MALICIA
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D2.3 Protocol for long-lived entanglement in room-temperature atomic ensembles

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D2.3: Protocol for long-lived entanglement in room-temperature atomic ensembles

Dissipative entangelment generation schemes for atomic ensembles make use of an interference process between light forward-scattered from the first and the second ensemble to engineer a dissipative dynamics with an entangled stationary state (see Fig. 1). Advantages of the method include robustness against timing, state preparation, and transient processes. In this work we have expanded on the results of [1,2] by addressing a central practical problem, namely the effect of the multi-level nature of the ground state (of the Cesium atoms used in the experiments, see Figure 1). As already discussed in [1], this generally decreases in the achievable entanglement, since the atoms can undergo transitions to internal levels whose dissipative dynamics cannot be engineered in the desired way. They can be pumped back to the two-level subspace, but this degrades the steady state.

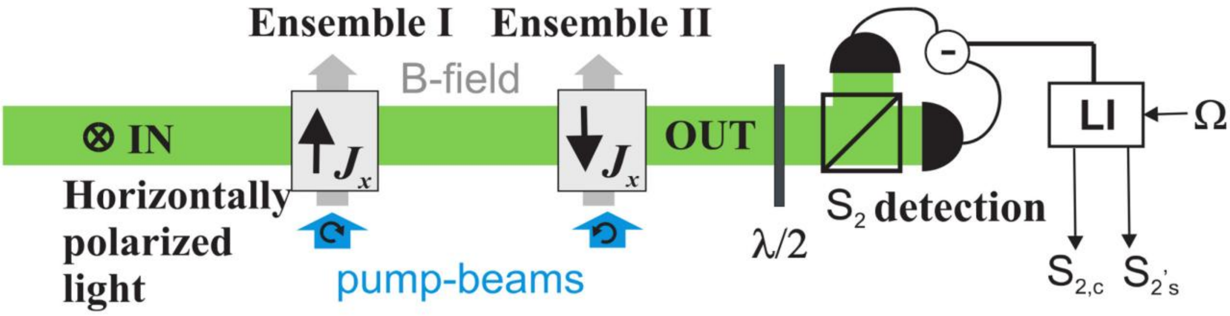

Fig. 1: Entanglement generation scheme: Horizontally polarized probe light passes through two oppositely oriented atomic ensembles from left to right. The orientation is generated via optical pumping (shaded arrows). The detector allows to measure atomic spin components.

We analyzed the ensuing dynamics using a Holstein-Primakoff approximation for the collective atomic spins. The noise induced by the repumping is seen to create unwanted entanglement between the ensembles and the forward scattered light, which reduces the desired atomic entanglement. Working at sufficient optical depth ensures that the entangling process dominates over the repumping noise and an entangled steady state is achieved (see Fig. 2). Alternatively, atoms such as ^{171}Yt without multi-level structure could be used.

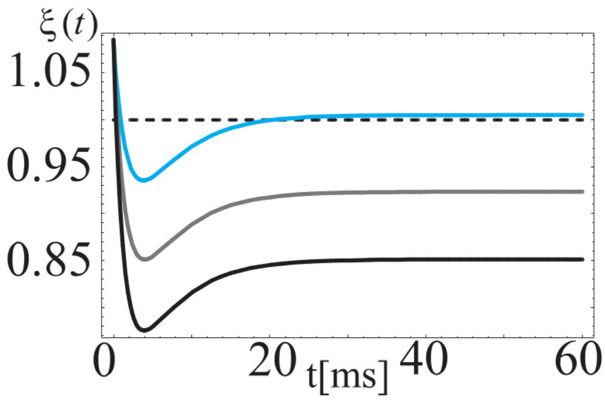

Fig. 2: Dissipatively generated steady-state entanglement: Predicted time-evolution of EPR-variance for different optical depths (d=55,100,150). Values below 1 certify entanglement.

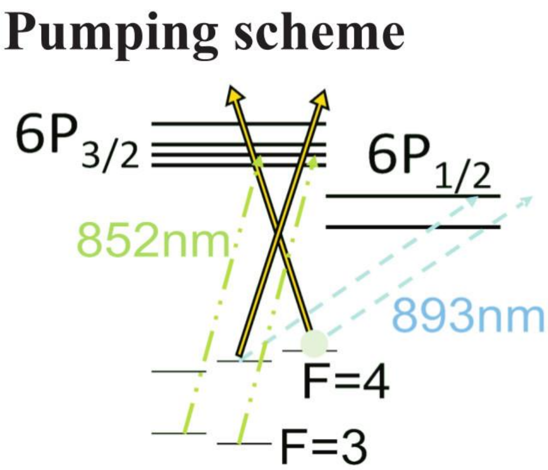

Fig. 3: Multi-level ground state structure of Cs atoms and proposed repumping scheme.

A further improvement of the scheme can be obtained by measurement-assistance: the detrimental effect of the entanglement between the atomic ensembles and the forward scattered light can be significantly reduced by suitable measurement of the light field (see Fig. 4). Since all our states and measurements are Gaussian, the entanglement is independent of the measurement result., hence no feedback is necessary.

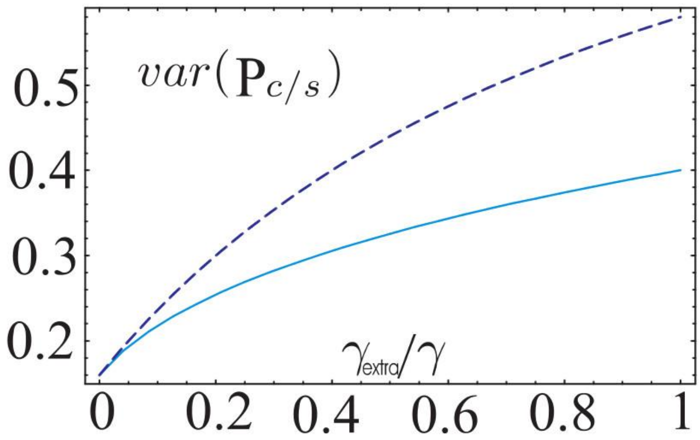

Fig. 4: Squeezed atomic variance in the steady state without (dashed) and with (solid) measurement vs ratio of good and bad noise processes.

In subsequent work [4], LUH has generalized this approach to determine the *optimal* Gaussian protocols for the generation of steady-state entanglement, both with and without measurements. In particular, we considered an arbitrary Gaussian interaction between two atomic ensembles (again modelled by bosonic modes under the Holstein-Primakoff approximation) and a 1D light field subjected to homodyne detection after the interaction. We found that the unconditional variance of the two oscillators' relative coordinates exhibits a trade-off with respect to an interaction parameter. The minimal value of the variance (corresponding to the maximal achievable unconditional entanglement) obtained for an optimal interaction parameter scales as the square root of inverse optical depth. This entanglement is generated unconditionally, that is without any detection of light. The degree of the stationary entanglement can be further improved by making use of the continuous measurement of the light field, in which case it turns out that a Quantum Non-Demolition measurement of Bell observables is the optimal strategy.

All our results have been derived by means of the formalism of quantum stochastic master equations. In [4], we combined this approach with the well-developed formalism of Gaussian states and operations of continuous variables. In particular we derived a simple mapping of a Gaussian stochastic master equation to a stochastic differential equation for the displacement vector plus a deterministic differential equation of Riccati-type for the covariance matrix. In simple cases it is thus possible to arrive at analytical results for, e.g., the final steady state entanglement, and in more general cases it is still possible to evaluate steady states efficiently.

Moreover, LUH, in close collaboration with UCPH, has developed a first-principles theory of quantum noise due to spontaneous emission in room-temperature atomic ensembles [5], which was actually used to estimate atomic noise in the experiment on deterministic quantum teleportation between distant atomic objects [6]. The figure of merit in the analysis of the experiment is the fidelity of teleportation, and careful estimation of this fidelity requires proper knowledge of the decoherence processes, as described by some noise coefficients in the model equations. The required noise coefficients for the spin polarized ^{133}Cs atoms were calculated from first principles according to the prescription developed in [5]. This theory of decoherence in atomic ensembles will become equally vital in the detailed analysis of the limitations that spontaneous emission imposes in the steady state entanglement achievable via the dissipative protocol described in the previous paragraphs.

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