Recording Quantum Properties of Light in a Long-Lived Atomic Spin State: Towards Quantum Memory

C. Schori, B. Julsgaard, J. L. Sørensen, and E. S. Polzik*

QUANTOP–Danish National Research Foundation Center for Quantum Optics, Institute of Physics and Astronomy, University of Aarhus, 8000 Aarhus, Denmark

(Received 5 March 2002; published 15 July 2002)

We report an experiment on mapping a quantum state of light onto the ground state spin of an ensemble of Cs atoms with the lifetime of 2 ms. Recording of one of the two quadrature phase operators of light is demonstrated with vacuum and squeezed states of light. The sensitivity of the mapping procedure at the level of approximately 1 photon/sec per Hz is shown. The results pave the road towards complete (storing both quadrature phase observables) quantum memory for Gaussian states of light. The experiment also sheds new light on fundamental limits of sensitivity of the magneto-optical resonance method.

DOI: 10.1103/PhysRevLett.89.057903 PACS numbers: 03.67.Lx, 32.80.Bx, 42.50.Dv, 42.50.Lc

Quantum state exchange between light and atoms is an important ingredient for the future quantum information networks. It is also crucial for sensitive atomic measurements in optics when quantum limits of accuracy are approached. As shown recently both theoretically [1,2] and experimentally [3,4], for ensembles of atoms such exchange is feasible via free space interaction with light, as opposed to the case of a single atom which requires cavity QED settings for that purpose [5]. In [3,4] a short-lived squeezed spin state of an atomic ensemble has been generated via complete absorption of nonclassical light. An alternative approach to mapping a quantum state of light onto an atomic state via electromagnetically induced transparency has been proposed [6] and first experiments showing the feasibility of the method for classical amplitude and phase of light have been carried out [7,8].

In this Letter, we demonstrate for the first time a possibility of recording manifestly quantum features of light in a long-lived atomic spin state. A novel approach utilizing a measurement induced back action along the lines of the proposal [9] is applied. We make use of the strong non-dissipative off-resonant coupling between the collective atomic spin and the polarization state of light. Such coupling has been recently used for generation of a spin squeezed atomic sample [10] and for entanglement of two separate atomic objects [11]. The coupling yields partial information about the ground atomic spin state via a measurement performed on the transmitted probe light. However, simultaneously via the same interaction the quantum state of the optical probe is mapped onto the conjugate atomic spin component which therefore serves as a quantum memory.

Consider an ensemble of atoms with the collective spin $\mathbf{J} = \Sigma \mathbf{j}^{(i)}$, where $\mathbf{j}^{(i)}$ is the total angular momentum of the ith atom in the ground state. The ensemble is assumed to be spin polarized along the x direction, i.e., J_x is classical. The transverse spin components satisfy $[\hat{J}_y, \hat{J}_z] = iJ_x$.

We study recording of Gaussian states of light; more precisely, a vacuum or a squeezed vacuum state. This light described by the continuum mode $\hat{a}_y$ [12] is taken to be linearly polarized along the y direction. In order to enable the free space quantum state exchange with atoms, $\hat{a}_y$ is mixed on a polarizing beam splitter (Fig. 1) with a strong classical field A_x polarized along the x direction. The polarization state of light after the beam splitter is described by Stokes parameters $\hat{S}_x = \frac{1}{2}(A_x A_x - \hat{a}_y^\dagger \hat{a}_y) = \frac{1}{2}A_x^2$, $\hat{S}_y = \frac{A_x}{2}(\hat{a}_y + \hat{a}_y^\dagger)$, $\hat{S}_z = \frac{A_x}{2i}(\hat{a}_y - \hat{a}_y^\dagger)$ normalized to have the dimension sec^{-1}. In the experiment we measure $2\hat{S}_y$ which is the difference between the photon fluxes polarized along $\pm 45°$ with respect to x.

The interaction between the light and the atoms is modeled following [9,13] to obtain

$$\hat{S}_z^{\mathrm{out}}(t) = \hat{S}_z^{\mathrm{in}}(t), \qquad \hat{S}_y^{\mathrm{out}}(t) = \hat{S}_y^{\mathrm{in}}(t) + aS_x\hat{J}_z(t), \quad (1)$$

where "in" and "out" refer to the light before and after interaction with the atoms. These equations are valid if the

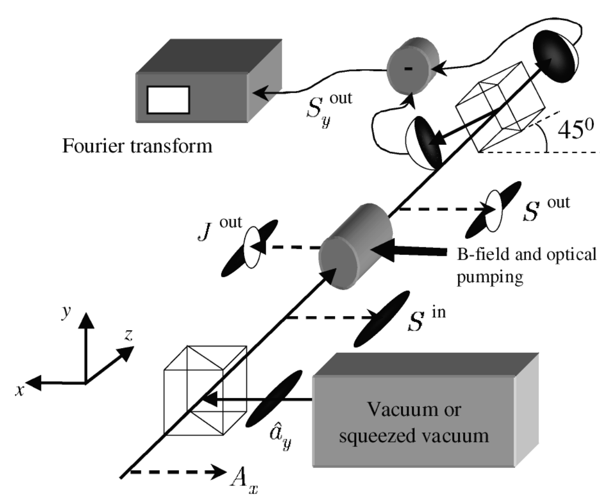

FIG. 1. A vacuum or squeezed vacuum field propagates through the atomic sample, and leaves its trace on the sample. The transmitted light which reads out this trace is analyzed at a polarization state analyzer.

 © 2002 The American Physical Society

light is sufficiently far detuned from the atomic resonance, so that polarization rotation from circular birefringence is the dominant contribution to the interaction. The strength of the interaction is described by the parameter a which depends on the beam geometry, detuning, and the interaction cross section [9].

The evolution of the atomic spins is described by the equations

$$\dot{\hat{J}}_z(t) = \Omega \hat{J}_y - \Gamma \hat{J}_z(t) + \hat{\mathcal{F}}_z(t), \tag{2}$$

$$\dot{\hat{J}}_y(t) = -\Omega \hat{J}_z + aJ_x\hat{S}_z(t) - \Gamma \hat{J}_y(t) + \hat{\mathcal{F}}_y(t), \tag{3}$$

where, as in [11], we introduce a constant magnetic field along the x direction giving rise to Larmor precession with the frequency Ω. The evolution corresponding to (1)–(3) is pictorially shown in Fig. 2. In what follows, the value of Ω determines the frequency component of light which can be stored in the atomic medium. The decay of the transverse ground state spin components is described by the rate Γ and their quantum statistics are described by the Langevin forces $\hat{\mathcal{F}}_y$, $\hat{\mathcal{F}}_z$. The term responsible for the back action of light onto atoms, $aJ_x\hat{S}_z(t)$, in Eq. (3), maps the operator $\hat{S}_z(t)$ of light onto atomic operator $\hat{J}_y(t)$. Magnetic field links $\hat{J}_y(t)$ and $\hat{J}_z(t)$ according to (2), which is then read out by light according to (1).

Equations (1)–(3) can be Fourier transformed and solved [14]. The result for the power spectrum $\Phi(\omega)$ of $\hat{S}_y^{\text{out}}$ observed in the experiment is

$$\Phi(\omega) = \frac{S_x}{2}\epsilon_y + \frac{\frac{1}{4}a^2S_x^2}{(\Omega-\omega)^2+\Gamma^2}\left\{\frac{a^2J_x^2S_x\epsilon_z}{2} + 2\Gamma J_x\right\}. \tag{4}$$

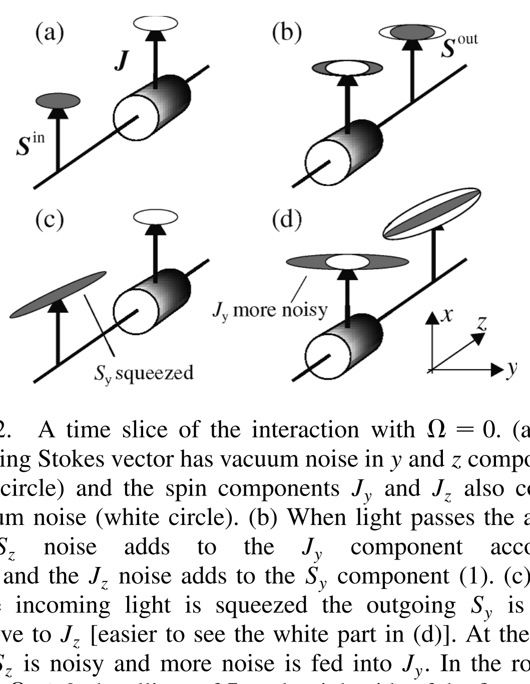

FIG. 2. A time slice of the interaction with $\Omega = 0$. (a) The incoming Stokes vector has vacuum noise in y and z components (gray circle) and the spin components J_y and J_z also contain quantum noise (white circle). (b) When light passes the atoms, the S_z noise adds to the J_y component according to (3) and the J_z noise adds to the S_y component (1). (c) If S_y of the incoming light is squeezed the outgoing S_y is more sensitive to J_z [easier to see the white part in (d)]. At the same time S_z is noisy and more noise is fed into J_y. In the rotating frame, $\Omega \neq 0$, the ellipse of **J** on the right side of the figures will rotate, obscuring the simple picture.

The quadrature phase variances are described by $\epsilon_{y,z}$ normalized such that $\text{Var}(\frac{1}{2}[\hat{a}_y + \hat{a}_y^\dagger]) = \epsilon_y \text{Var}(\frac{1}{2}[\hat{a}_v + \hat{a}_v^\dagger])$ and similarly for ϵ_z. Here $\hat{a}_v$ is the vacuum operator. $\epsilon_{y,z}$ completely describe the vacuum ($\epsilon_{y,z} = 1$) or squeezed vacuum ($\epsilon_y < 1$, $\epsilon_z > 1$, or vice versa) state [4]. The first term in the equation is determined by the input light. The rest is due to the narrow band atomic state fluctuations with the lifetime Γ^{-1}. The second term in the curly brackets is the projection noise of the initial atomic coherent spin state. The first term in the curly brackets is the back action due to the $\hat{S}_z$ component of the quantum state of the input light, i.e., due to the operator $\frac{1}{2i}(\hat{a}_y - \hat{a}_y^\dagger)$. This is the "quantum memory term." Note, that only one of the two quadrature operators is mapped onto the atomic state.

Turning now to the experiment, we achieve nontrivial $\epsilon_{y,z}$ values by using squeezed vacuum light generated by the frequency tunable degenerate optical parametric amplifier below threshold [15]. This light is overlapped with the orthogonally polarized strong (up to 5 mW) beam on a polarizing beam splitter (see Fig. 1). As shown in [4] we can, by using this technique, vary the quantum fluctuations in $\hat{S}_y$ to be below or above the coherent state limit depending on the relative phase between squeezed vacuum and the classical field. Typically the degree of squeezing emerging from our source is about -5 dB, but due to various imperfections and losses only -3 dB of Stokes parameter squeezing is detected, corresponding to $\epsilon_y = 0.5$. The degree of antisqueezing is typically 8–9 dB relative to the coherent state probe, corresponding to $\epsilon_z = 6$–8.

Our atomic sample is Cs vapor in a paraffin coated glass cell. The atomic angular momentum is created by optical pumping along the x axis with two σ_+ polarized diode lasers resonant with the $6S_{1/2}(F=4) \rightarrow 6P_{1/2}(F=4)$ transition and the $6S_{1/2}(F=3) \rightarrow 6P_{3/2}(F=4)$ transition. By adjusting the relative power of the lasers we are able to control the number of atoms in the $F=4$ ground state, which is the one used for memory. The degree of spin polarization ($\approx 95\%$) and the number of atoms is measured by observing the magneto-optical resonance of the ground spin state.

The output Stokes parameter $\hat{S}_y$ is measured by a polarizing beam splitter oriented at a 45° angle with respect to the mean input optical polarization. The probe is blue detuned by 875 MHz from the $6S_{1/2}(F=4) \rightarrow 6P_{3/2}(F=5)$ transition of Cs atoms at rest. This detuning is close to optimal for mapping given various limitations due to absorption, technical noise, etc., The power spectrum of $\hat{S}_y$ is recorded in a frequency window varying from 1.6 to 3.2 kHz around Ω. The resulting spectrum is a narrow Lorentzian centered at Ω with a width Γ (Fig. 3). Our linewidths and hence our storage times are limited by collisions, quadratic Zeeman effect, and power broadening due to the probe amounting to about 100 Hz altogether. In our experiment the power broadening is hard to avoid since a strong probe is needed to obtain the required sensitivity to

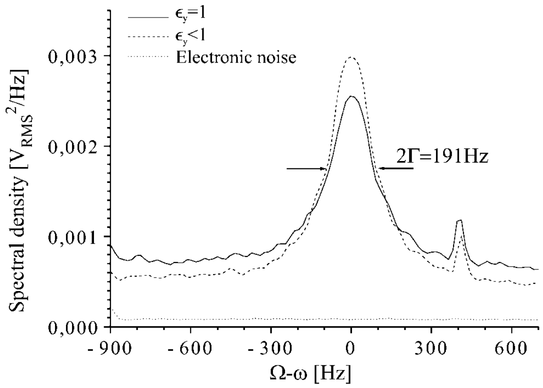

FIG. 3. The measured spectrum of the transmitted probe. The solid line is obtained with the input light in a vacuum state ($\epsilon_y = \epsilon_z = 1$). When the input mode is in a squeezed state (dashed line) the Lorentzian part from atoms increases while the wings decrease. The peak on the right is technical noise. In the experiment $\Omega = 325$ kHz.

atomic spin noise at the quantum level. Optical pumping lasers also contribute to the power broadening. Although this contribution can be eliminated with pulsed pumping, in our experiment power broadening by the optical pumping lasers ranging from 100 Hz to 1 kHz FWHM was used to verify the model.

The spin noise resonance at Ω contains contributions from the spin projection noise, the back action term, and the technical noise of the spin. The latter is not known, however, as shown below, it can be evaluated, and the consistency of the model can be verified by varying the quantum state of the probe. The two upper traces in the figure correspond to the vacuum state of the mode $\hat{a}_y$ (the probe in a coherent polarization state) and the squeezed vacuum state of $\hat{a}_y$ (the probe in a squeezed polarization state), respectively. The reduction of the optical quantum noise of $\hat{S}_y$ is clearly seen in the wings of the atomic resonance when the polarization squeezed probe is applied. However, more interesting is that the atomic spin noise *grows* when the probe is squeezed in $\hat{S}_y$. This is due to the light-induced back action noise of the atoms. Note that this back action may completely wash out the advantages of using squeezed light in sensitive magnetometry [16].

Figure 3 represents the evidence of antisqueezed Stokes parameter $\hat{S}_z$ being stored in the atoms. This storage takes place over a time scale on the order of $(2\pi\Gamma)^{-1}$ which here corresponds to about 2 ms. Note that squeezed vacuum output of the optical parametric amplifier [15] at our values of the gain contains about 1 photon per sec per Hz of the bandwidth. Hence Fig. 3 shows the effect of approximately 200 photons/sec stored within the atomic bandwidth. We may expect therefore the sensitivity of the atomic memory at the level of a single photon for pulses with $(2\pi\Gamma)^{-1} \approx$ 2 ms duration.

From Eq. (4) we know that the *back action noise area* (BANA) is proportional to ϵ_z, so that we can extract this contribution from the overall atomic spin noise by $\mathrm{BANA} = (A_{\mathrm{SQ}} - A_{\mathrm{COH}})/(\epsilon_z - 1)$, where A_{COH} and A_{SQ} are the measured spin noise areas with a coherent and squeezed probe, respectively. We can also define the *residual spin noise* $\mathrm{RSN} = (\epsilon_z A_{\mathrm{COH}} - A_{\mathrm{SQ}})/(\epsilon_z - 1)$.

To compare the experimental results with theoretical predictions we integrate (4) over frequencies and calculate the back action noise area $\mathrm{BANA} = \frac{\pi a^4 J_x^2 \epsilon_z}{\Gamma}(\frac{S_x}{2})^3$ and the *projection noise area* $\mathrm{PNA} = 2\pi a^2 J_x (\frac{S_x}{2})^2$. Knowing the *shot noise level* $\mathrm{SNL} = S_x/2$ we obtain $\mathrm{PNA} = 2\sqrt{\pi\Gamma \times \mathrm{BANA} \times \mathrm{SNL}}$ for a coherent probe ($\epsilon_y = \epsilon_z = 1$). Varying ϵ_z we can determine the back action term BANA, which is in turn determined by the quantum state of the probe light. With the knowledge of the BANA and the SNL, we are able to deduce the size of the PNA.

We now vary the probe power to confirm the S_x^3 dependence of the back action noise and the number of atoms to confirm the J_x^2 dependence. The latter is varied by adjusting the repumping laser power and hence the relative populations in the $F = 3, 4$ ground states. We find the BANA to scale with S_x^p, where $p = 2.8 \pm 0.2$, and J_x^q with $q = 2.0 \pm 0.2$ in good agreement with the theory. During the sequence of measurements ϵ_y and ϵ_z are monitored several times and variations are found to be less than 10%. Even more exciting is to observe the variation of BANA and RSN with Γ. From Fig. 4(a) we see that the BANA decreases as expected with Γ^{-1} to within a few percent. The RSN dependence on Γ, shown in Fig. 4(b), is found to fall off roughly with Γ^{-1} until a value of approximately $2\Gamma = 500$ Hz is reached. Here the RSN starts leveling out to approach a constant value. This is due to the higher degree of optical pumping, and hence higher Γ, which pushes the atomic spin towards the coherent spin state (CSS) and thereby washes out any additional (technical) noise in the spin state. We therefore expect the RSN to converge to a level set by the CSS. In our notation this level is just the PNA, which can be estimated from the BANA and the SNL. This estimate is also shown in Fig. 4(b) where we see that the RSN indeed is approaching the PNA at higher values of Γ.

Finally, we fix Γ and vary the number of atoms (J_x). Again from the measured BANA we have inferred the PNA and observe that it grows proportionally with J_x.

In summary, we have shown how partial information about an unknown Gaussian quantum state of light, more precisely the value of one of the quadrature phase operators $\frac{1}{2i}(\hat{a}_y - \hat{a}_y^\dagger)$, can be recorded onto the atomic ground state spin, where it is stored for approximately 2 ms. We have also demonstrated how this information is read out again by the probe via the narrow band atomic spin noise around the Larmor frequency. Most importantly, we have demonstrated that long-lived atomic spin ensembles can serve as storage for light sensitive enough to store quantum states of optical fields containing just a few photons.

For an arbitrary Gaussian state of light the state is completely defined by two variances of the quadrature

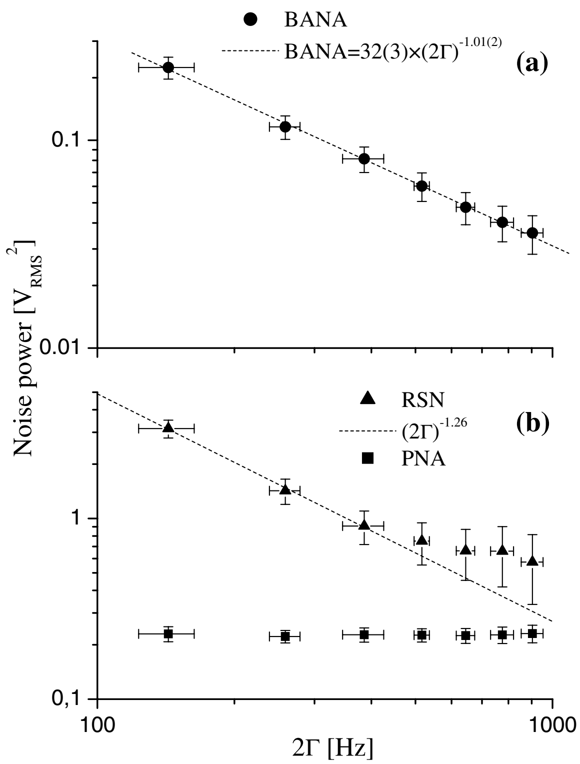

FIG. 4. (a) The measured back action noise area (BANA) for the vacuum light input as a function of decay rate Γ on a log-log scale. The error bars indicate the statistical error derived from Lorentzian fits to the spin noise resonances and a 10% uncertainty in ϵ_z. (b) The measured residual spin noise (RSN) and the inferred projection noise area (PNA). See text for details.

phase components (in addition to the mean values). These two components, $\frac{1}{2i}(\hat{a}_y - \hat{a}_y^\dagger)$ and $\frac{1}{2}(\hat{a}_y + \hat{a}_y^\dagger)$, are noncommuting variables and therefore their values cannot be measured simultaneously. The full quantum memory should be capable of recording both components. To claim that a Gaussian state is exactly reproduced after the storage one will have to check that the variances of the input and output states have close enough values. Such a check is similar to the teleportation fidelity for continuous variables. In this paper we have demonstrated enough sensitivity for distinguishing between a vacuum state and a squeezed state judging by the variance of one quadrature only. The theoretical proposal [9] shows how to achieve the complete Gaussian state exchange between atoms and light with the same type of interaction as in the present paper using two entangled atomic ensembles [11] or two entangled beams of light [17]. This will be the goal of the next generation of experiments.

In our continuous wave experiment the probe effectively reads out its own quantum state at an earlier time which has been stored in atoms. Future experiments using two pulses, one to be stored and another to read out the stored information, are clearly feasible.

The narrow band frequency response of the atomic ground state spin allows only for storage of a few hundred Hz wide frequency band of the optical state around the carrier frequency Ω. One way to overcome this limit would be to apply a linear magnetic field gradient in the z direction, or to use an inhomogeneously broadened solid state medium [18]. This would make atoms at different positions have different Larmor frequencies, hence they would store different frequency components of the optical state and the entire optical spectrum of interest could then be recorded in atoms.

This work was supported by the Danish National Research Foundation and by the EU via the QUICOV and CAUAC projects.

*Electronic address: polzik@ifa.au.dk

[1] A. Kuzmich, K. Mølmer, and E. S. Polzik, Phys. Rev. Lett. **79**, 4782 (1997).
[2] A. E. Kozhekin, K. Mølmer, and E. S. Polzik, Phys. Rev. A **62**, 033809 (2000).
[3] J. Hald, J. L. Sørensen, C. Schori, and E. S. Polzik, Phys. Rev. Lett. **83**, 1319 (1999).
[4] J. Hald, J. L. Sørensen, C. Schori, and E. S. Polzik, J. Mod. Opt. **47**, 2599 (2000).
[5] H. J. Briegel, J. I. Cirac, W. Dur, S. J. van Enk, H. J. Kimble, H. Mabuchi, and P. Zoller, Lect. Notes Comput. Sci. **1509**, 373 (1999).
[6] M. Fleischhauer and M. D. Lukin, Phys. Rev. Lett. **84**, 5094 (2000).
[7] D. F. Phillips, A. Fleischhauer, A. Mair, R. L. Walsworth, and M. D. Lukin, Phys. Rev. Lett. **86**, 783 (2001).
[8] C. Liu, Z. Dutton, C. H. Behroozi, and L. V. Hau, Nature (London) **409**, 490 (2001).
[9] A. Kuzmich and E. S. Polzik, Phys. Rev. Lett. **85**, 5639 (2000).
[10] A. Kuzmich, L. Mandel, and N. P. Bigelow, Phys. Rev. Lett. **85**, 1594 (2000).
[11] B. Julsgaard, A. Kozhekin, and E. S. Polzik, Nature (London) **413**, 400 (2001).
[12] K. J. Blow, R. Loudon, S. J. D. Phoenix, and T. J. Shepherd, Phys. Rev. A **42**, 4102 (1990).
[13] L.-M. Duan, J. I. Cirac, P. Zoller, and E. S. Polzik, Phys. Rev. Lett. **85**, 5643 (2000).
[14] B. Julsgaard *et al.* (to be published).
[15] E. Polzik, J. L. Sørensen, and J. Hald, Appl. Phys. B **66**, 759 (1998).
[16] D. V. Kupriyanov and I. M. Sokolov, Quantum Opt. **4**, 55 (1992).
[17] C. Schori, J. L. Sørensen, and E. S. Polzik, quant-ph/0205015.
[18] A. V. Turukhin, V. S. Sudarshanam, M. S. Shahriar, J. A. Musser, B. S. Ham, and P. R. Hemmer, Phys. Rev. Lett. **88**, 023602 (2002).