Project Title:

Ultrastrong coupling regime of three-body interaction

Name:
○ Fabrizio Minganti (1), Franco Nori (1,2)
Laboratory at RIKEN:
(1) Theoretical Quantum Physics Laboratory, RIKEN Cluster for Pioneering Research, Wako-shi, Saitama 351-0198, Japan
(2) Department of Physics, University of Michigan, Ann Arbor, Michigan 48109-1040, USA

1. Background and purpose of the project, relationship of the project with other projects

Exotic phenomena in open quantum systems, such as phase transitions, emergence of exceptional points, and collective modes protected from decoherence, are at the center of an intense theoretical and experimental reasearch. These problems are at the crossroad of many different fields of physics: quantum optics, condensed matter, out-of-equilibrium physics, and quantum computing. In many of these systems, the contribution of the environment is pivotal both to correctly describe the physics of the system and to harness their properties engineering the exchanges between the system and an external reservoir.

The physics of these systems under very general hypothesis can be studied using a Lindblad Master Equation. Particularly interesting, is the possibility of quantum simulation, e.g., the possibility to engineer quantum systems which mimic the properties of more "elusive" or difficult to measure ones.

A remarkably active field of research is that of the Ultra-Strong Coupling (USC) regime, where light and matter interact so strongly that the simultaneous creation of light and matter particles becomes energetically favorable, making the vacuum populated by photons. Combining the ideas of quantum simulation and USC, it was recently shown that it is possible to simulate these systems using bosonic excitations.

Using such quantum simulators, it is possible to go beyond this conventional USC. Thus, by engineering the system reservoir, we have studied the particularly intriguing regime of a three-body USC, i.e., three light excitations can be simultaneously generated. This type of interaction can be implemented in superconducting quantum circuits thanks to very recent developments.

2. Specific usage status of the system and calculation method

The exponential scaling of the Hilbert space makes it impossible to treat in a fully quantum fashion problems with few tens of particles. In the case of open quantum systems, the situation is even worse. It requires to use the Liouvillian (i.e., the matrix encoding the time evolution of the system), which reaches very large sizes for small number of particles in the system. For example, for 16 two-level systems (a two-level system is the smallest possible quantum system) the full Liouvillian has dimension 4 bilion.

A true quantum dissipative investigation of these phenomena is necessary to correctly capture the onset of a superradiant phase transition, thus making this problem difficult to tackle. Instead of using the Liouvillian superoperator approach, here we use the quantum-trajectory algorithm for open systems.

Such an algorithm transforms the deterministic evolution of a mixed state (encoded in a density matrix) into the stochastic evolution of a wave function. The price to pay is that, in order to obtain the results of the Lindblad master equation, an average over a high number of trajectories is required.

As such, the parallelizable architecture of Hokusai and the high number of cores proves a useful resource.

3. Result

We are still carrying out the analysis of this model, and we expect this article to require still some significant time. We have finished the main numerical computations, but we expect further data to be necessary.

Our main findings up to now can be summarized as follows:

- The phase transition taking place in the three-body USC seems to be a superradiance, but in the presence of jump in the photon number (see Fig. 1). This, seemingly, indicates the presence of a first-order phase transition.
- The symmetry group characterizing this transition is different with respect to standard USC, thus making the transition more intriguing and challenging to characterize.

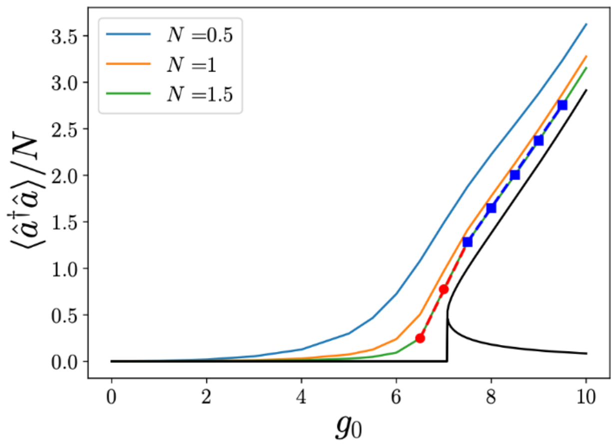

Fig. 1 As a function of the coupling strength g_0, the photon number for different effective parameters N. The black line indicates the result of the semiclassical approach, showing a bifurcation (second-order transition) and a jump (first-order transition). The results of a full quantum simulation seem to agree on the presence of a first-order transition, although we are still trying to characterize it in details.

4. Conclusion

There seems to be an interesting type of criticality taking place in the three-body USC case. Its characterization, however, is far from definitive, and for the moment we can only point out the differences with respect to standard USC.

5. Schedule and prospect for the future

This plan was supposed to be in collaboration with several visiting scientists, where I should have taken care of the numerical part and they of the more analytical one. They were supposed to come to RIKEN in 2020. Due to COVID-related problems, the project could not advance at the expected speed. Nevertheless, in the future we plan to continue this project, and in particular to analyze the obtained data, in order to better understand this new USC regime. In particular, we are trying to find entanglement characters across the transition.