Generation and Distribution of Heralded Entanglement Between Atomic Ensembles for Scalable Quantum Networks

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Abstract: Entanglement is generated by path-erasing detection of single photon emitted indistinguishably by two atomic ensembles. We characterize relationship of degree of entanglement to local dephasing. Parallel pairs of entanglement are distributed to polarization entanglement via conditional control.

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A critical requirement for realizing quantum computation and communication protocols over a scalable quantum network is the creation, storage and exquisite control of *entanglement* [1]. Significant experimental efforts have been focused on the interaction of a collective excitation of atomic ensembles and a single photon [2]. In this setting, we demonstrate the creation [3], and distribution of heralded entanglement between atomic ensembles [4]. Entanglement is generated by a path-erasing detection of single photon emitted indistinguishably by two atomic ensembles. We characterize the relationship of degree of entanglement to local dephasing. Parallel pairs of entanglement are distributed to polarization entanglement via conditional control, which can be used potentially for distributing quantum keys over a quantum network.

In the experiments, a sequence of write and read pulses illuminate cold atomic ensembles loaded from a magneto-optical trap (MOT) where the atomic ensembles are optically pumped to F=4 gound state. A forward scattered photon, field 1, is generated from a write pulse (10 MHz red-detuned from D_2 line, F=4↔F=4' transition), which imprints a single collective spin-wave in the atomic ensemble. When a weak write pulse is applied on two distinct atomic ensembles, quantum interference in detecting of a single photon emitted indistinguishably by one of the two ensembles after beam-splitter projects the two atomic ensembles into an entangled state. By way of collective enhancement, the entangled atomic state is coherently mapped into entangled modes containing a single photon, field 2, after an application of a strong read pulse (resonant to D_2 line, F=3↔F=4' transition). As the read-out process is a local operation, the degree of entanglement between the optical modes of field 2 is less or equal to the entanglement between the atomic samples. Entanglement between these modes is explicitly quantified by way of Concurrence [5].

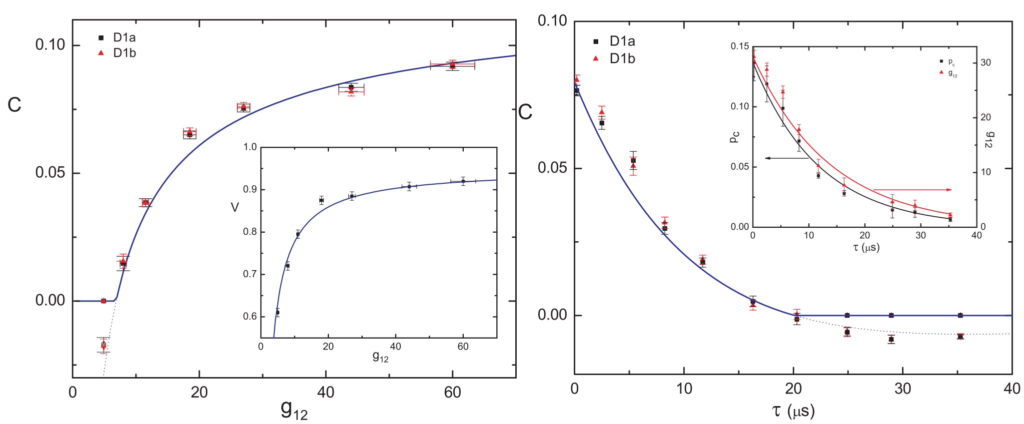

Fig. 1. The decay of concurrence C as a function of cross-correlation g_{12} and storage time τ. The inset shows the decay of conditional probability as a function of τ for each individual ensembles. The local dephasing depicted in the inset is used to model the decay of concurrence.

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First, we study the relationship of degree of entanglement to the excitation probability χ. By varying the write intensity, we map the concurrence as a function of the normalized cross-correlation function g_{12} between fields 1 and 2, where $g_{12}=1+1/\chi$. Because the ideal entangled state is approximated in the limit of vanishing higher order excitations, we observe a decrease in the concurrence at low g_{12} (high χ) as the higher order terms cannot be neglected. When the excitation probability is reduced to χ~0.02 (g_{12}=60), the concurrence between the optical modes is C_γ=0.35±0.10 and the inferred concurrence between the two atomic ensembles is C=0.9±0.3. We also study the degree of entanglement as a function of the storage time by varying the timing of the read pulse. In this measurement, we use a simple equation to model the global evolution of the entangled state to a separable state by independently characterizing the local dephasing g_{12} in the individual ensembles due to inhomogeneous Zeeman broadening. We find good agreement of the measured concurrence to this theoretical prediction, and thereby demonstrate the close relationship of the global decoherence to the local dephasing of a subsystem. For our system, an entangled state onsets to a separable state after 20 μs of storage time as shown in fig. 1.

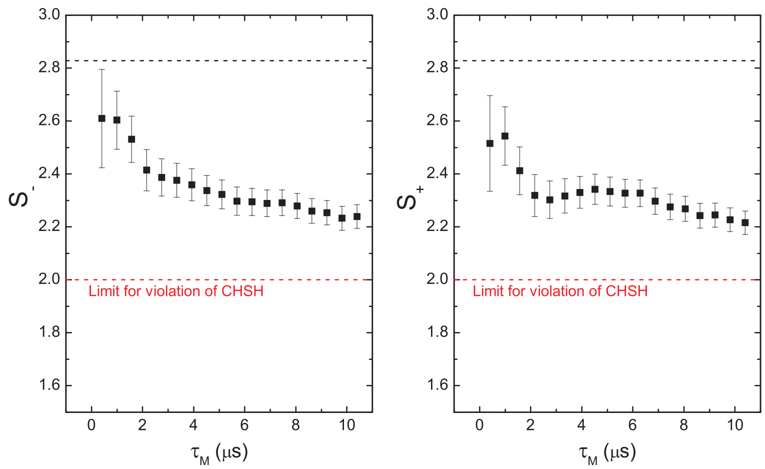

Fig. 2. Bell's parameter S as a function of storage time τ_M.

Then, we operate two parallel pairs of such entangled system where the generation of each of the entangled pair is heralded by the detection of field 1. Each of the entangled pair comprises of two atomic ensembles located at a distance of 3 m in hands of Alice and Bob. When one of the two pairs is prepared into an entangled state, we store the entanglement until the remaining pair is projected into an entangled state. The resulting enhancement factor for the (successful) preparation probability of the protocol is 20 due to the finite storage time. At each party, the atomic state is locally converted into photonic states. In the ideal case, the distribution protocol results in an effective polarization entangled state with success probability 25% when post-selected on each of the party. We verify the presence of the polarization entanglement after post-selecting detection events at both parties, and violate the CHSH inequality by 5 standard deviations with Bell's parameter S= 2.21 ± 0.04. We emphasize that the effective polarization entangled state, secure against individual attacks for key distribution, is generated in a distribution protocol with favorable scaling behavior for quantum networks with the help of conditional control of entangled atomic memories. In particular, as illustrated in fig. 2., we find that polarization entanglement can be maintained upto 10 μs of storage time, at which one pair holds the entangled state until the other pair is prepared, largely due to the measured increase in the two photon contamination of each entangled pair at large storage time. Thus, we demonstrate the first functional quantum nodes for entanglement distribution via real-time control over a potentially scalable quantum network [2].

[1] H.-J. Briegel, W. Dur, J.I. Cirac, P. Zoller, "Quantum repeaters: The role of imperfect local operations in quantum communication," Phys. Rev. Lett. **81**, 5932-5935 (1998).

[2] L.-M. Duan, M. Lukin, J. I. Cirac and P. Zoller, "Long-distance quantum communication with atomic ensembles and linear optics," Nature **414**, 413-418 (2001).

[3] J. Laurat, K. S. Choi, H. Deng, C.-W. Chou and H. J. Kimble, "Heralded entanglement between atomic ensembles: Preparation, decoherence, and scaling," Phys. Rev. Lett. **99**, 180504 (2007).

[4] C.-W. Chou. *et al,*. "Functional quantum nodes for entanglement distribution over scalable quantum networks," Science **316**, 1316-1320 (2007); published online 5 April 2007 (DOI 10.1126/science.1140300).

[5] W. K. Wooters, "Entanglement of formation of an arbitrary state of two qubits," Phys. Rev. Lett. **80**, 2245-2248 (1998).