Quantum Manipulation of Ultracold Atoms and Photons

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1. Interfacing collective atomic excitations and single photons

Sponsors
National Science Foundation – Award ID number PHY 0555509

The generation of non-classical correlations (entanglement) between atoms, photons, or combinations thereof, is at the heart of quantum information science. Of particular interest are material systems serving as quantum memories that can be interconnected optically [1-7]. An ensemble of atoms can store a quantum state in the form of a quantized collective spin excitation (magnon), that can be mapped onto a photon with high efficiency [8,9]. In such a system we have recently demonstrated phase-coherent transfer of a single magnon from one ensemble to another via an optical resonator serving as a quantum bus that in the ideal case is only virtually populated [10]. Partial transfer deterministically creates an entangled state with one excitation jointly stored in the two ensembles. The entanglement is verified by mapping the magnons onto photons, whose correlations can be directly measured. These results will enable deterministic multipartite entanglement between atomic ensembles.

A quantum memory, i.e. a device for storing and retrieving quantum states, is a key element of any quantum information processor. Optical memory access is highly desirable, since it is intrinsically fast, and single photons are robust, easily controlled carriers of quantum states. While a bit of quantum information (qubit) can be stored in a single two-level system, it can be expedient to instead use long-lived collective spin excitations of an atomic ensemble. The ensemble can then be viewed as a “macro-atom" whose excitations are quantized spin waves (magnons), such that transitions between its energy levels (magnon number states) correspond to highly directional (superradiant) photon emission or absorption [1,8,9]. Making use of the strong coupling between magnons and a single electromagnetic mode, single photons emitted by one sample have been captured in another demonstrating the single-photon character of the captured field, but not phase coherence between the ensembles [6]. Two ensembles can also be correlated by joint projective measurements. This has been used to generate coherence between two macro-atoms within a single atomic cloud, although entanglement between the ensembles was not verified [5]. For two remote atomic ensembles, a similar projective measurement has been used to generate probabilistic, but heralded entanglement [4]. Continuous spin variables of two atomic ensembles have also been entangled by joint measurement [11].

Instead of using projective measurements of emitted fields for two-ensemble manipulation, we directly couple two macro-atoms *A,B* via an optical resonator. After probabilistic but heralded generation of a single magnon in macro-atom *A*, we transfer the magnon (or, if we choose, a portion of it) to macro-atom *B* while suppressing the population of the photonic mode by means of quantum interference (adiabatic dark-state transfer). Successful transfer is verified by subsequent on-demand superradiant conversion of the magnon now stored in *B* into a photon. Partial transfer of the magnon creates in a superposition state, where the two macro-atoms share a single spin-wave quantum. This deterministically generates magnon-number entanglement between the two ensembles, as deduced by mapping the spin waves onto light fields, and performing quantum state tomography.

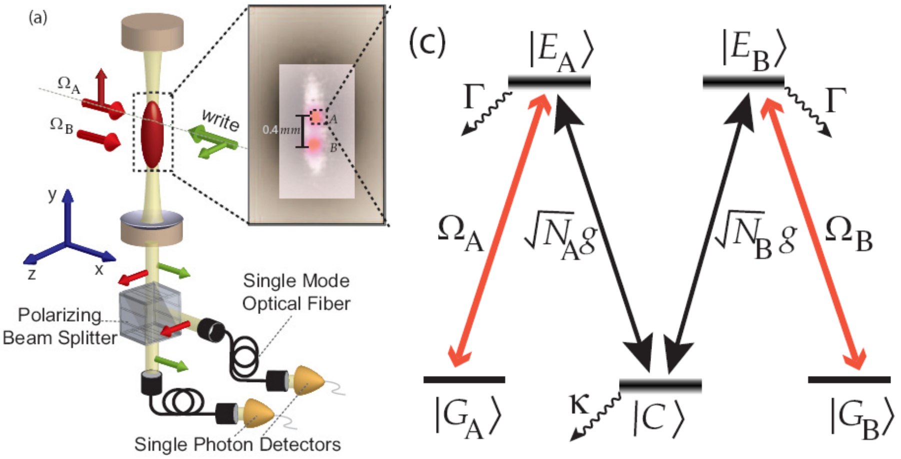

Fig. 1 (Left): Setup for phase-coherent optical transfer of a spin-wave quantum between two ensembles, and entanglement generation. (a) Two ensembles *A,B*, each typically containing 10^3 atoms, are defined within a cloud of laser-cooled cesium atoms by two read pump beams Ω_A, Ω_B. (Right) Spin-wave transfer from macro-atom A to macro-atom B via adiabatic passage in a five-level system. The write process populates the state $|G_A\rangle$. $\sqrt{N_A}g$, $\sqrt{N_B}g$ are the collective couplings of the magnons to the optical resonator mode, while Ω_A and Ω_B are pump couplings. In analogy to adiabatic passage in a three-level system, application of a “counter-intuitive” pulse sequence (see Fig. 2) transfers the system from $|G_A\rangle$ to $|G_B\rangle$, corresponding to magnon-transfer from A to B via the optical resonator. Population of the photonic mode (state $|C\rangle$), and the corresponding excitation loss due to resonator decay, are suppressed by quantum interference.

Our setup consists of two laser-cooled ensembles *A* and *B* of $N \approx 10^3$ cesium atoms each, inside a medium-finesse (F = 240) optical resonator (Fig. 1). The resonator TEM_{00} mode is weakly coupled to a single atom (single-atom emission probability into the resonator (cooperativity) $\eta \approx 10^{-3} \ll 1$), but strongly to the magnon (collective emission probability $N\eta \gg 1$). When ensemble *A* is weakly illuminated with light, the detection (by a single photon counting module) of a randomly emitted spontaneous Raman “write" photon leaving the resonator heralds the creation of a quantized spin excitation (spin Dicke state [1] or magnon [9]) inside the ensemble. For sufficiently low write probability, the ideal system is thereby prepared in the product state $|1_A\rangle\,|0_B\rangle$, specifying the number of magnons inside the corresponding macro-atom. By illuminating *A* at a later time with a read pump Ω_A that is phase matched [8] to the generated magnon and the optical-resonator mode, the magnon is converted into a read photon that can be detected upon leaving the resonator. This mapping of collective spin excitations onto photons is key: inferences about magnon states can be derived from measured photon correlations.

If a pump beam Ω_B is applied to ensemble *B* during readout of ensemble *A*, then the photon emitted by ensemble A into the resonator can be converted into a spin wave in ensemble *B*. In this case, the system is described by five mutually coupled collective states (Fig. 1c), where the outermost states $|G_A\rangle = |1\rangle_A\,|0\rangle_B\,|0\rangle_C$ and $|G_B\rangle = |0\rangle_A\,|1\rangle_B\,|0\rangle_C$ correspond to a magnon stored in macro-atoms A and B, respectively, with no photons in the cavity (C). $|G_A\rangle$ and $|G_B\rangle$ are connected to each other through three intermediate states $|E_A\rangle = |E\rangle_A\, |0\rangle_B\, |0\rangle_C$, $|E_B\rangle = |0\rangle_A\, |E\rangle_B\, |0\rangle_C$; $|C\rangle = |0\rangle_A\, |0\rangle_B\, |1\rangle_C$, representing a collective electronic excitation in samples *A* and *B*, and a photonic excitation in the cavity, respectively. While $|G_A\rangle$; $|G_B\rangle$ are long-lived, the intermediate states are unstable and decay via photon emission either into free space ($|E_A\rangle$ and $|E_B\rangle$), or out of the resonator ($|C\rangle$). It may appear difficult to transport population through several short-lived intermediate states. However, as in the simpler case of a three-level system, for sufficiently strong coupling the transfer $|G_A\rangle \rightarrow |G_B\rangle$ is possible via adiabatic passage, while suppressing the population of the intermediate unstable states by means of quantum interference. By applying a so-called counter-intuitive pulse sequence, i.e., by turning on pump Ω_B coupling the initially empty level $|G_B\rangle$ first, then ramping up pump beam Ω_A, and subsequently ramping down Ω_B, we are able to transfer the collective excitation from macro-atom *A* to macro-atom *B* while reducing decay from $|E_A\rangle$, $|E_A\rangle$, or $|C\rangle$ (Fig. 2a). If the transfer was successful, later application of only pump Ω_B, that is automatically phase matched to the transferred magnon and the resonator, converts the *B*-magnon into a photon that can be detected upon leaving the resonator (Fig. 2d)

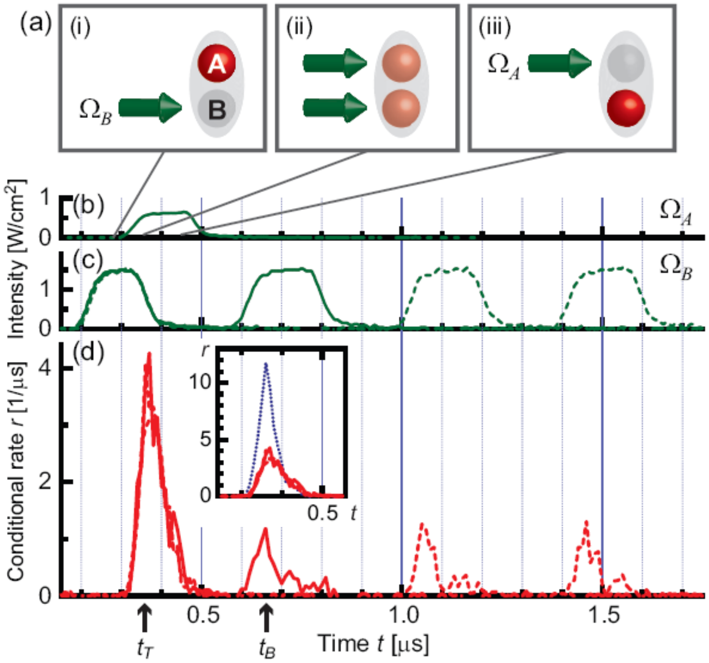

Fig. 2: Magnon transfer from macro-atom A to macro-atom B via “counter-intuitive" pulse sequence. (a) After a magnon has been prepared in sample A by the write process, the excitation is transferred according to the sequence: (i) Pump beam Ω_B is turned on. (ii) Pump Ω_A is ramped up and subsequently (iii) pump Ω_B is ramped down - between (ii) and (iii) the magnon is shared between the two samples. When Ω_B is fully extinguished (iii), the magnon has been transferred to ensemble B. (b), (c) Applied pulse sequences of the pump beams Ω_A and Ω_B, respectively. The dashed curves correspond to different read-out times from ensemble *B*. (d) The read-photon probability density, conditioned on the preparation of a magnon in sample A, as heralded by a detected write photon near t = 0. The dashed curves show the read-out probability density from macro-atom B at various read times. The inset shows the cavity leakage both with (solid red curve) and without (dotted blue curve) magnon transfer to ensemble B. Incomplete suppression of the cavity leakage indicates imperfect adiabatic transfer.

Since the magnon transfer process $|G_A\rangle \rightarrow |G_B\rangle$ corresponds to the net transfer of a photon from pump beam Ω_A into pump beam Ω_B, the phase of the two-ensemble superposition state during the transfer is well-defined, and given by the phase difference ϕ between Ω_B and Ω_A.

Consequently, if we interrupt the transfer process by advancing the turn-off time of Ω_A until the magnon has the same probability to be found in either macro-atom (adiabatic $\pi/2$ pulse), we expect, in the idealized limit of unit transfer efficiency, to prepare the entangled state

$$|\pi/2,\phi\rangle = |1\rangle_A |0\rangle_B - e^{i\phi} |0\rangle_A |1\rangle_B, \tag{1}$$

where the minus sign is characteristic of the dark state that leads to a suppression of population in the intermediate cavity state $|C\rangle$.

The existence of a well-defined phase ϕ between the two components $|1\rangle_A |0\rangle_B$ and $|0\rangle_A |1\rangle_B$ can be verified by applying at a later time t_{AB} both read pump beams Ω_A, Ω_B simultaneously, and varying the relative phase φ of Ω_B and Ω_A during joint readout. The interference of the read-out processes from the two macro-atoms results in a sinusoidal dependence of the joint magnon-photon conversion efficiency on $\phi-\varphi$ (Fig. 3).

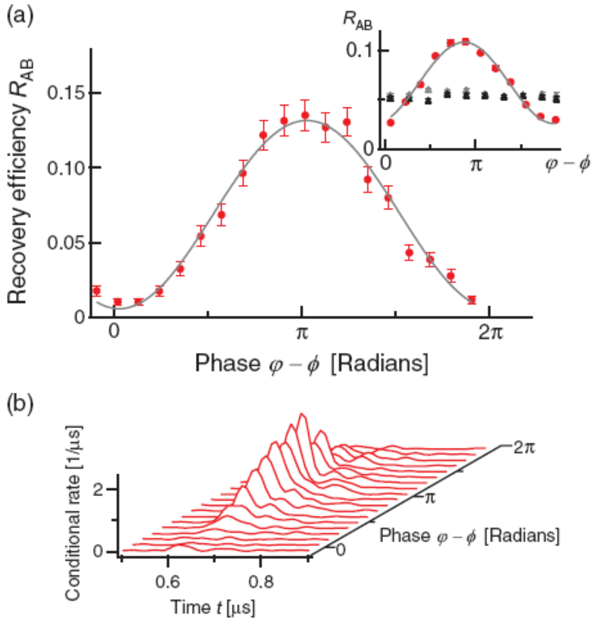

Fig. 3: Coherence of the two ensembles A, B after partial adiabatic transfer of a magnon. (a) By varying the phase difference j between the read pump beams during joint readout of samples *A*, *B* for fixed preparation phase ϕ, we measure the coherence between the atomic ensembles. R_{AB} (red circles) is the read photon probability inside the resonator, conditioned on the previous detection of a write photon. The visibility is $V = 0.88(4)$. The inset shows (for slightly different experimental conditions) that the individual read probabilities p_{10}; p_{01} (gray and black triangles, respectively) are independent of $\phi-\varphi$. (b) The joint readout probability density referenced to within the cavity, conditioned on the preparation of a magnon in sample *A* at $t = 0$.

Due to imperfect single-magnon generation and magnon loss, our state also contains the vacuum component $|0\rangle_A |0\rangle_B$ and the two-magnon component $|1\rangle_A |1\rangle_B$, the combination of which may spoil the entanglement inherent in the ideal state (1) given above. Nevertheless, it is possible to verify the presence of entanglement by quantum state tomography, and quantify it, e.g., by the concurrence $0 \le C \le 1$ that measures the entanglement of formation [12]. From the measured values for the visibility and the magnon-magnon cross-correlation function between ensembles *A* and *B*, we find that the concurrence is bounded by $C \ge 0.042(10) > 0$, demonstrating that the two ensembles are entangled. *C* is primarily limited by the finite transfer and magnon-photon conversion efficiencies, or equivalently, by the large vacuum component $|0\rangle_A |0\rangle_B$ compared to the ideal state (1). Both transfer and magnon-photon conversion can be significantly improved by increasing the optical depth of the system, and for key applications the vacuum component can be eliminated by post-selection [1]. For such post-selected entanglement, the concurrence would be given by $C_{\text{post}} \geq 0.42(10)$.

In conclusion, we have demonstrated deterministic entanglement generation between two ensembles, achieved by phase coherent optical transfer of a single spin excitation quantum via an photonic bus. Quantum interference reduces the population of the photonic mode, thereby reducing excitation loss from the system. The system holds promise for quantum information tasks, e.g. long-distance quantum communication that requires optically addressable quantum memory systems.

2. Towards spin squeezing on an atomic-clock transition for an atomic ensemble trapped on a microchip

Sponsors

DARPA
National Science Foundation – Award ID number PHY 0555509

Magnetic traps and waveguides produced by microfabricated structures can trap ultracold atoms and Bose-Einstein condensates in very small volumes. This results in very large optical depth for trapped samples, which is a prerequisite for non-linear quantum optics with atomic ensembles. The strong non-linearity can be used not only to generate non-classical states of the light field, e.g. single photons or photon pairs, but also to create non-classical (entangled) states of the atomic ensemble. Such states can be useful for a variety of purposes, including the simulation of other, less controlled, quantum mechanical systems, and precision experiments. In the latter case, entanglement, i.e. non-classical correlations between the atoms, can be used to overcome the so-called standard quantum limit that arises from the shot noise in the measurement of independent particles.

In the present work we are trying to generate entanglement on an atomic clock transition. The atoms are first to be prepared (independently of each other) in an equal superposition of two quantum states whose energy difference can be used to define a frequency or time standard. In our case, these are two hyperfine and magnetic sublevels of ground-state Rb atoms. The two states are selected such that they can both be trapped in a microchip magnetic trap, while the difference in Zeeman shift disappears to lowest order [13,14].

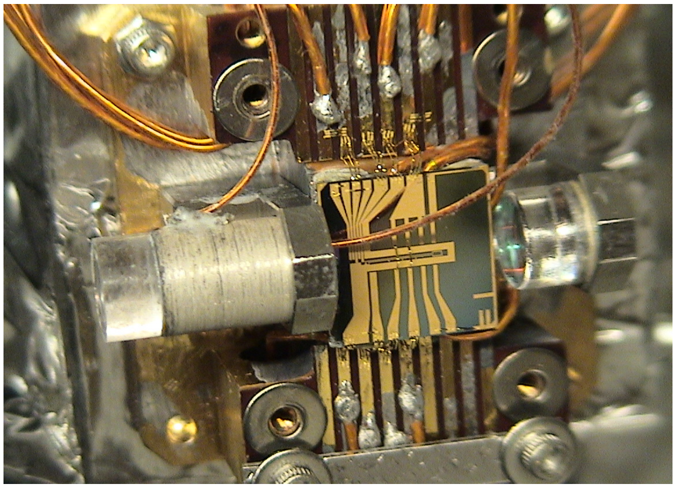

Fig. 4. Microfabricated chip with mounted optical resonator. The resonator mode is aligned 200 μm above the surface of the microchip. The left mirror is mounted on a piezoceramic tube for tuning of the resonance frequency. The resonator finesse is F = 8000.

The entanglement between the atoms is then to be generated by a collective measurement, where the number of atoms in one of the states is determined to better than the shot noise limit via the interaction with an optical-resonator mode, while it remains, even in principle, impossible to determine which atom is in which state. This creates a reduced uncertainty in the atom number difference between the two states (spin squeezing). The sub-shot noise uncertainty can then be transferred onto the phase of the superposition state by a simple rotation (microwave pulse), such that the sub-shot noise signal is available for a phase (or frequency) measurement.

Fig. 4 shows the microchip used to confine the atoms, together with the optical resonator for the measurement-induced squeezing that is mounted to the chip. We typically load 10^4 to 10^5 atoms into the magnetic trap located inside the resonator. The atom number is then measured via the shift of the cavity resonance due to the atomic index of refraction, where the challenge is to eliminate technical noise sources, and to perform this measurement as close to the quantum limit (photon shot noise limit) as possible.

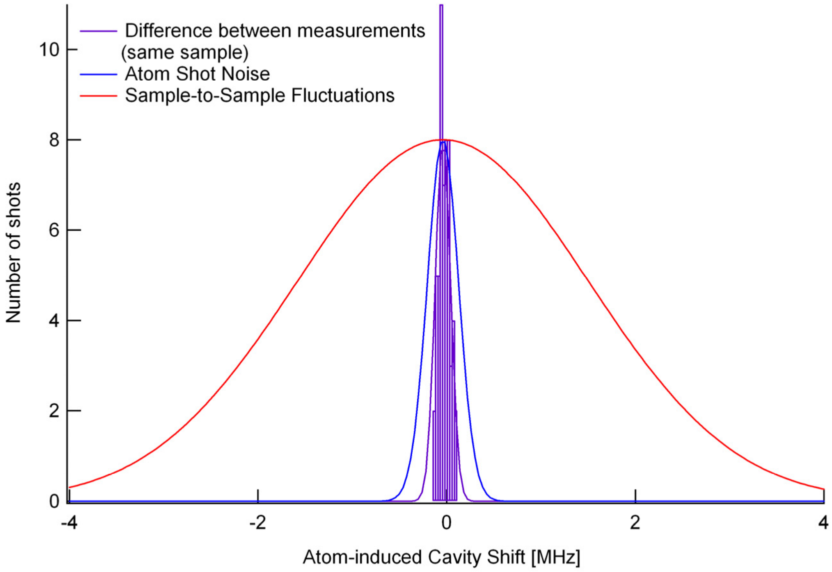

Fig. 5. Non-destructive sub-shot-noise measurement of the atom number. The horizontal axis is the atom-induced cavity frequency shift, that is proportional to the atom number. The blue curve indicates a shot-noise limited atom number distribution, the red curve is the super-Poissonian atom number noise due to fluctuations in the number of laser-cooled atoms. The purple distribution is the variance for two non-destructive measurements of the same sample, which is below the atom number shot-noise limit.

We have recently achieved non-destructive sub-shot noise measurement of the atom number, albeit for atoms prepared in a single quantum state, rather than a superposition of states. Fig. 5 shows the histogram of the inferred atom number difference for two non-destructive measurements of the same sample, together with the atom number shot noise (blue curve), and the much larger super-Poissonian atom number preparation noise (red curve). So far we have been able to reduce the atom number variance by a factor 5 below the shot noise limit. The next task is to demonstrate this for a quantum superposition state, which would amount to spin squeezing. Given that the coherence time for such a microchip systems is comparable to, or longer than, the available measurement time for an atomic fountain, such microchip clocks hold promise for portable high-precision time-keeping devices. The main disadvantage of the miniaturization is the higher atomic density, that leads to larger collision-induced clock shifts [13]. However, in the case of Rb, a fortuitous quantum interference process for the colliding atoms leads to a near cancellation of the collisional clock shift. Therefore we expect to be able to control the collision-induced errors in spite of the high atomic density. This collision-induced shift is also the reason why a low-temperature thermal gas is expected to provide a better clock than a colder, but denser Bose-Einstein condensate.

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Publications

1. Journal Articles

a. Published:

“Interfacing Collective Atomic Excitations and Single Photons,” J. Simon, H. Tanji, J. K. Thompson, and V. Vuletic, Phys. Rev. Lett. **98**, 183601 (1-4) (2007).

“External-feedback laser cooling of molecular gases,” V. Vuletic, A.T. Black, J. Simon, and J. K. Thompson, Phys. Rev. A **75**, 051405(R) (1-4) (2007).

“When Superatoms Talk Photons,” V. Vuletic, Nature Physics News & Views **2**, 801 (2006).

“Influence of grating parameters on the linewidths of external-cavity diode lasers,” H. Loh, Y. Lin, I. Teper, M. Cetina, J. Simon, J.K. Thompson, and V. Vuletic, Applied Optics **45**, 9191-9197 (2006).

b. Submitted for publication:

“Bright Source of Cold Ions for Surface-Electrode Traps,” M. Cetina, A. Grier, J. Campbell, I. Chuang, and V. Vuletic, submitted to Phys. Rev. Lett. (2/2007).

“Single-Photon Bus between Spin-Wave Quantum Memories,” J. Simon, H. Tanji, S. Ghosh, and V. Vuletic, submitted to Nature Physics (5/2007).

2. Meeting Papers

“Entanglement between atomic ensembles via optical transfer of a spin-wave quantum,” J. Simon, H. Tanji, S. Ghosh, and V. Vuletic, Seminar of the MIT/Harvard Center for Ultracold Atoms (Cambridge 2/2007).

“Single and twin photons from many entangled atoms,” J. Simon, H. Tanji, and V. Vuletic, Seminar, Ecole Normale Superieure, Paris (11/2006).

“Detection of single atoms trapped on a microchip.” I. Teper, Y. Lin, I. Leroux, M. Schleier-Smith, and V. Vuletic, Physics Colloquium, Collège de France (11/2006).

“Generation and Quantum Storage of Single Photons,” J.K. Thompson, J. Simon, H. Loh, and V. Vuletic, Physics Colloquium, MIT (11/2006).

“Single and twin photons from many entangled atom,” J. Simon, H. Tanji, and V. Vuletic, LANL Quantum Institute, Los Alamos (10/2006).

“Resonator-aided single-atom detection on a microchip,” I. Teper, Y. Lin, I. Leroux, M. Schleier-Smith, and V. Vuletic, European meeting on atom chips, (Sicily, 9/2006).

“A deterministic source of narrowband single photons,” J.K. Thompson, J. Simon, H. Loh, and V. Vuletic, US-Japan Joint Seminar on Coherent Quantum Systems, (Breckenridge, 8/2006).

“Single and paired photons from many entangled atoms,” J.K. Thompson, J. Simon, H. Loh, and V. Vuletic, Physics Colloquium, Yale University (2/2006).