Rydberg atoms in the vicinity of an optical nanofiber

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Abstract. Highly excited (so-called Rydberg) atoms are the key ingredient of many quantum information schemes. In this presentation, we shall theoretically investigate how spontaneous emission properties and van der Waals interactions of such atoms are modified in the neighbourhood of an optical nanofiber with respect to the free-space (vacuum) case. This work constitutes a very preliminary step towards the realization of a quantum network based on atomic ensembles linked via optical nanofibers.

1 Introduction

Within the past two decades, the strong dipole-dipole interaction experienced by two neighboring Rydberg-excited atoms has become the main ingredient for many atom-based quantum information protocol proposals [1]. This interaction can indeed be so large as to forbid the simultaneous resonant excitation of two atoms if their separation is less than a specific distance, called the blockade radius, which typically depends on the intensity of the laser excitation and the interaction between the Rydberg atoms. The discovery of this "Rydberg blockade" phenomenon [2] paved the way to numerous proposals for atomic quantum registers [3] and repeaters [4].

Scalability is one of the crucial requirements for quantum devices : interfacing atomic ensembles into a quantum network is a possible way to reach this goal. Photons naturally appear as ideal information carriers. Photon-based protocols considered so far include free space setups which are relatively easy to implement but present the drawback of strong losses. An alternative option would be to use optical fibers and in particular nanofibers which permit strong coupling and transverse mode selection.

Such fibers have recently received much attention [5, 6] because the coupling to the evanescent guided modes of a nanofiber allows for easy-to-implement atom trapping [7] and detection [8]. This coupling increases in strength as the fiber diameter reduces and the atoms approach the fiber surface. It has also been shown that energy could be exchanged between two distant atoms via the guided modes of the fiber [9]. This suggests that optical nanofibers could play the role of a communication channel between the nodes of an atomic quantum network consisting of Rydberg-excited atomic ensembles.

Preliminary steps have been taken towards building a quantum network based on Rydberg-blockaded atomic ensembles linked via an optical nanofiber. On the experimental side, the excitation of cold ^{87}Rb atoms towards Rydberg 29D state was demonstrated at submicron distances from an optical nanofiber surface [10], in a two-photon ladder-type excitation scheme. On the theory side, the spontaneous emission of a highly excited (Rydberg) sodium atom in the neighborhood of a silica optical nanofiber was investigated [11]. In particular, the dependence of the emission rates into the guided and radiative modes on the radius of the fiber, the distance of the atom to the fiber, and the symmetry of the Rydberg state was studied. Since it used the so-called mode function approach, this work could unfortunately not account for the fiber's absorption and dispersion. This point is critical with Rydberg atoms since they can de-excite along many transitions of different frequencies for which the fiber index is different and potentially complex.

By contrast, here, we resort to the framework of Macroscopic Quantum Electrodynamics (MQE) based on the dyadic Green's function [12]. This formalism enables us to take the exact refractive index of silica into account and relaxes all constraints on the transitions we can address. This framework also offers a natural way to compute not only spontaneous emission rates and Lamb shifts of an atom close to the nanofiber (Sec. 2), but also van der Waals interaction potential between two atoms in the vicinity of the fiber (Sec. 3).

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2 Spontaneous emission and energy shifts of a Rydberg rubidium atom close to an optical nanofiber

In this presentation, we shall present the numerical results we obtained in the MQE approach for a rubidium atom prepared in a Rydberg-excited state $|n = 30; L = S, P, D; JFM_F\rangle$ in the vicinity of a multimode silica optical nanofiber [13]. We chose ^{87}Rb as it is commonly used in Rydberg atom experiments [10]. In particular, we show that a non-negligible fraction of spontaneously emitted light is guided along the fiber and study how it depends on the principal quantum number, n, the radius of the nanofiber, a, the distance of the atom to the nanofiber axis, R, and the direction of angular momentum polarization. Interestingly, when the quantum and fiber axes do not coincide, spontaneous emission becomes directional, as already noticed for low-excited atoms [14] due to the peculiar polarization structure of the field in the neighborhood of the fiber. This effect is particularly strong for photons emitted into the fiber-guided modes and persists even for high principal quantum numbers, n. This is promising in view of potential applications in chiral quantum information protocols [15] based on a Rydberg atom-nanofiber interface. We also address Lamb shifts and associated dispersion forces that arise. In particular, we show that, as n increases, the contribution of quadrupolar transitions becomes more important. This contrasts with spontaneous emission rates for which quadrupolar transitions have negligible influence.

3 Van der Waals Interaction of two Rydberg rubidium atoms close to an optical nanofiber

Giant van der Waals interactions are among Rydberg atoms' most striking features. For two atoms prepared in levels of principal quantum numbers $n > 50$ and a few μm apart, such interactions can indeed induce energy shifts of the order of tens of GHz. In this area, the interatomic interaction between two atoms (A, B) separated by the distance r_{AB} follows the law identified by London [16]

$$U_{AB}^{(0)} = -\frac{C_6(A,B)}{r_{AB}^6}$$

The C_6 coefficient depends on the states in which atoms (A, B) are prepared as well as their geometric arrangement. It scales with the principal quantum number as n^{11}. For a pair of rubidium atoms in the state $|60S_{1/2}\rangle$ in vacuum it is of the order of 100GHz.$(\mu\text{m})^{-6}$. In this presentation we shall investigate how the presence of the fiber modifies this interaction with respect to the vacuum case [17]. This study follows other works in plane geometries involving Rydberg atoms in front of a conducting half-space [18].

We shall first briefly recall the form of the interaction Hamiltonian between two Rydberg atoms in the presence of a dieletric medium. Then we shall study the effect of this Hamiltonian on two atoms prepared in the same state $|nS_{1/2}\rangle$, with $n \geq 30$ and compare with the case of dielectric half-space. On the example of two atoms prepared in the state $|nP_{3/2}, M_j = \frac{3}{2}\rangle$, with $n \geq 30$, we shall also demonstrate a strong enhancement of the interaction potential related to the existence of a Förster quasi-resonance. Furthermore, we shall show that it is possible to change the nature of the Van der Waals force for $n > 38$. Finally, we shall consider the influence of the fiber on the anisotropy of the C_6 coefficient, which also exists in vacuum.

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