Heralded single-magnon quantum memory for photon polarization states

Haruka Tanji,1,2 Saikat Ghosh,2 Jonathan Simon,1,2 Benjamin Bloom,2 and Vladan Vuletić2

1Department of Physics, Harvard University, Cambridge, Massachusetts 02138, USA
2Department of Physics, MIT-Harvard Center for Ultracold Atoms, and Research Laboratory of Electronics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA
(Dated: February 2, 2022)

We demonstrate a heralded quantum memory based on mapping of a photon polarization state onto a single collective-spin excitation (magnon) shared between two spatially overlapped atomic ensembles. The polarization fidelity is measured by quantum state tomography to be above 90(2)% for any input polarization, which far exceeds the classical limit of 24%. The process also constitutes a quantum non-destructive probe that detects and regenerates a photon without touching its — potentially undetermined — polarization.

The power of quantum communication can be boosted by quantum memories that can receive, store, and release a quantum state typically carried by a photon. The advantages memories offer, however, are often thwarted by photon losses. Such unpredictable failure may be largely remedied by a heralding feature that announces photon arrival and successful storage without destroying or revealing the stored quantum state. Heralded storage may thus advance long-distance quantum communication, or schemes aimed towards a continuous-variable memory include the recent demonstration of storage and retrieval of squeezed vacuum.

Quantum state storage has been investigated in various systems. Atomic-ensemble quantum memories have been pursued both for continuous variables of electromagnetic fields and for quantized photonic excitations. In an elegant experiment, Julsgaard et. al. mapped the quadrature variables of a weak coherent field onto an atomic ensemble through a field measurement and subsequent feedback onto the ensemble. Other advancements towards a continuous-variable memory include the recent demonstration of storage and retrieval of squeezed vacuum.

Much progress has been made in the storage and retrieval of individual photons. Early work demonstrated capture and release of single photons of fixed polarization using electromagnetically induced transparency, as well as their adiabatic transfer between two ensembles via an optical resonator. Matsukevich and Kuzmich showed that two atomic ensembles can serve as a two-level system whose state can be prepared by a projective measurement. Recently, Choi et. al. mapped photonic entanglement created by a polarizing beamsplitter onto two ensembles, and later retrieved the photon, realizing un heralded, but relatively high-efficiency, polarization storage. In work by Chen et. al., a successful Bell measurement between two photons resulted in probabilistic teleportation of a photon polarization state onto two atomic ensembles. This can be viewed as a partially heralded quantum memory, where a two-photon coincidence between two beams with Poissonian statistics sometimes, but not always, heralds a successful Bell measurement and teleportation.

In this Letter, we demonstrate a system where a single photon announces polarization storage in the form of a single collective-spin excitation (magnon) that is shared between two spatially overlapped atomic ensembles. The heralded storage occurs rarely (p ~ 10^-6 in our non-optimized setup), but when it does, the incident photon is stored and can later be recreated with good efficiency (ε ~ 50%) and sub-Poissonian statistics (g2 ≈ 0.24), while its polarization state is restored with very high fidelity (F > 90%).

Heralded storage is achieved by means of a spontaneous Raman process that simultaneously creates a photon of fixed polarization (that serves as the herald), and a collective spin excitation (magnon) that is a copy of the input-beam polarization. To store an arbitrary polarization state

\[ |\psi\rangle = \cos \theta |R\rangle + e^{i\phi} \sin \theta |L\rangle , \]

written as a superposition of two right/left circularly polarized states |R⟩, |L⟩ with two arbitrary angles θ, φ, we use two spatially overlapped atomic ensembles A, B inside an optical resonator. The atomic levels are chosen such that ensemble A (B) absorbs only |R⟩ (|L⟩) polarized light, while both can emit a photon of the same polarization (π) into the resonator on the Raman transition of interest (Fig. 4). The detection of the emitted π photon heralds the mapping of the input polarization onto a magnon, but does not provide “which-path” information to distinguish between A and B. The heralding also ensures that, even if the input is a coherent beam, only one magnon is generated between the two ensembles in the limit of small Raman scattering probability. The “write” process thus projects a polarization state |ψ⟩ onto a magnon superposition state

\[ |\psi\rangle \rightarrow |\Psi\rangle = \cos \theta |1\rangle_A |0\rangle_B + e^{i\phi} \sin \theta |0\rangle_A |1\rangle_B , \]

where |n⟩k denotes n magnons in ensemble k (k = A, B). For general input polarization (θ ≠ 0), this process creates an entangled state of the two ensembles. At a
later time, the stored state can be retrieved on demand as a single photon by utilizing the strong coupling of the magnon to the resonator mode \( |g\rangle \) (“read” process).

The heralding serves to enhance the fidelity of the write process by announcing successful events. In our present non-optimized setup, the heralding probability \( p = \alpha_\perp \eta q \approx 10^{-6} \), being the product of optical depth perpendicular to the resonator (\( \alpha_\perp = 0.01 \)), emission probability into the resonator (single-atom cooperativity \( \eta = 10^{-3} \)), and photon detection efficiency \( q = 0.1 \), is low. Whenever there is a heralding event, however, a single magnon corresponding to the input-field polarization is stored with high fidelity. The single-photon nature of the retrieved field is confirmed by a conditional auto-correlation measurement indicating four-fold suppression of two-photon events compared to a Poissonian source (\( g_2 = 0.24(5) \)). The heralding process may thus be alternatively viewed as a quantum non-demolition measurement of a single photon \([24]\) which preserves the polarization, and stores the photon.

The heralded storage is performed with precessing spins \([25]\) in order to make use of atomic symmetries for good polarization fidelity, and resonator emission in both heralding and read processes for mode selection and coupling efficiency. We choose a \( \pi \) transition for the heralding photon, while any input state is expressed as a superposition of \( \sigma^\pm \) polarization (Fig. 1b). Given the corresponding atomic angular emission patterns, we then need to rotate the atomic spin direction by \( 90^\circ \) between the heralding and the readout. This is achieved with a magnetic field of 1.4 G that induces Larmor spin precession with a period of \( \tau_L = 2 \mu s \) (Fig. 1a, 1d), enabling us to access the same magnon with different light polarizations at different times. Note that a spatially homogeneous magnetic field maintains the inter-atomic coherence, and does not affect the magnon momentum, or equivalently, the phase matching condition for the read process \([3]\).

An ensemble of \( N_0 \approx 3 \times 10^4 \) cesium atoms at a temperature of 30 \( \mu \)K is loaded from a magneto-optical trap into a far-detuned (trap wavelength \( \lambda_t = 1064 \) nm) one-dimensional optical lattice overlapped with the mode of a medium-finesse (\( f = 140 \)) optical resonator at the waist. We prepare a subset \( N \) of the atoms in the \( 6S_{1/2}, F = 3 \) hyperfine ground state with a resonant optical depth \( N\eta \approx 16 \). Ensembles \( A \) and \( B \) each consist of approximately \( N/2 \) atoms, optically pumped into hyperfine and magnetic sublevels \( |g_\pm\rangle \equiv |6S_{1/2}, F = 3, m_F = \pm 3\rangle \), respectively, in the rotating frame. (The quantization axis is defined to rotate with the atomic spins and coincide with the propagation direction of the write beam at the optical pumping time \( t_{\text{op}} = 0 \).) Optical pumping in this frame is achieved by periodic application of a short (100 ns \( \ll \tau_L \)) linearly \((\times-)\) polarized optical pumping pulse, resonant with the \( 6S_{1/2}, F = 3 \rightarrow 6P_{3/2}, F' = 2 \) transition. The ensembles \( A,B \) thus form macroscopic spins that point in opposite directions, and Larmor precession with a period of \( \tau_L \) in the \( x-z \) plane (Fig. 1c). We choose a pumping period of 1.5\( \tau_L \), such that the ensembles are interchanged at every trial which removes any systematic effects due to a population imbalance between \( |g_\pm\rangle \).

The atomic-spin precession and the efficiency of the optical pumping may be monitored by sending a weak, linearly \((\mathbf{\times})\) polarized probe beam through the resonator. In a coordinate system rotating with the atomic spin, the probe beam polarization changes periodically with time. When the probe beam as seen by the atoms is \( \pi \)-polarized, the states \( |g_\pm\rangle \) do not couple to the probe light on the chosen transition \( F = 3 \rightarrow F' = 2 \) (see Fig.
and the otherwise observable atom-induced splitting (Rabi splitting) of the cavity resonance disappears. The sinusoidal variation of the Rabi splitting (Fig. 1c) is observed only for a polarized sample. By maximizing the contrast of the oscillation, we optically pump more than 99% of the atoms in the \( F = 3 \) hyperfine manifold into either of the \( |g_L \rangle \) sublevels.

The photon storage and readout processes are timed to match the sample precession (Fig. 1a). A sequence of optical-pump, write and read pulses is applied once every \( 1.5\tau_L = 3 \mu s \) for 30 ms, corresponding to a total of \( 10^4 \) trials. The set of sequences is repeated at \( \sim 0.5 \) Hz to allow for recoupling of the sample in between. The write beam whose polarization, as set by a variable retarder and a half-wave plate, is to be stored, propagates along the \( \hat{x} \) direction, and is tuned to \( F = 3 \rightarrow F' = 2 \) atomic transition. It is pulsed on for 50 ns \( \ll \tau_L \) at \( t_w = \tau_L/2 = 1 \mu s \), when the macroscopic spins are aligned along \( \mp \hat{x} \). At this time, \( |R \rangle \) and \( |L \rangle \) correspond to \( \sigma^+ \) transitions along the quantization axis \( \hat{x} \), such that \( A \) and \( B \) can absorb only \( |R \rangle \) and \( |L \rangle \) photons, respectively (Fig. 1a). The write intensity is adjusted such that much less than one photon is scattered into the resonator mode per pulse. For equal populations in \( A \) and \( B \), a \( \pi \)-polarized photon originating from a spontaneous \( \pi \rightarrow -\pi \) (absorbing a \( \sigma^+ \) photon and emitting a \( \pi \) photon) Raman process has the same probability for having been emitted by either ensemble. Thus, it does not provide any “which-path” information, and, if detected, serves as a heralding photon that announces the storage of a (not revealed) polarization state \( |\psi \rangle \) as a magnon \( |\Psi \rangle \). The heralding photon is detected by detector D1 (Fig. 1a).

At \( t_r = t_w + \tau_L/4 = 1.5 \mu s \), when the atomic spins point along the resonator axis \( \pm \hat{z} \), the read beam, linearly polarized along \( \hat{z} \) and tuned to \( F = 3 \rightarrow F' = 2 \) transition, is applied for 100 ns \( \ll \tau_L \). The read beam excites the atoms on a \( \pi \) transition, such that collectively enhanced \( \pi \rightarrow -\pi \) Raman scattering maps the magnon state onto a single-photon polarization state. If the relative populations, \( \cos \theta^2, |\sin \theta|^2 \), and the relative phase \( \phi \) of the magnons in ensembles \( A, B \) are preserved between the write and read processes (Eq. 2), the polarization of the regenerated photon should be a faithful copy of the write beam polarization.

To investigate the quality of the heralded polarization memory, we evaluate the polarization fidelity of the retrieved single photon with respect to the input state. We determine the density matrix \( \rho_{\text{meas}} \) of the output polarization by measuring the projection onto three polarization bases: \( |(L) \pm |R\rangle \rangle \) \((H-V), |L\rangle \rangle \) \((L-R), \) and \( |(L) \pm i |R\rangle \rangle \) \((S-T)\). As the phase \( \theta \) of the input state Eq. 1 is varied, the projection onto those bases displays a sinusoidal variation as expected (inset of Fig. 2), confirming that the system behaves linearly.

The polarization fidelities \( \mathcal{F} \) of the retrieved single photons for the ten states shown in Fig. 2 as well as for the six fiducial input states \( H, L \) and \( S \). The measured degrees of polarization (\( \rho_{\text{out}} \)) and fidelities (\( \mathcal{F} \)) of the retrieved single photons for the six fiducial input states. The symbols with tilde denote the values with the independently measured photon background subtracted.
six fiducial states the measured fidelity $F$ without any background subtraction is significantly above the classical limit of $2/3$ for state-independent storage (Fig. 3B). If we subtract the independently measured photonic backgrounds present during the readout, the degrees of polarization $F_{\text{out}}$, as well as the fidelities $F$, approach unity (Fig. 3B), indicating that the polarization fidelity inherent in the magnon storage even exceeds that displayed in Fig. 2.

The major source of photon backgrounds is the finite Larmor precession of 0.3 rad during the 100-ns read process. The read pump beam acquires a small admixture of $\sigma^\pm$ component in the frame precessing with the atomic spin (see Fig. 1B), which results in strong photon scattering by atoms in $|g\pm\rangle$ into the resonator. These backgrounds deteriorate not only the stored-polarization fidelity, but also the single-photon character of the retrieved field, i.e., increase the autocorrelation function. These limitations can be overcome by slowing down the Larmor Doppler coherence time of a few microseconds [23]. Implementation of a tightly confining three-dimensional optical lattice is expected to substantially reduce the decoherence, and increase the storage time.

Finally, we estimate the degree of entanglement present between samples $A$ and $B$ during storage. The amount of entanglement may be quantified by the concurrence $C$ [25], where $1 \geq C > 0$ indicates entanglement. The concurrence of an atomic state $C$ is bounded by that of the corresponding photonic state $C_{\text{ph}}$ as discussed in the Supplementary Information of Ref. 21. $C_{\text{ph}}$ is observed to vary with zenith angle $\theta$, as expected, with a maximum value of $C_{\text{ph}} = 0.034(4)$ for the $|H\rangle = \frac{1}{\sqrt{2}}(|L\rangle + |R\rangle)$ state.

To conclude, we have demonstrated a heralded memory for photon polarization states with an average fidelity of 0.93(5). The low success probability (currently $\sim 10^{-6}$ per trial, including detection efficiency) may be improved upon by a dipole trap and a modified resonator which will realistically increase the transverse optical depth to 1 and the single-atom cooperativity in the cavity mode to 0.1, respectively. The success probability and the effective success rate will then be $\geq 1\%$ and 200 s$^{-1}$, respectively. The retrieved photons in this scheme have controllable waveforms, and can easily be interfered with one another with high fringe contrast because of their narrow, nearly Fourier-limited bandwidth [10]. This is a crucial feature for any quantum information application. Furthermore, by applying this scheme to photons of undetermined polarization from a source of entangled-photon pairs [23], it should be possible to realize a heralded source of high-quality entangled-photon pairs for various tasks in quantum information processing.

We gratefully acknowledge support by the NSF and DARPA. J.S. thanks the NDSEG and NSF for support.

[1] L.-M. Duan, M. D. Lukin, J. I. Cirac, and P. Zoller, Nature 414, 413 (2001).
[2] D. Kielpinski, V. Meyer, M. A. Rowe, C. A. Sackett, W. M. Itano, C. Monroe, and D. J. Wineland, Science 291, 1013 (2001).
[3] C. W. Chou, S. V. Polyakov, A. Kuzmich, and H. J. Kimble, Phys. Rev. Lett. 92, 213601 (2004).
[4] D. N. Matsukevich and A. Kuzmich, Science 306, 663 (2004).
[5] A. Blais, R.-S. Huang, A. Wallraff, S. M. Girvin, and R. J. Schoelkopf, Phys. Rev. A 69, 062320 (2004).
[6] T. Chamiere, D. N. Matsukevich, S. D. Jenkins, S. Y. Lan, T. A. B. Kennedy, and A. Kuzmich, Nature 438, 833 (2005).
[7] M. D. Eisaman, A. Andre, F. Massou, M. Fleischhauer, A. S. Zibrov, and M. D. Lukin, Nature 438, 837 (2005).
[8] A. T. Black, J. K. Thompson, and V. Vuletic, Phys. Rev. Lett. 95, 133601 (2005).
[9] J. R. Petta, A. C. Johnson, J. M. Taylor, E. A. Laird, A. Yakoby, M. D. Lukin, C. M. Marcus, M. P. Hanson, and A. C. Gossard, Science 309, 2180 (2005).
[10] J. K. Thompson, J. Simon, H.-Q. Loh, and V. Vuletic, Science 313, 74 (2006).
[11] K. S. Choi, H. Deng, J. Laurat, and H. J. Kimble, Nature (London) 452, 67 (2006).
[12] C. Simon, H. de Riedmatten, M. Afzelius, N. Sangouard, H. Zbinden, and N. Gisin, Phys. Rev. Lett. 98, 190503 (2007).
[13] L. Jiang, J. M. Taylor, and M. D. Lukin, Phys. Rev. A 76, 012301 (2007).
[14] Z.-B. Chen, B. Zhao, Y.-A. Chen, J. Schmiedmayer, and J.-W. Pan, Phys. Rev. A 76, 022329 (2007).
[15] E. Knill, R. Laflamme, and G. Milburn, Nature 409, 46 (2001).
[16] G. Brassard, N. Lütkenhaus, T. Mor, and B. C. Sanders, Phys. Rev. Lett. 85, 1330 (2000).
[17] B. Julsgaard, A. Kozhekin, and E. S. Polzik, Nature 413, 400 (2001).
[18] B. Julsgaard, J. Sherson, J. I. Cirac, J. Fiurášek, and E. S. Polzik, Nature 432, 482 (2004).
[19] K. Honda, D. Akamatsu, M. Arikawa, Y. Yokoi, K. Akiba, S. Nagatsuka, T. Tanimura, A. Furusawa, and M. Kozuma, Phys. Rev. Lett. 100, 093601 (2008).
[20] J. Appel, E. Figueroa, D. Korytov, M. Lobino, and A. I. Lvovsky, Phys. Rev. Lett. 100, 093602 (2008).
[21] J. Simon, H. Tanji, S. Ghosh, and V. Vuletić, Nature Physics 3, 765 (2007).
[22] Y.-A. Chen, S. Chen, Z.-S. Yuan, B. Zhao, C.-S. Chuang, J. Schmiedmayer, and J.-W. Pan, Nature Physics 4, 103 (2008).
[23] J. Simon, H. Tanji, J. K. Thompson, and V. Vuletić, Phys. Rev. Lett. 98, 183601 (2007).
[24] C. Guerlin, J. Bernu, S. Delégile, C. Sayrin, S. Gleyzes, S. Kuhr, M. Brune, J.-M. Raimond, and S. Haroche, Nature 448, 889 (2007).
[25] D. N. Matsukevich, T. Chamiere, S. D. Jenkins, S.-Y. Lan, T. A. B. Kennedy, and A. Kuzmich, Phys. Rev. Lett. 96, 033601 (2006).
[26] Y. Zhu, D. J. Gauthier, S. E. Morin, Q. Wu, H. J. Carmichael, and T. W. Mossberg, Phys. Rev. Lett. 64, 2490 (1990).
[27] D. F. V. James, P. G. Kwiat, W. J. Munro, and A. G. White, Phys. Rev. A 64, 052312 (2001).
[28] W. K. Wootters, Phys. Rev. Lett. 80, 2245 (1998).
[29] T. Wilk, S. C. Webster, A. Kuhn, and G. Rempe, Science 317, 488 (2007).