GENERATION OF ARBITRARY QUANTUM STATES FROM ATOMIC ENSEMBLES

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A holy grail in quantum information processing is the ability to obtain complete control over a particular subspace [1]. Such quantum state engineering has been recently accomplished in the optical [2], microwave [3] and trapped ion [4] regimes. A natural next frontier is to extend these methods to collective spin excitations (CSEs) of atomic ensembles. In addition to applications in long distance quantum communication [5] and quantum metrology [6], engineering of CSEs is of fundamental interest as it allows one to explore the isomorphism between the Hilbert space of a CSE and a single electromagnetic mode [7]. So far, engineering of CSEs has been limited to squeezed spin states [8] and a single CSE quantum state [9]. Here, we present a general method for producing arbitrary superpositions of CSE states and provide the first proof of principle experiment to this end.

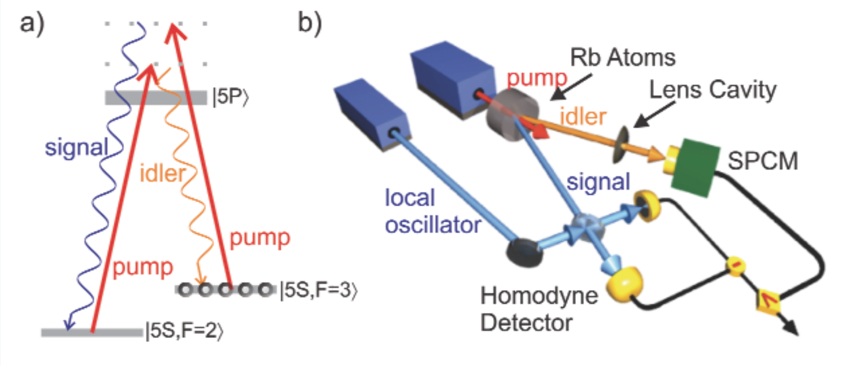

Fig. 1 (a) The atomic level diagram. Raman scattering of the pump leads to the creation of a collective spin excitation into the F = 2 state, followed by immediate recycling back into F = 3. This results in a correlated pair of signal and idler photons. (b) Sketch of experimental setup.

The single CSE quantum state can be prepared by Raman scattering from an atomic ensemble conditioned on detection of an *idler* photon according to the idea of Duan, Lukin, Cirac and Zoller (DLCZ) [5]. While DLCZ utilize only the first-order term of the evolution under the system's Hamiltonian, higher-order terms can be used in combination with specific measurements on the scattered optical mode to produce arbitrary quantum CSE states akin to [2]. To measure the produced state, the readout stage of the DLCZ protocol may be employed, in which the CSE is converted into the optical domain via the *signal* channel. Full information about the retrieved optical state, and hence about the CSE, can then be acquired using optical homodyne tomography.

SUMMARY

Using a four-wave mixing process in atomic vapour, we generate nonclassical states of light and propose a method of manipulating the collective quantum state of an atomic ensemble.

In order to test the feasibility of the above protocol, we simultaneously write-in and read-out the CSE in accordance with the DLCZ protocol using a single laser, then measure the state of the signal channel conditioned on the detection of an idler photon (Fig. 1). Ideally, the creation of a single CSE should accompany a single photon Fock state in the signal channel, but loss and background photons will lead to a mixture with vacuum and incoherent light. In order to filter background photons, we employ a monolithic spherical Fabry-Perot cavity with a 55 MHz linewidth constructed from a standard lens with high reflectivity coating on each side, that can be tuned by varying its temperature [10].

Idler photon events occur at a rate of $\simeq 300$ kHz. Upon each event, the signal channel is measured using a balanced homodyne detector (HD) with a 100-MHz bandwidth [11]. The local oscillator for the HD stems from a separate diode laser that is phase locked at a frequency 3.035 GHz higher than the pump [12]. The spatial mode of the local oscillator is matched to that of the signal photon by injecting an auxiliary laser beam into the idler channel, which interacts with the pump inside the cell to generate a bright field in the signal and idler modes [13]. A quadrature measurement Q_θ of the heralded state is obtained from the homodyne current by integrating over its temporal mode

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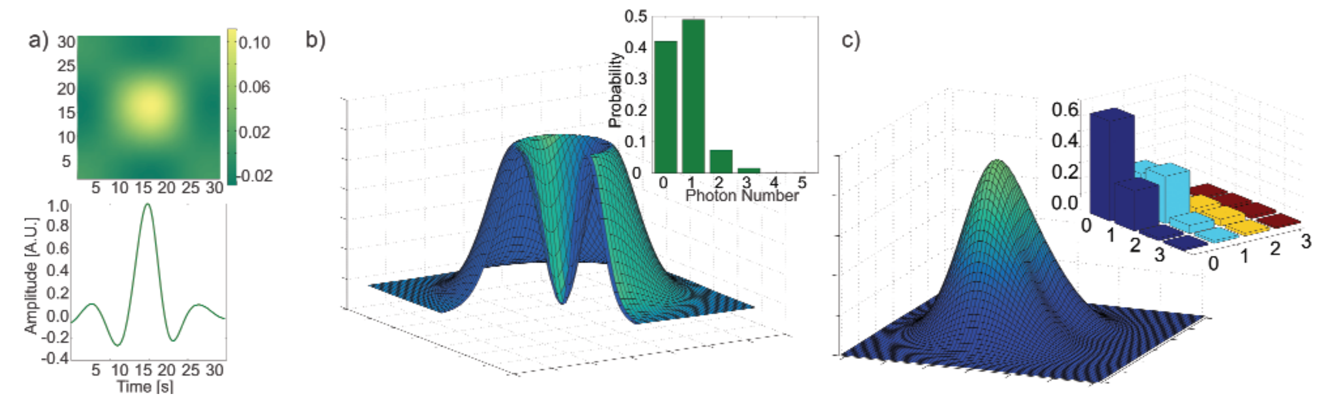

Fig. 2 (a) The symmetry of the autocorrelation matrix (upper) indicates a pure temporal mode, given by the principle eigenvector (lower) (b) The reconstructed density matrix and Wigner function of the narrowband photon reaches a value of -0.0045 at the origin. No corrections are made for losses in this plot. (c) The Wigner function of a coherent superposition of 0 and 1 photons, corrected for the 20% loss in the experiment.

function $\psi(t)$:

$$\psi(t):Q_{\theta}=\int_{-\infty}^{\infty} q_{\theta}(t)\psi(t)dt$$

where $q_{\theta}(t)$ is proportional to the instantaneous homodyne detector output photocurrent, and θ is the phase of the local oscillator with respect to the quantum state.

To determine ψ (t), which is not know a priori, we observe the autocorrelation $< q(t_1)\, q(t_2) >$ of the HD photocurrent as a function of delay from the trigger, corresponding to the density matrix of the heralded state in the time domain (Fig. 2(a)). The autocorrelation function has a round shape, showing high purity of the temporal mode of the heralded photon. This observation is further confirmed by the eigenvalue spectrum of the autocorrelation matrix. The eigenvector corresponding to the primary eigenvalue yields the temporal mode function as shown in Fig. 2(a).

We measure the marginal quadrature distribution corresponding to the determined temporal mode for 10^5 samples and reconstruct the density matrix using a maximum likelihood technique [2]. The density matrix shows an approximate 49% single photon component and the corresponding Wigner function becomes negative at the origin reflecting its nonclassical nature [14].

By weakly seeding the trigger channel with a coherent state α of comparable mean photon number to that emitted by the 4WM process, the detection of an idler photon from α is indistinguishable from a detection stemming from the creation of a CSE. This results in a coherent superposition of 0 and 1 CSEs $|\psi\rangle = a|0\rangle + b|1\rangle$, with coefficients a and b determined by the phase and magnitude of the coherent state. To verify the creation of this state, we collect quadrature data for a number of angles in phase space and reconstruct the Wigner function as above. The resultant Wigner function (Fig. 2(c)) shows both a coherent displacement as well as a dip near the origin, characteristic of a coherent superposition of 0 and 1 photons. Moving to the pulsed regime as in DLCZ, we can employ conditional measurements akin to [2] and engineer increasingly complex superposition states. This work thus not only provides a high quality source of quantum light, but also opens the door to extend previous quantum optical state generation to collective spin excitations.

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