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Atom-photon interactions in slow-light waveguide QED

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Abstract:

Waveguide quantum electrodynamics (QED) refers to a scenario where single or multiple atoms or solid-state emitters are coupled to a one dimensional optical channel. The efficient interaction between individual quantum systems with photons that are confined along a single direction makes this setting particularly interesting for investigating quantum optical phenomena and for future quantum networking applications.

In this thesis, we go beyond the standard scenario and address the new regime of "slow-light waveguide QED", where due to a narrow photonic bandwidth the maximal photonic group velocity inside the waveguide is significantly reduced compared to free space. We first discuss the properties of atom-photon bound states, which emerge as the new elementary excitations of the system when the atom-field coupling strength becomes comparable to the photonic bandwidth. Such bound states are formed by an atom and a localized photonic excitation and represent the continuum analog of the familiar dressed states in single-mode cavity QED. In this thesis we analyze the linear and nonlinear spectral features associated with single- and multi-photon dressed states and we describe how the formation of bound states affects the waveguide-mediated dipole-dipole interactions between separated atoms.

We then consider a narrow-bandwidth waveguide coupled to atoms that are moving with velocities comparable to the reduced speed of light. Under these conditions, we observe a velocity-induced directionality and the emergence of effective divergencies in the photonic density of states. This anomalous interaction between atoms and co-propagating Cherenkov photons gives rise to a range of novel phenomena and nonperturbative effects in the emission of photons and the resulting photon- mediated interactions between moving atoms.

Finally, we consider the coupling of multiple emitters to a slow-light waveguide in the presence of propagating acoustic waves. In this case, the strong index modulations induced by such waves can substantially modify the effective photonic density of states and thereby influence the strength, the directionality, as well as the overall characteristic of photon emission and absorption processes. The generalization of these control techniques to two dimensional photonic lattices creates a new scenario for chiral quantum optics, where non- reciprocal light-matter interactions are established along a single direction and with an extremely slow radial decay. These effect provide a versatile tool for implementing various quantum communication protocol in large-scale photonic networks.