SR2. Towards Topological Quantum Fluids of Microwave Light

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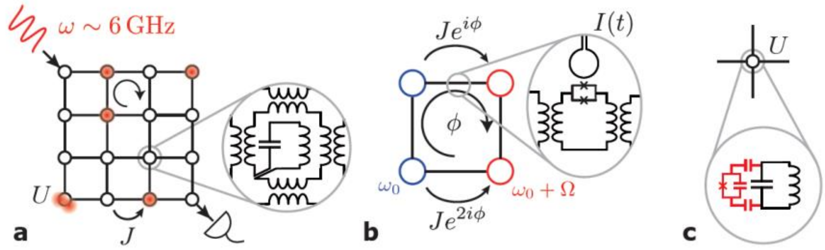
Context: The quantum behavior of boson or fermion gases can be simulated by creating artificial lattices for electrons, photons or cold atoms in which the inter-site and the intra-site coupling can be finely tuned. This not only allows to investigate the ground state of interacting particles following different quantum statistics but also to raise new questions on topological phases out-of-equilibrium. The recent developments and understanding of complex quantum circuits give one way to fabricate quantum meta-materials. Thus quantum engineering becomes crucial to explore new routes in condensed matter. Jérôme Estève and Julien Gabelli (LPS) are following this way. This merging field at the intersection of solid state physics, quantum optics and cold atoms brings together different expertise of the IDEX. Antoine Browaeys and Thierry Lahaye (LCF) are studying topological bands with Rydberg excitations hoping on a 2D array, Karyn Le Hur (CPHT) theoretically investigates interacting many-body systems using quantum circuitry. The Quantronics group at the CEA is pursuing its work on fundamentals of quantum electronics and it is also exploring alternatives to strong non-dissipative non-linear elements based on highly disorder superconductors. This benefits from the expertise of Claire Marrache and Helène le Sueur at (CSNSM) on controlled and tunable high inductive superconductors. This project will give us the opportunity to create a local incubator of topological many-body physics in open quantum systems within the IQUPS.

Scientific Objectives: This project will explore the possibilities offered by circuit Quantum Electrodynamics (cQED) to realize quantum fluids of light on lattices. By implementing arrays of coupled non-linear superconducting microwave resonators, we will create artificial lattices for microwave photons in the presence of an artificial gauge field and strong photon-photon interactions (see figure). Such circuits will simulate the two dimensional out-of-equilibrium Bose-Hubbard model in a gauge field. Arbitrary lattice geometries can be created and the key parameters of the model (hopping, interaction strength, artificial magnetic field strength …) are tunable.

We expect that our experimental efforts will result in the observation of new states of light that will be the out-of-equilibrium counterpart of well-known quantum phases, including topological states, such as quantum Hall phases, and strongly correlated phases, such as Tonks-Girardeau gases. The main objectives of the project can be summarized as follows:

- Realization of an artificial magnetic field for photons; observation of the integer quantum Hall effect and robust edge states; observation of the Hofstadter spectrum.
- Implementation of photon-photon interactions using Josephson junctions; observation of strongly correlated states of light in small lattices; study of ergodicity and thermalization of a microwave polariton gas.
- Combine artificial gauge field with interactions; towards the observation of the fractional Quantum Hall effect with light.

The project will advance along two lines of research: controlling the photon tunneling amplitude between adjacent resonators in the lattice and controlling the onsite photon-photon interaction. Towards the end of the project, we will merge the two techniques. We have carefully planned our research program to combine low-risk experiments with more ambitious ones to consider the technological risk associated to the project. We insist on the fact that many interesting experiments have been proposed that only require a small number of lattice sites (<10), which is well within reach of the current circuit QED technology.



Simulating the Bose-Hubbard model with microwave photons: a) Coupled superconducting LC resonators realize a lattice for microwave photons. b) The tunneling amplitude J can be made complex by parametrically coupling resonators that are slightly detuned through an element (e.g. a SQUID) driven by a time dependent signal. A photon hopping around a plaquette accumulates a phase, which mimics the effect of a vector potential. c) Inserting a Josephson junction, which is a non-dissipative non-linear element, results in an onsite effective photon-photon interaction U.

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