Generation of a macroscopic singlet state in an atomic ensemble

Naeimeh Behbood, Mario Napolitano, Giorgio Colangelo, Brice Dubost, Silvana Palacios Álvarez, Robert J. Sewell, Geza Tóth, Morgan W. Mitchell

1. ICFO-Institut de Ciencies Fotoniques, Mediterranean Technology Park, 08860 Castelldefels (Barcelona), Spain
2. Laboratoire Matériaux et Phénomènes Quantiques, Université Paris Diderot et CNRS, UMR 7162, Bât. Condorcet, 75205 Paris Cedex 13, France.
3. Theoretical Physics and History of Science, The University of the Basque Country, 48080 Bilbao, Spain.

naeimeh.behbood@icfo.es

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 ξ < 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) α = 50, 75, 100. In our experiment we are in the regime of α = 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 ξ = \( \frac{(\Delta F_x)^2 + (\Delta F_y)^2 + (\Delta F_z)^2}{N_f} \) 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 $\xi \sim 1$.

$$H = \hbar \Omega F_z J_z$$

Fig. 2. Schematic of the experiment: We trap $\sim 10^6$ $^{87}\text{Rb}$ atoms in an optical dipole trap at a temperature of $25 \mu K$. We probe the atomic spin state with $\mu s$ 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 $^{87}\text{Rb}$ 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 $5S_{1/2} \rightarrow 5P_{1/2}$ $D_2$ line transition of $^{87}\text{Rb}$ to measure the collective angular momentum component $F$ 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 $z = S^m_y + \kappa F^m_z$. 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 candidate and the added
amount of noise is negligible. The optical pumping is on resonance with the $F_z \rightarrow F'_z$ transition of $^{87}$Rb D2 line to have minimum loss of atoms to $F_z$ ground state. We use the $\sigma_+$ polarized optical pumping to remove negative $F_z$ population and $\sigma_-$ polarized light source to remove the positive $F_z$ population.

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 $\mathbf{F} = (x, y, z) \rightarrow (y, z, x)$ 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 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