Quantum Nonlinear Optics without Photons, how to excite two or more atoms simultaneously with a single photon, and other unusual properties of ultra-strongly-coupled QED systems.

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How to excite two or more atoms simultaneously with a single photon: We consider two separate atoms interacting with a single-mode optical or microwave resonator. When the frequency of the resonator field is twice the atomic transition frequency, we show that there exists a resonant coupling between *one* photon and *two* atoms, via intermediate virtual states connected by counter-rotating processes. If the resonator is prepared in its one-photon state, the photon can be jointly absorbed by the two atoms in their ground state which will both reach their excited state with a probability close to one. Like ordinary quantum Rabi oscillations, this process is coherent and reversible, so that two atoms in their excited state will undergo a downward transition jointly emitting a single cavity photon. This joint absorption and emission process can also occur with three atoms. The parameters used to investigate this process correspond to experimentally demonstrated values in circuit quantum electrodynamics systems.

Quantum nonlinear optics without photons: Spontaneous parametric down-conversion is a well-known process in quantum nonlinear optics in which a photon incident on a nonlinear crystal spontaneously splits into two photons. Here we propose an analogous physical process where one excited atom directly transfers its excitation to a pair of spatially separated atoms with probability approaching 1. The interaction is mediated by the exchange of *virtual* rather than *real* photons. This nonlinear atomic process is coherent and reversible, so the pair of excited atoms can transfer the excitation back to the first one: the atomic analog of sum-frequency generation of light. The parameters used to investigate this process correspond to experimentally demonstrated values in ultrastrong circuit quantum electrodynamics. This approach can be extended to realize other nonlinear interatomic processes, such as four-atom mixing, and is an attractive architecture for the realization of quantum devices on a chip. We show that four-qubit mixing can efficiently implement quantum repetition codes and, thus, can be used for error-correction codes.

A few recent references (mostly 2016-2021) on this topic (ultra-strong coupling cavity QED) are listed below and freely available online at: http://dml.riken.jp/pub/Ultra-strong/

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