 934; D. Tanese et al., *Nature Comm.* 4, 1749 (2013); M. Abbarchi et al., *Nature Phys.* 9, 275 (2013).
[2] A. J. Kollar *et al.*, Nature 571, 45 (2019).
[3] M. Milicevic et al., *Phys. Rev. Lett.* 118, 107403 (2017); F. Baboux et al., *Phys. Rev. Lett.* 116, 66402 (2016).
[4] G. Dagvadorj et al., Phys. Rev. X 5, 041028 (2015)

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