Usage Report for Fiscal Year 2021

Project Title:

Ultrastrong coupling regime of three-body interaction

Name:

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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.

We study 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.

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 qubits, which is the size of a typical IBM quantum computer, the full Liouvillian has dimension of 4 billions.

Instead of using the Liouvillian superoperator approach, here we use the quantum-trajectory algorithm for open systems implemented in QuTiP.

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.

3. Result

We carried out the simulation of this model in the thermodynamic limit, which requires increasingly large computational resources due to the growth of the Hilbert space with the number of modes N.

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 photons number. This 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.

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

We plan to analyze the data, in order to better understand this new USC regime. In particular, we are trying to find entanglement characters across the transition.

Fiscal Year 2021 List of Publications Resulting from the Use of the supercomputer

[Paper accepted by a journal]

Fabrizio Minganti, Ievgen I Arkhipov, Adam Miranowicz, Franco Nori, “Continuous dissipative phase transitions with or without symmetry breaking”, New J. Phys. 23 (2021) 122001

Fabrizio Minganti, Ievgen I Arkhipov, Adam Miranowicz, Franco Nori, “Liouvillian spectral collapse in the Scully-Lamb laser model”, Phys. Review Research 3, 043197 (2021)