

## D1.1 Establish analytical and numerical theory of light emission from cloud of moving atoms

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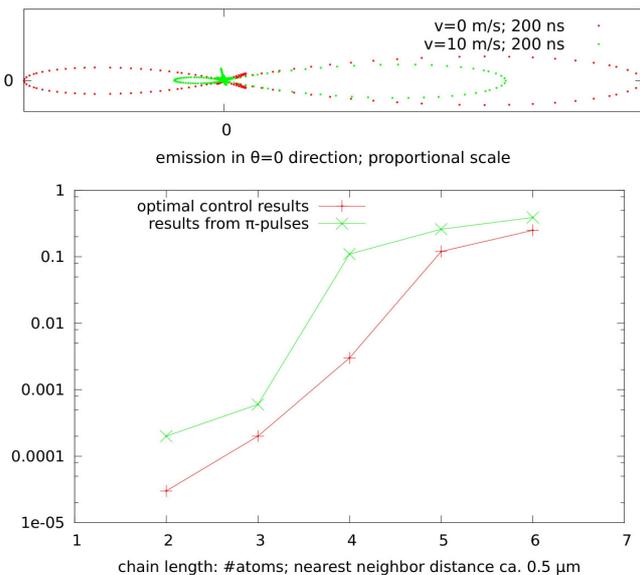
## Establish analytical and numerical theory of light emission from cloud of moving atoms

### USTUTT

We have performed numerical simulations on the four wave mixing scheme presented in the WPI report. As internal parameters we included the couplings of the different electronic states given by the applied laser fields as well dissipative effects as spontaneous decay and dephasing. For the external degrees of freedom we included the actual beam shapes with their intensity distributions, the wave-fronts of the Gaussian beams and the velocity of the atoms in terms of Doppler shifts. We did not take the actual movement of the atoms into account, which will only be relevant in the interacting case. As we observe an excellent agreement of our theoretical modeling with the actual data we can trust in simulated quantities not accessible in the experiment. This is on the one hand the phase distribution of the emitting atoms leading to a specific radiation pattern and on the other hand the excited state fraction responsible for the interaction strength between Rydberg atoms. Here we can learn two things: First we are able to address specific subclasses of the full Doppler distribution allowing us to select by detuning and intensity of the laser fields only slow atoms, which remain longer inside a specific blockade volume and will finally lead to a better performance. Second we notice in a steady state excitation only a small fraction of excited Rydberg atoms, which is in conflict to a strongly interacting Rydberg gas. This problem can be avoided by a pulsed excitation scheme, as already discussed in the initial MALICAI proposal, and is now approached in close collaboration with UULM and AU.

### UULM

We are applying optimal control theory to assist the experiment of USTUTT theoretically. The goal is to prepare a symmetric entangled state with exactly one excitation shared by the atoms involved. This shared excitation will then decay with superradiant emission patterns yielding a single photon with high directionality. The Rydberg blockade interaction will prevent double excitations within a blockade radius. However, the question arises whether the thermal motion of atoms does not destroy the desired emission pattern. To solve that problem we have studied a correspondence between temperature of an atomic cloud and average time and directionality of excitation decay. We are close to establishing a bound on the velocity of atoms above which decay rate



no longer differs from a single atom regime and directionality is lost. The figure shown below depicts the probabilities of a photon to be emitted with a given wave vector for two different variances of the velocities of atoms during the same collection time. It shows that the probability of emission of a photon along the expected direction (forward, along x-axis) gets smaller when atoms move. Optimal control theory enters especially during the state preparation of the symmetric entangled state. We have to develop an appropriate model to project the evolution of the gas cloud onto a one-dimensional chain of atoms that we can handle using matrix product states (MPS). The particular kind of interaction, basically a blockade of doubly-excited Rydberg states causes the very convenient fact that dynamics do not depend very much on numbers of atoms in and geometrical shape of an atom cloud but rather on the characteristic size of the cloud, e.g. chain length in a 1D model or diameter in a 3D cloud in the experiment. On the other hand this Rydberg-Rydberg interaction is very long-ranged and thus we had to develop an MPS-code that allows for describing such kind of interaction. Here we present in a plot preliminary results that show the scaling of fidelity of the prepared state with chain length for few-atom chains and 10ns-pulses, showing the improvement due to optimal control.

AU

The work is in good progress, but a small delay will occur due to our implementation of a more complete and correct description treatment of the problem.

The collective emission by a cloud of atoms is described fully quantum mechanically, and the quantum field emitted by each atom is propagating and hence affects all other atoms in the sample.

Our previous attempts on this problem, dealt with i) a scalar electromagnetic model field, ii) atoms at rest, iii) restriction of the dynamics to a single excitation sector.

In MALICIA we have generalized the equations to a vector field model, including a small manifold of Zeeman excited atomic levels which interact differently with the different field polarization components. The ensuing equations have been simulated for atoms at rest, and it is a minor effort to include motion in the equations and thus to formally fulfill the deliverable.

The recent literature on collective emission, however, has put serious questions to the validity of restricting the calculations to a pure single-excitation sector, and in particular Marlan Scully et al have demonstrated that virtual excitation of components with two excitations play important roles for the outcome of the process. Scully et al have shown, that in the scalar field model, the inclusion of virtual photons yields exactly the same as the inclusion of rotating terms, i.e., by performing the calculations without the usual rotating wave approximation (RWA). For large ensembles the effect is not negligible, and the calculations should be done correctly.

No immediate explanation is offered why the virtual photons are simply included by the non-RWA treatment, and hence our task of solving the problem with real atoms and vector fields, requires an independent analysis. We have just completed this analysis and derived the proper equations of motion for the system including virtual photon excitations. It turns out through elaborate analyses, that also in the vector case, inclusion of the non-RWA terms yields exactly the same results. Although fundamental in nature, we consider this an important achievement, and we will publish it as a separate result of the MALICIA network. The improved vector model has now been coded and first results have been obtained. Incorporation of atomic motion has begun, and over the next few months we will produce results, both for direct communication to experimental partners and for our main MALICIA publication, reporting this deliverable.

Further work has begun, spurred by discussion with our Stuttgart MALICIA partner on the possibility to observe light emission by four-wave mixing from the atomic ensemble, and in particular to see the effects of Rydberg atom mediated interactions between the atoms. This work is being modelled by effective rate equations for the individual atoms, which are amenable to numerical simulations to incorporate atomic interactions in the blockade regime, and to mean field theory in the weak interaction regime.