Free Space QED and Emergent Universal Dynamics with a Single Rydberg Superatom

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Introduction

The interaction of a single photon with an individual two-level system is the textbook example of quantum electrodynamics. Achieving strong coupling in this system has so far required confinement of the light field inside resonators of waveguides. Here, we present the theoretical background of the experimental demonstration of strong coherent coupling between a single Rydberg superatom and a propagating light pulse containing only a few photons [1].

We also study the influence of the coherent exchange interactions between the atoms inside the superatom mediated by exchange of virtual photons in a simple one-dimensional setup. In contrast to the naive expectation of fast dephasing of the bright state due to exchange interactions, we find oscillations and dephasing on a time scale that grows with the number of atoms inside the superatom. Further, we analyze this behaviour analytically using perturbation theory finding excellent agreement with our numerical simulations.

Free Space QED with a Single Rydberg Superatom [1]

Setup and Model

- $N$ driven Rydberg atoms
- Rydberg blockade leads to collective states
- directional emission into forward propagating mode due to collective excitations (averaged over atomic positions)

Master Equation and Dynamical Phase Diagram

- derive master equation from effective Hamiltonian by integrating out photonic degrees of freedom for coherent input field $\alpha(t)$
- open system's dynamics of single two-level system

Quantum Regression Theorem [2]

- time evolution of the density matrix
- correlation functions

Influence of the Interactions - Emergent Universal Dynamics

Waveguide Model [5]

- We study the influence of interactions between the atoms inside the superatom mediated by exchange of virtual photons within a simple one-dimensional waveguide model. The atomic positions are assumed to be randomly distributed with the density distribution given by $n(x)$ with a characteristic width $\delta$.

coherent exchange interaction (Lamb shift)

Lindblad dissipator (spontaneous decay)

Incoherent Dynamics

- enhanced spontaneous emission rate into forward propagating mode

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Emergent Universal Dynamics

Analytical Calculation of the Spectrum

- split $H_D = H_{\text{int}} + H_{\text{f}}$, with $H_{\text{f}} = \frac{\hbar}{2} \int dx \sqrt{n(x)} S'(x)\sqrt{n(x)}$

Estimates of $\gamma_{\text{int}}$

- with $\gamma_{\text{int}}$ the characteristic width of the density distribution

Spectrum in Perturbation Theory

- two analytical limits

References


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