Squeezing a cold ensemble of Cs atoms for precision measurements and quantum communication

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The progress with a project implementing a Quantum Non-Demolition (QND) measurement of the population number difference of Cesium atoms in a superposition of the two $6S_{1/2}$ (F=3) and $6S_{1/2}$ (F=4) ground states is presented. This technique can be used to improve the accuracy of atomic fountain clocks as well as to entangle two spatially separated ensembles of cold atoms.

One of the aims of this project is to improve the accuracy of Cold Atom Clocks. As first reported by G. Santarelli et al. in 1999, the accuracy of today's state-of-the-art clocks is limited by quantum projection noise of atoms [1]. The value of interest in atomic clocks is the difference between the phase of Cs atoms and an external interrogation field. This difference arises during the free evolution of the atoms between two $\pi/2$ interactions with the field: the first $\pi/2$ interaction brings the Bloch vector to the equatorial plane of the Bloch sphere, and the second $\pi/2$ interaction converts the phase error into the population difference, which is finally measured using standard fluorescence techniques. However, the measurement of population number differences is subject to quantum projection noise. For instance, when preparing atoms in linear superpositions of two states $|\,0\,\rangle$ and $|\,1\,\rangle$ with equal mean populations $\langle N_0\rangle=\langle N_1\rangle=N/2$, the variance of a population difference measurement is given by $\delta\beta^2=\mathrm{Var}\{(N_1-N_0)/N\}=1/N$.

Here we propose the following scheme: since the direct squeezing of the coherences of the atomic ensemble is difficult (unlike in the case of real spin), we suggest to squeeze the population distribution first, then, using an additional RF-pulse, correct the measured population difference, and finally, using another additional RF-pulse, convert the population squeezing into phase squeezing (Fig. 1).

The suggestion to use a QND measurement to suppress this projection noise was made by A. Kuzmich et al. [2]. Briefly, a variation of the population difference gives rise to a variation of the index of refraction of the atomic ensemble. Probing the refractive index with off-resonant beams using an interferometric setup thus enables to measure the population difference in a non destructive way and hence to acquire more precise knowledge about the value of the now squeezed property. Obviously, this goes along with an increased uncertainty of the value of the atomic coherences. The resolution of such a QND measurement is always limited by the shot-noise of the light used to probe the atoms. A concern is thus to maximize the variation

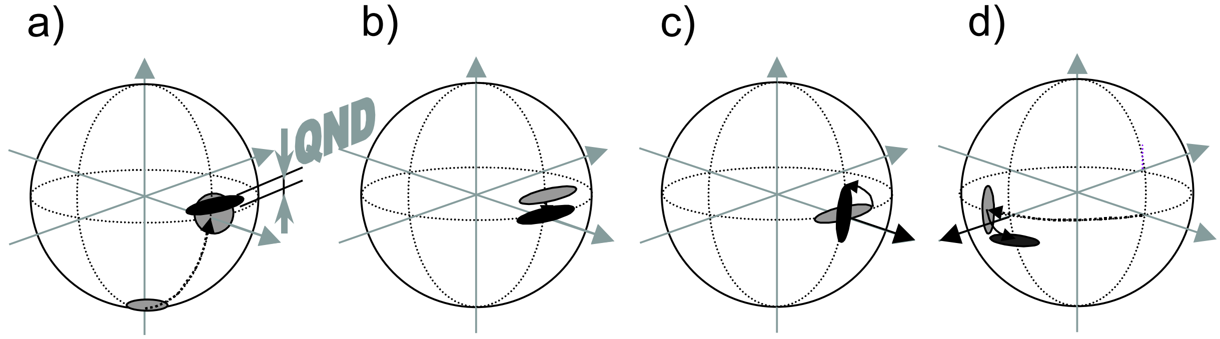

Figure 1: a) QND measurement; b) population difference correction with RF pulse; c) conversion of population squeezing to squeezing of coherences with $\pi/2$ pulse; d) phase precession and conversion of squeezing of coherences to population squeezing.

of the light intensity due to variation of the population number difference with respect to the light shot noise while keeping the rate of real transitions in the atomic ensemble low, i.e. while keeping the measurement non-destructive. Taking account of the real level scheme and the saturation parameters of Cesium, we find the best ratio of atomic noise to light shot noise when implementing a measurement with a single probe beam, red detuned by 4270 MHz with respect to the F=3→F'=2 transition. Assuming 10^5 atoms with a density of $10^{12} cm^{-3}$ (confined in a trap of ø $6\times\ 600\mu m^3$), and using a Mach-Zehnder interferometer with higher transmission through the reference arm compared to the arm containing the atoms, we find this ratio to be of around 7 [3]. This is promising to observe significant squeezing of the quantum projection noise.

Probing an atomic sample with far off-resonant beams requires atomic densities of the order of at least 10^{12} atoms/cm^3, higher than those obtained in standard MOT. To this end we will apply a four-stage cooling and trapping scheme:

1. Ordinary MOT with 6 $\sigma^+\sigma^-$ beams, ø3cm, Δ f=-3Γ, I=2.2mW/cm^2
2. Bright Molasses with the same beams, I=1.1mW/cm^2, B=0;
3. Gray Molasses [4], 6 $\sigma^+\sigma^-$ beams, ø3cm, Δ f=+4.5Γ, I=1.1mW/cm^2
4. Optical Dipole Trap using 700mW YAG beam at 1064nm [5]

Two AR-coated master diode lasers with external cavities and two powerful (200mW) injection-locked slave lasers are used in our setup. In the MOT we use 6 diagonal beams intersecting inside the Titanium chamber. The chamber has the symmetry of a cubeoctahedron (a cube with truncated corners); the side ø64 mm windows used for MOT , and eight corner windows - for beam imaging, dipole trapping beam, QND beams, and - at the next stage of the experiment - for launching the atoms upward. One or two additional diode lasers will be used for QND measurement.

Another application of off-resonant projection measurements is the possibility to create entanglement between atomic ensembles as needed for future applications such as quantum teleportation and quantum memory [6]. Given the analog between the measurement of the refractive index for population number squeezing and the rotation of polarization for squeezing of the collective spin of atoms, it is obvious that the recent observation of entanglement between the collective spins of two distant atomic ensembles [7] can be generalized to create entanglement between the population number and coherences of atomic ensembles.

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