Appunti di Fisica '18
&
Dottorato di Ricerca in Fisica

31 Maggio ore 15:00
Sala seminari, CNR-IPCF

Exploring new regimes of quantum optics: giant atoms and ultrastrong coupling

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Superconducting circuits can be made to function as artificial atoms. The properties of these artificial atoms can be designed and tuned by physicists in ways that are hard or impossible to achieve with natural atoms. In this talk, I will summarise theoretical results from two new regimes of quantum optics that have been opened up through experiments with superconducting qubits.

First, atoms can usually be approximated as point-like compared to the wavelength of the electromagnetic radiation they interact with. However, superconducting qubits coupled to a meandering transmission line, or to surface acoustic waves [1,2,3], can realize "giant artificial atoms" that couple to a bosonic field at several points which are wavelengths apart [4,5]. I will discuss setups with multiple giant atoms coupled at multiple points to a one-dimensional (1D) waveguide [6]. I will show that the giant atoms can be protected from decohering through the waveguide, but still have exchange interactions mediated by the waveguide. This is not possible with "small" atoms. I will further show how this decoherence-free interaction can be designed in setups with multiple atoms to implement, e.g., a 1D chain of atoms with nearest-neighbor couplings or a collection of atoms with all-to-all connectivity. This may have important applications in quantum simulation and quantum computing.

Second, I will discuss ultrastrong coupling (USC) between light and matter, i.e., when the coupling strength is comparable to the bare transition frequencies in the system. I will show that USC makes it possible to realize analogues of many nonlinear-optics phenomena in simple setups with one or more two-level atoms coupled to one or more resonator modes. The reason for this is that the full quantum Rabi Hamiltonian (QRH), unlike the approximate Jaynes–Cummings model which is a valid description of

these systems at lower coupling strengths, allows for processes that do not conserve the number of excitations in the system. For example, the standard scenario of a coherent Rabi oscillation, where a cavity and an atom exchange a single photon, can now be extended to multiphoton Rabi oscillations [7]. Extending such processes to more resonators and qubits, a complete table with translations between three-wave and four-wave mixing processes in nonlinear optics and analogous realizations in USC systems can be constructed [8]. I will present a unified picture of how all these effects are realized via intermediate virtual states (connected by the counterrotating terms in the QRH) and calculate the relevant transition rates.

[1] M. V. Gustafsson *et al,* Science **346**, 207 (2014).
[2] T. Aref *et al,* in "Superconducting devices in quantum optics" (Springer, 2016).
[3] R. Manenti *et al,* Nat. Commun. **8**, 975 (2017).
[4] A. F. Kockum *et al,* Phys. Rev A **90**, 013837 (2014).
[5] L. Guo *et al,* Phys. Rev. A **95**, 053821 (2017).
[6] A. F. Kockum *et al,* Phys. Rev. Lett. **120**, 140404 (2018).
[7] L. Garziano *et al,* Phys. Rev. A **92**, 063830 (2015).
[8] A. F. Kockum *et al,* Phys. Rev. A **95**, 063849 (2017).