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PhD THESIS DEFENSE: Novel approaches for quantum technologies with atoms and photons in free space

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Elements Room

The rapid advancement of quantum technologies is currently pushing the boundaries of scientific and technological innovation. Among the various platforms for translating quantum theory into practical applications, photons have emerged as particularly strong contenders. Their inherent advantages, such as low decoherence and swift propagation, make them ideal carriers of quantum information for communication, computation and sensing purposes.?

However, the efficient manipulation and control of photonic quantum states present significant challenges, often requiring the use of interfaces. In this Thesis, we investigat several novel approaches to engineer and control the properties of light using a ver traditional system: trapped neutral atoms in free space.

? In Chapter 2, we introduce a novel method to observe and manipulate strong quant m interference effects between a few photons and a single free-space atom. The approach us s a Maltese-cross configuration, where two perpendicular pump and probe coherent fiel s drive the atom. Even for a weak atom-light coupling, we demonstrate that adjusting t e relative pump-probe strength ratio and phase can simulate an artificially enhanced coupli g efficiency for specific observables. In particular, we are able to engineer photon correlatio s from fully anti-bunched to extremely bunched states, and control the linear transmissi n properties in specific direction

. In Chapter 3, we propose the combination of ordered atomic arrays and Rydbe g Electromagnetically Induced Transparency (EIT) as a promising platform for quant m nonlinear optics. The spatial periodicity of the array enables precise control over phot n scattering, reducing the inherent dissipation associated with traditional Rydberg E T protocols. Using a two dimensional array, we design and characterize a single photon switc , where the storage of a single photon as a Rydberg excitation results in a strong change in t e system's optical response. This switch can be used to implement a photon-photon gate wi h an error scaling with the Rydberg blockade radius as Rb^{-4}, potentially reaching ga e efficiencies of up to 99% for realistic experimental parameters. Additionally, we model t e optical properties of the array in the strong driving regime, where the system is multip y excite

. In Chapter 4, we discuss a recent experiment that observed features of the Driven-dissipati e Dicke phase transition in a driven elongated cloud in free space. This is unexpected, as t e Dicke model typically involves an ensemble coupling identically to a single, lossy photon c mode, akin to an ensemble coupled to a cavity. Instead, a free-space ensemble interacts wi h a continuum of modes, encoding propagation effects. Solving a simple model to explain th s behavior, based on the one-dimensional Maxwell-Bloch equations, we observe nonanalyt c behavior in certain observables. However, a closer analysis reveals a significant spati l inhomogeneity in atomic properties. We thus argue that the free-space system does n t undergo a phase transition but rather a ï¿½phase separation,ï¿½ roughly speaking, b tween saturated and unsaturated regions. Beyond understanding the phase transition, w also elucidate under which conditions some properties of atoms in cavities can be map ed to atoms in free

pace. Together, the results in this Thesis represent a meaningful contribution towards etter understanding phenomena associated to atom-light interactions in free space, and t wards translating that knowledge into practical useful implementa

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