PhD THESIS DEFENSE: Nonlinear optics with a Rydberg ensemble for quantum information processing purposes

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Photons have emerged as the main candidates for carrying quantum information due to their weak interaction with the environment. Unfortunately, their limited interaction with one another poses challenges for photonic quantum information processing. One of the possible solutions lies in the unique behavior of interacting Rydberg excitations in cold atomic ensembles, where strong nonlinearities enable engineering interactions among individual photons. This phenomenon makes Rydberg ensembles a promising platform for quantum information applications, notably in long-distance quantum communication. This thesis presents a series of experiments that explore and exploit Rydberg-mediated interactions, all

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with the long-term objective of building an efficient quantum repeater.
The thesis begins with a concise theory overview of Rydberg and ensemble physics. This is followed by an explanation of the experimental setup. I discuss how, building upon a previously existing setup, we improved the stability and spectral properties of our laser system, along with enhancing the quality of the atomic ensemble. The introductory section of the thesis concludes with a description of two different single-photon generation methods and an in-depth review of various decoherence mechanisms impacting Rydberg ensemble excitations. The single-photon generation performance has been improved by the modifications implemented in the setup, resulting in higher generation rates and better single-photon purity. Supported by experimental data and a careful analysis of experimental parameters, we identify the most probable sources of significant decoherence and suggest potential strategies for mitigation.
In our initial experiment, we achieve the storage and subsequent retrieval of an on-demand single photon. This photon is generated through the collective excitation of Rydberg states in one cold atomic ensemble, and it is stored in a low-noise Raman quantum memory situated in another cold atomic ensemble. Our results show the capability to store and retrieve these single photons while maintaining a high signal-to-noise ratio of up to 26 and preserving strong antibunching characteristics. We also explore the built-in temporal beam splitting capabilities of the Raman memory and successfully use the memory to control the single photon waveshape.
In the second experiment, we demonstrate for the first time an interaction and storage of single photons in a highly non-linear medium based on cold Rydberg atoms. We employ the DLCZ protocol in a cold atomic ensemble to create single photons, guiding them to another ensemble for storage in a highly excited Rydberg state under conditions of electromagnetically induced transparency. By studying the statistics of the light retrieved from the Rydberg atoms, we show for the first time single-photon filtering with non-classical input light. Moreover, through Monte Carlo simulation, we get an intuitive understanding of the effect of the (partial) Rydberg blockade upon the Fock state distribution of arbitrary input light pulses. This allows us to conclude that the response of the medium is determined by the input Fock state distribution, what confirms the established understanding of Rydberg ensemble nonlinearity. This demonstration can be seen as a step towards realization of deterministic photon-photon gates based on Rydberg ensembles with single photon inputs.?
The results presented in this thesis affirm the potential of Rydberg ensembles to becom central elements of future quantum networks, both as single photon sources and processin nodes. Furthermore, auxiliary outcomes provide an additional understanding of the Rydber ensemble physics and offer insight into limitations that we need to overcome to improv further our setup

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