1.3.10 Quantum simulators

Artificial many-body systems can be also employed as quantum simulators, i.e. to simulate other quantum systems [as forecasted by Feynmann more that three decades ago]. Crucial for all these applications is the ability to manipulate many-body systems in a controlled fashion.

Recent theoretical advances in cavity quantum-electrodynamics (QED) have shown that arrays of coupled nonlinear cavities are potential candidates to explore quantum many-body phenomena of light. The initial proposals [1] to realize a Mott phase of polaritons have initiated an intense activity to investigate the properties of cavity QED arrays. Cavity arrays, periodic arrangements of neighbouring QED cavities, have been introducedas prototype systems to study many-body states of light. Their very rich phenomenology arises from the interplay between strong local non-linearities and photon hopping.

Cavity arrays are ideal open system quantum simulators. Indeed experiments in cavity-QED are typically performed under non-equilibrium conditions, with an external source acting on the system to compensate for the loss of photons due to the finite quality factor of the cavities. Hence, particle number per cavity is determined by a dynamical balance between the external drive and loss instead of a chemical potential. It is therefore of paramount importance to find signatures of the different phases of an array of cavities under non-equilibrium conditions. In addition it is very interesting to explore new phases and phase transitions that occur only in non-equilibrium situations. In these years we explored both situations.

We analyzed [2] the non-equilibrium dynamics of a gas of interacting photons in an array of coupled dissipative nonlinear cavities driven by a pulsed external coherent field. Using a mean-field approach, we showed that the system exhibits a phase transition from a Mott-insulator-like to a superfluid regime. For a given single-photon nonlinearity, the critical value of the photon tunneling rate at which the phase transition occurs increases with the increasing photon loss rate. We checked the robustness of the transition by showing its insensitivity to the initial state prepared by the the pulsed excitation. Moreover we found that the second-order coherence of cavity emission can be used to determine the phase diagram of an optical many-body system without the need for thermalization. Our proposal makes a further link to the physics of quantum quenches [3] which is nowdays attracting inreasing interest. What we showed, in essence, is that under certain circumstances it is possible to reconstruct the equilibrium phase diagram from a quantum quench experiment.

Looking for unique signatures of non-equilibrium dynamics we further introduced [4] cavity arrays with coupling mediated by non-linear elements (see the figure 1) opening the way to study a variety of new possibilities, including correlated photon hopping and finite-range photon blockade. We concentrated on this last point studying the effect of a cross-Kerr non-linearity on the steady state and found a very rich phase diagram. A photon solid characterized by a checkerboard ordering of the average photon number appears for a substantial range of the coupling constants.In addition we see that, for some choice of the parameters, a finite hopping stabilizes a phase where the crystalline ordering coexists with a globally synchronized dynamics of the cavities, suggesting an analogy to a non-equilibrium supersolid.

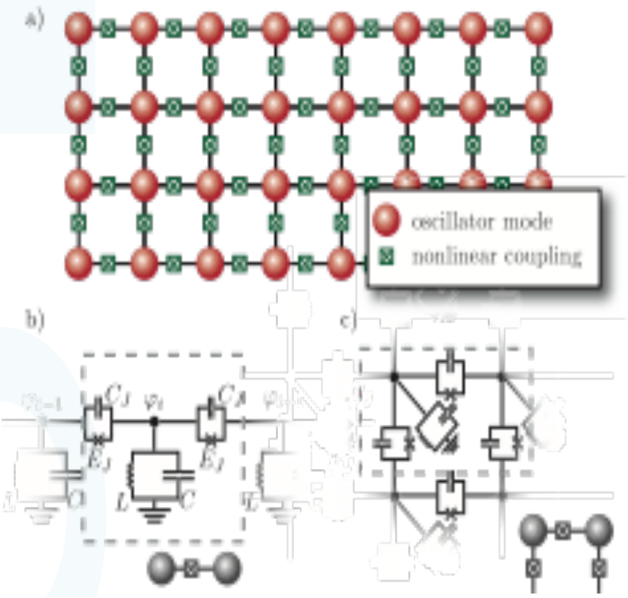

Figure 1. a) An array of QED-cavities described by oscillator modes (red circles) that are coupled via nonlinear elements (crossed boxes). b) and c) Implementation of its building blocks in circuit-QED for one- and two-dimensional lattices.

In some cases it is also possible to engineer the external bath [5]. As a result the steady state of the system under consideration can be "guided" by controlling the interplay between its internal dynamics and the coupling to the environment. We discussed [6] an open driven-dissipative many-body system, in which the competition of unitary Hamiltonian and the dissipative Liouvillian dynamics lead to a non-equilibrium phase transition. This situation shares features of a quantum phase transition in that it is interaction driven, and of a classical phase transition, in that the ordered phase is continuously connected to a thermal state. Within a generalized Gutzwiller approach which includes the description of mixed state density matrices, we characterized the complete phase diagram and the critical behavior at the phase transition approached as a function of time. We found a novel fluctuation induced dynamical instability, which occurs at long wavelength as a consequence of a subtle dissipative renormalization effect on the speed of sound.

In the study of open quantum open systems already understanding the motion of a quantum particle is a complex problem which has a long history. Polarons, originally studied in the context of slow-moving electrons in ionic crystals, and impurities in 3He are two prototypical examples in which the bath is bosonic and fermionic, respectively. Recently, thanks of the realisation of quantum simulators, it has become possible to investigate the real-time dynamics of this problem. Moreover it has become possible to tunel in a controlled fashion the coupling to the bath and the properties of the bath itself.

We studied [6] the impurity dynamics in a one-dimensional bath of interacting bosons numerically by means of a time-dependent density-matrix renormalization group. We have shown that, against the conventional wisdom, a Luttinger-liquid description of the bath is applicable only in a very small region of parameter space, where the impurity suffers an Abraham-Lorentz radiation-reaction friction. Among the most striking features, we have found a non-monotonic behavior of the damping rate and the large renormalization of the oscillation frequency for attractive impurity-bath interactions. The unveiled signatures of interactions in the bath on the impurity dynamics are amenable to future experimental verification.

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