Generation of a macroscopic singlet state in an atomic ensemble

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Abstract: We report on an experiment for generating singlet states in a cold atomic ensemble. We use quantum non-demolition measurement and feedback control to produce a macroscopic spin state with total spin zero and reduced spin fluctuations.

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1. Introduction

Future applications of quantum physics for quantum simulations, computation, communication and metrology will require an extremely high degree of control of the preparation, manipulation and detection of strongly correlated states of quantum many-body systems. Cold atoms offer an unprecedented playground for the realization of these goals. One such highly correlated state is the singlet state, i.e., a state with total spin zero and no spin fluctuations. It appears as ground state of many fundamental spin models and is invariant under the unitary transformation which describes the effect of an external magnetic field on the spins. Possible applications of such state include encoding quantum information in a decoherence free subspace, sending information independently of the reference frame, or metrological applications in which insensitivity to external homogenous magnetic fields is needed.

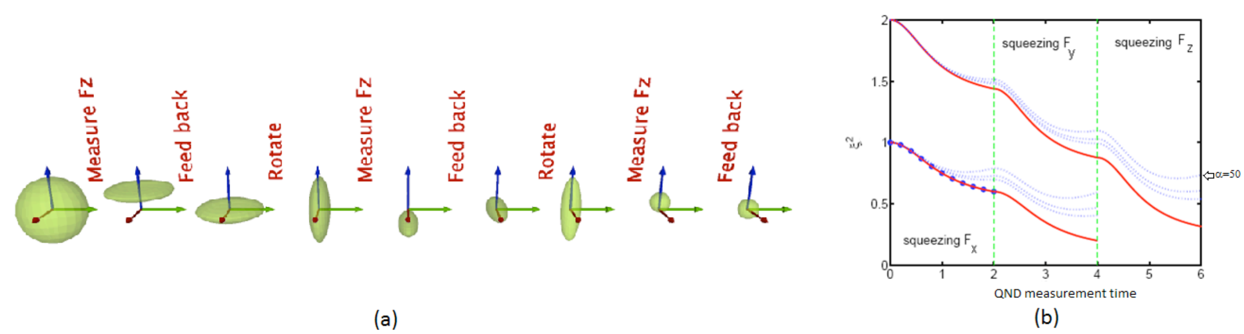

Fig. 1. (a) Sequence for producing a macroscopic singlet state by applying QND measurement and feedback to all components of angular momentum. (b) The theoretical simulation shows sequential QND measurement on angular momentum components of an initial thermal state (upper trace) produce a state with $\xi < 1$ i.e. a highly entangled state and to some approximation a singlet state [1]. The red line is for the idealistic case and dotted blue line are correspond to different optical depth (from top to bottom) $\alpha = 50, 75, 100$. In our experiment we are in the regime of $\alpha = 50$.

We report on an experiment for generating a singlet state in a cold atomic ensemble. The experiment is based on a recent proposal to generate these states by applying a quantum non-demolition (QND) measurement and feedback scheme to an unpolarized ensemble [1]. It has been experimentally demonstrated and theoretically investigated that QND measurement is a useful tool for reducing spin fluctuations i.e. spin squeezing. Our criterion for generating the singlet state is the spin squeezing parameter $\xi = \frac{(\Delta F_x)^2 + (\Delta F_y)^2 + (\Delta F_z)^2}{Nf}$ where F_i are the components of the collective angular momentum, N is the number of atoms and f is the spin of a single particle. Any state with $\xi < 1$ is an entangled state [2]. Our procedure, described bellow, will lead to a highly entangled state with $\xi \ll 1$ starting from a non-entangled state with $\xi \sim 1$.

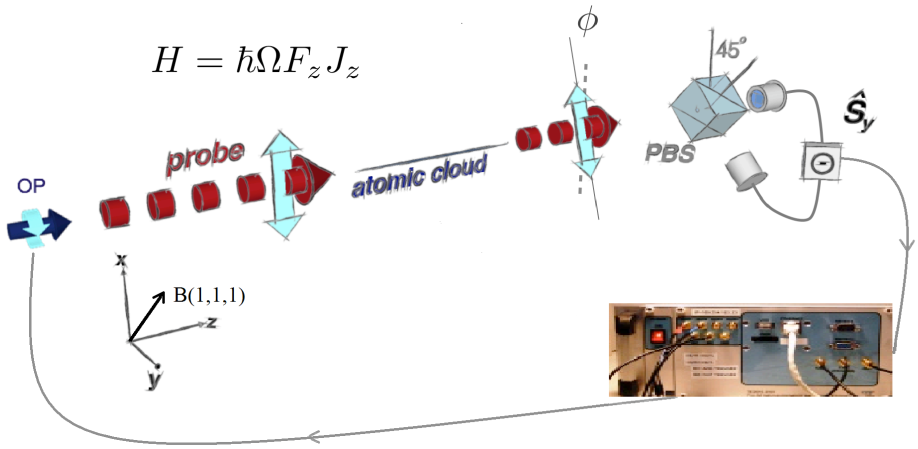

Fig. 2. Schematic of the experiment: We trap $\sim 10^6$ ^{87}Rb atoms in an optical dipole trap at a temperature of 25 μK. We probe the atomic spin state with μs pulses of light propagating along the trap axis and detected by a shot-noise limited balanced polarimeter. The elongated trap geometry provides strong atom-light coupling, with an effective on-resonance optical depth above 50 [3]. We prepare a thermal spin state via omnidirectional optical pumping, as described in ref. [4]. In order to probe orthogonal spin components, we rotate the atomic state with a uniform magnetic field $B(1,1,1)$. Feedback is applied via optical pumping with circularly polarized light propagating along the trap axis.

2. Experiment

2.1. *Thermal state preparation*

We use omnidirectional optical pumping to prepare an ensemble of $\sim 10^6$ cold ^{87}Rb atoms in a completely thermal mixture of three Zeeman levels of the $F = 1$ hyperfine ground state. This mixed state has zero average spin, and a variance $\langle F \cdot F \rangle = 2N$, so that $\xi = 2$.

2.2. *QND Measurement*

A nondestructive measurement of the spin component F_z with a precision better than the intrinsic quantum noise will project the atoms onto a spin state with reduced fluctuations in that component. The demonstrated sensitivity of the QND measurement in our experiment is 2.8 dB better than the intrinsic noise level for thermal state [4]. We apply the QND measurement using detuned pulses of light from $5S_{1/2} \rightarrow 5p_{3/2}$ D_2 line transition of ^{87}Rb to measure the collective angular momentum component $\mathbf{F}$ of cold atom ensemble. A detuned probe on the D_2 transition experiences an interaction $H_I = \hbar\Omega F_z S_z$, where S_z is the collective Stokes operator describing the polarization of the probe light. This Hamiltonian describes the rotation of the polarization of the light proportional to F_z.

2.3. *Feedback and real-time detection scheme*

Since the QND measurement is projective, it results in general in a spin state with $\langle F_z \rangle \neq 0$. To generate the singlet state, we need to restore the mean spin to zero. We do this feedback via optical pumping with circularly polarized light propagating along the trap axis, based on the measurement variable $z = S_y^{in} + \kappa F_z^{in}$. In this process the redistribution of the population of the state will remove the net $\langle F_z \rangle$ measured value via an incoherent feedback process. Simulation and experimental demonstration (see figure 3.(b)) prove this feedback procedure is a good condidate and the added amount of noise is negligible. The optical pumping is on resonance with the $F_1 \to F_0'$ transition of ^{87}Rb D2 line to have minimum loss of atoms to F_2 ground state. We use the σ_+ polarized optical pumping to remove negative F_z population and σ_- polarized light source to remove the positive F_z population.

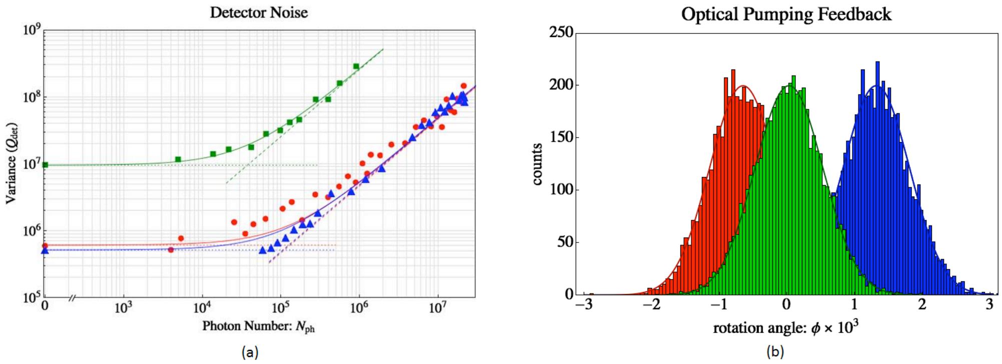

Fig. 3. (a) Quantum noise calibration of real-time detector for two different gain settings (green and blue), compared with oscilloscope detection (red). Symbols show measured points, curves show fits. The real-time detector is shot-noise limited above 3×10^5 photons/pulse. (b) State displacement by optical pumping. Histograms show measured spin distributions for mixed state (green), or mixed states displaced by optical pumping with σ_- or σ_+ light, (blue and red respectively). Analysis of distribution widths versus displacement show a broadening by < 0.1 times the width of the distribution for displacements up to one width.This confirms that the feedback is effectively noise-free.

In order to be able to do feedback in appropriate way, real-time measurement capability is necessary. We have developed a new detection system which is shot noise limited and provides integrated pulse measurement and proportional signal with a bandwidth of 200kHz in real- time. This detection system gives us the signal that we can use in real-time to do optical pumping feedback. The new detection system has sampling rate of 50 MSps and speed of 100Mbps.

2.4. *Spin rotation*

To generate a macroscopic singlet state we need to perform measurement and feedback on all components of angular momentum.To reach this aim, a magnetic field, applied along the (1,1,1) direction, continuously rotates the spin state such that $\mathbf{F} = (x, y, z) \to (y, z, x)$ after one-third cycle, allowing measurement+feedback on all three axes of the distribution by properly timed stroboscopic measurements of the single componenet F_z. This will able us to successively measure, squeeze and set to zero each spin component F_i, producing progressively closer approximation to an ideal macroscopic singlet state.

References

1. G. Tóth, M. W. Mitchell, New Journal of Physics, **12** (2010) 053007.
2. G. Tóth, C. Knapp, O. Gühne, H. J. Briegel, Phys. Rev. Lett. **99**, 250405 (2007).
3. M. Kubasik, M. Koschorreck, M. Napolitano, S. R. de Echaniz, H. Crepaz, J. Eschner, E. S. Polzik, M. W. Mitchell, Phys. Rev. A **79**, 043815 (2009).
4. M. Koschorreck, M. Napolitano, B. Dubost, M. W. Mitchell, Phys. Rev. Lett. **104**, 093602 (2010).
5. S. T. Merkel, P. S. Jessen, I. H. Deutch, Phys. Rev. A **78**, 023404 (2008).