

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

Cold atoms offer an unprecedented playground for the realization of applications of quantum physics for quantum simulations, computation, communication and metrology. We report on an experiment for generating macroscopic singlet state in a cold atomic ensemble. The singlet state is 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.

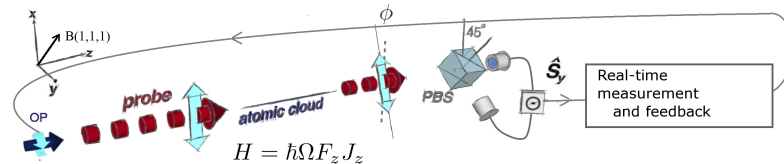


Fig. 1. Schematic of the experiment: We trap $\sim 10^6$ ^{87}Rb atoms in an elongated dipole trap with an effective on-resonance optical depth above 50 and temperature of $25\ \mu\text{K}$. We probe the atomic spin state with μs pulses of light propagating along the trap axis and detected by a shot-noise limited balanced polarimeter [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.

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 below, will lead to a highly entangled state with $\xi \ll 1$ starting from a non-entangled state with $\xi \sim 1$ [1].

2. Experiment

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 $\xi = 2$.

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 F_z of the 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 .

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 $z = S_y^{\text{in}} + \kappa F_z^{\text{in}}$. 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 2.(b)) shows that the added amount of noise is negligible. The optical pumping is on resonance with the $F_1 \rightarrow F_0'$ transition of ^{87}Rb D_2 line to have minimum loss of atoms to the F_2 ground state. In order to be able to do feedback, we have developed a new shot noise limited real-time detection system with a bandwidth of 200kHz. This detection system gives us the signal that we can use in real-time to do optical pumping feedback.

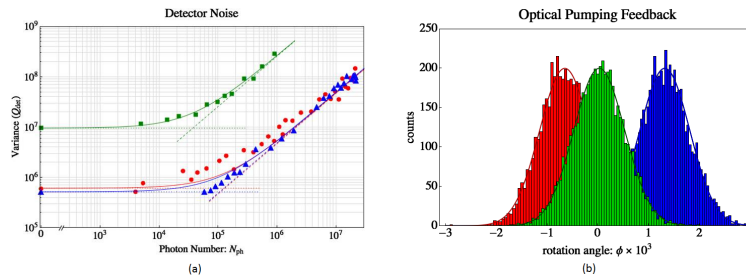


Fig. 2. (a) Quantum noise calibration of real-time detector for two different gain settings (green and blue), compared with oscilloscope detection (red). Symbols show measured points, curves show fits. The real-time detector is shot-noise limited above 3×10^5 photons/pulse. (b) State displacement by 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 introduces negligible noise.

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

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