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Realistic model for quantum noise in light matter interfaces

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Realistic model for quantum noise in light matter interfaces

The strong and coherent interaction of light with matter is a prerequisite for many approaches towards quantum information technologies. In particular long distance quantum communication relies on efficient light-matter interfaces which allow for a coherent transfer of quantum information from light to stationary carriers and back \cite{Kimble:2008if}. Also architectures for quantum computations based on light will depend on efficient light-matter interfaces for buffering and storing quantum information carried by light.

Optically dense atomic ensembles have proven to be a particularly promising technique for achieving strong coherent light matter interaction. Thereby quantum states of propagating pulses of light are mapped onto states of collective atomic (pseudo) spins. This essentially requires a mechanism to fiducially and reversibly convert photons into ground state spin excitations with long coherence times. The Faraday effect – which consists in the rotation of light polarization depending on atomic spin polarization, and vice versa – provides a promising route towards achieving these goals. It has been successfully used to create spin squeezed states, entangled states of collective atomic ensembles, quantum teleportation from states of light to atoms, and quantum memory for light.

These protocols can all be understood in terms of a rather simple model of the Faraday interaction. In this model atoms are assumed to have a spin ½ ground state and a spin ½ excited state. Far off resonant light probing this dipole allowed transition will then experience a polarization rotation due to the dipole selection rules for such a ½ to ½ transition. By the same effect the atomic polarization will be rotated by light. For far off resonant light atoms will be only very weakly excited such that this birefringence of the atomic medium can be understood as being due to the polarizability of the atomic ground states alone. The *coherent* interaction of light with atoms arises from the *real* part of the atomic polarizability. By the Kramers-Kronig relation it is clear that the corresponding *imaginary* part will necessarily be non-zero and add some *incoherent* effects to the dynamics. Sure enough, these effects can be understood as resulting from spontaneous emission events. They will cause both, decoherence of light (absorption) and decoherence of atoms (spin decay). While both effects can be kept small as compared to the coherent dynamics, they are ultimately unavoidable on a fundamental level.

Both decoherence effects – light losses and spin decay – can be included on the level of the simple spin ½ model giving a qualitative understanding of the tradeoff between coherent and incoherent contributions to the light matter interaction. However, in view of the experimental achievements it is becoming increasingly important to further gain a detailed and more quantitative understanding of these effects and the resulting tradeoff. A theoretical description based on a realistic atomic level scheme, and starting from first principles has not been given so far. Within the first reporting period of MALICIA we have derived such a description [Denis V. Vasilyev, Klemens Hammerer, Nikolaj Korolev, Anders S. Sørensen, arXiv:1112.5394].

From the standard dipole interaction of a single multi-level atom with the three dimensional electromagnetic field we consistently derived effective equations of motion for the collective ground state spin and the forward-propagating light modes relevant to the description of the light matter interface. In the derivation we kept track of the effects of events where photons are emitted to any other than the forward direction. This eventually adds decay and noise terms to the equations of motions whose origin and dependence on the details of the atomic level structure are fully understood and explained for the first time in this work. The insight gained by the detailed knowledge of losses and decoherence will enable an optimized operation of the light matter interface based on the Faraday interaction, and therefore contribute to boost its performance and fidelity.

In particular we found in accordance with earlier work that spontaneous emission occurs faster if the polarization of light and atomic spins is parallel than if they are polarized perpendicular – a consequence of selection rules and Clebsch—Gordan coefficients. We have also found the precise decay rates and noise correlations that take into account the full level structure of the atom and our procedure can easily be applied to similar systems. In agreement with previous treatments based on simplified models our theory shows that the decay and noise can be made to vanish for a sufficiently large optical depth of the ensemble. Given that experiments will always work with a finite optical depth it is, however, important to have a detailed understanding of the noise. In particular, in view of the rapid experimental advances a thorough understanding of fundamental noise sources will be crucial for further increasing the efficiency of quantum memories and for assessing the feasibility of new advances for light matter quantum interfaces. The tradeoff between the coherent dynamics and unavoidable fundamental losses, investigated in full detail in our work, will set the ultimate limits to the performance of future quantum networks.

This work is published as an eprint (arXiv:1112.5394) and was submitted to the special issue on quantum memory of Journal of Physics B: Atomic, Molecular and Optical Physics, see <http://cms.iopscience.iop.org/alfresco/d/d/workspace/SpacesStore/3077b8a0-927b-11e0-bab1-8dcfe2821188/J%20JPhysB%20LF%200611%20A4%20v4.pdf>.