Generation of macroscopic singlet states in atomic ensembles

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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 of such highly correlated states is the singlet state, that is, a state with total spin zero and no spin fluctuations. It appears as the 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, which makes it applicable for encoding quantum information in a decoherence free subspace, for sending information independent of a reference direction, or possibly for metrological applications in which insensitivity to external homogenous magnetic fields is needed.

We will report on an experiment underway for generating singlet states 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 to an unpolarized ensemble[1]. It has been demonstrated both experimentally and theoretically that QND measurement is a useful tool for spin squeezing. Our criteria for generating the singlet state is the spin squeezing parameter

$$\xi_s = \frac{(\Delta F_x)^2 + (\Delta F_y)^2 + (\Delta F_z)^2}{Nj} \tag{1}$$

where F_i are the components of the collective angular momentum, N is the number of atoms and j is the spin of a single particle. Any state with $\xi_s < 1$ is an entangled state[2]. Our procedure will lead to a highly entangled state with $\xi_s < 1$ from a non-entangled state with $\xi_s \sim 1$.

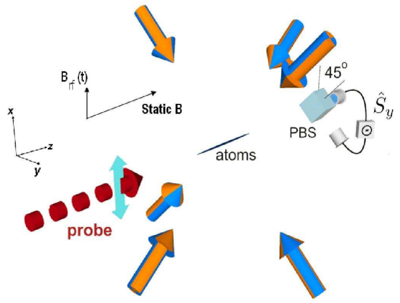

FIG. 1: Schematic of the dipole trap: The experimental apparatus is an optical dipole trap which is able to trap about one million ^{87}Rb atoms at temperature of about $25\mu K$. The geometry of dipole beam provides us a large atom-light interaction with an effective on-resonance optical depth above 50 [3]. The demonstrated sensitivity is 2.8 dB better than the intrinsic noise level for the thermal spin state[4].

The starting point of the experiment is the preparation of a completely mixed spin state in the atomic ensemble of cold ^{87}Rb via omnidirectional optical pumping. The advantage of using such a state is that the mean angular momentum of this completely mixed state is zero and it is the most similar classical state to the quantum state that we are going to produce. Applying QND measurement to this state will reduce the fluctuations in the system and in this way lead to reduction of ΔF_z. A detuned probe on the D_2 transition experiences an interaction $H_I = \hbar\Omega F_z S_z$ which will lead to input-output relations for the components of **F** and **S** up to first order in the interaction time τ, $S_y^{out} = S_y^{in} + \Omega\tau F_z S_x$. The interaction Hamiltonian will provide us information about F_z without direct measurement on the atomic state, which will decrease the uncertainty of F_z. To generate the singlet state, the measurement outcome $x = S_y^{in} + \kappa F_z^{in}$ is fedback into the atomic variable F_z. Feedback in the form of optical pumping is our main candidate to restore $\langle F_z \rangle = 0$.

In our set up we can measure one of the components of angular momentum, F_z, in order to measure the other components of **F**, we must rotate the spin state [5]. Our proposal is to use magnetic field rotation. In this way atomic spin will adiabatically follow the change of the magnetic field direction as long as $\frac{d\theta}{dt} \ll \omega_{\mathrm{Larmor}}$. This will allow us to measure all the components of angular momentum which will reduce ΔF_x and ΔF_y and lead us to squeezing of ξ_s.

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