Conditions for Spin Squeezing in Laser-Cooled Rubidium

S. R. de Echaniz[1*], M. W. Mitchell[1], M. Kubasik[1], M. Koschorreck[1], H. Crepaz[1], J. Eschner[1], and E. S. Polzik[2]

[1] *ICFO - Institut de Ciències Fotòniques, Jordi Girona 29, Nexus II, E-08034 Barcelona, Spain*
[2] *QUANTOP, Niels Bohr Institute, Copenhagen University, Blegdamsvej 17, DK-2100 København, Denmark*
[*] *E-mail: sebastian.echaniz@icfo.es*

ICFO Institut de Ciències Fotòniques

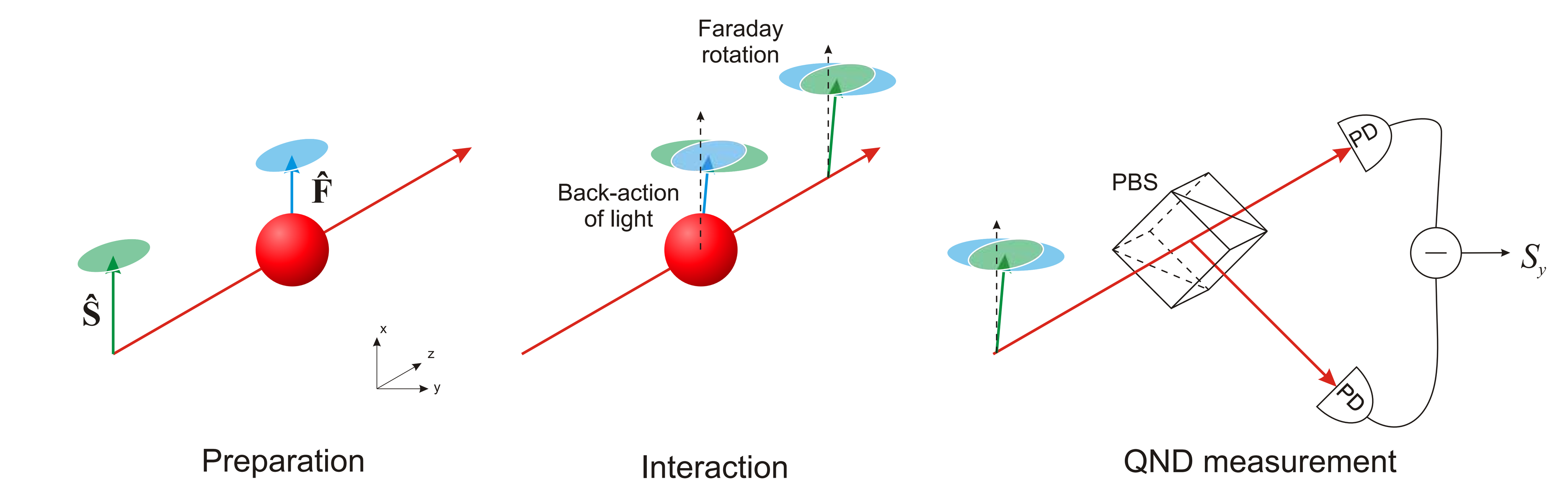
QUANTOP

Introduction

There has recently been much interest in coupling light with atomic ensembles to develop a quantum interface. Several proposals have been published to utilise this kind of interface for spin squeezing, quantum memories, quantum teleportation, and entanglement. Many of these proposals have been realised experimentally. Spin squeezing is the simplest of these applications, and has been demonstrated several times. However, all of these realisations have been performed using squeezed states of light or samples in vapour cells with relatively low coupling between atoms and light.

We propose a scheme to generate spin squeezing via a QND measurement in a cold sample of ^{87}Rb atoms using the $5S_{1/2}(F=1)$ hyperfine ground state. In this system we expect to have a much higher coupling than in previous work. Suitable Zeeman substates and operators to perform the QND interaction in this scheme are identified, together with the possible sources of error and noise.

Light-atomic-ensemble interaction



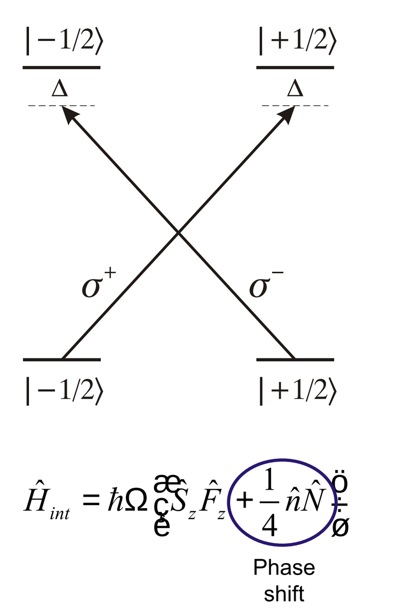
The atoms are prepared in a coherent spin state $\hat{\mathbf{F}}$ and a probe pulse in a coherent polarisation state $\hat{\mathbf{S}}$ is sent through the ensemble. The light and atoms undergo dipole interaction, where the light polarisation is rotated (Faraday effect) and so is the spin (back-action of light). At the quantum level, light and atoms exchange quantum fluctuations according to:

$$\hat H_{int} \propto \hat F_z \hat S_z \quad \Rightarrow \quad \begin{cases} \hat S_y^{out} = \hat S_y^{in} + a\langle \hat S_x^{in}\rangle \hat F_z^{in} \\ \hat S_z^{out} = \hat S_z^{in} \\ \hat F_y^{out} = \hat F_y^{in} + a\langle \hat F_x^{in}\rangle \hat S_z^{in} \\ \hat F_z^{out} = \hat F_z^{in} \end{cases}$$

After the interaction, $\hat F_z$ can be QND measured by measuring the quantum fluctuations on $\hat S_y$, inducing squeezing on the atomic spin.

Ideal spin-1/2 vs. ^{87}Rb system

Ideal spin-1/2 scheme



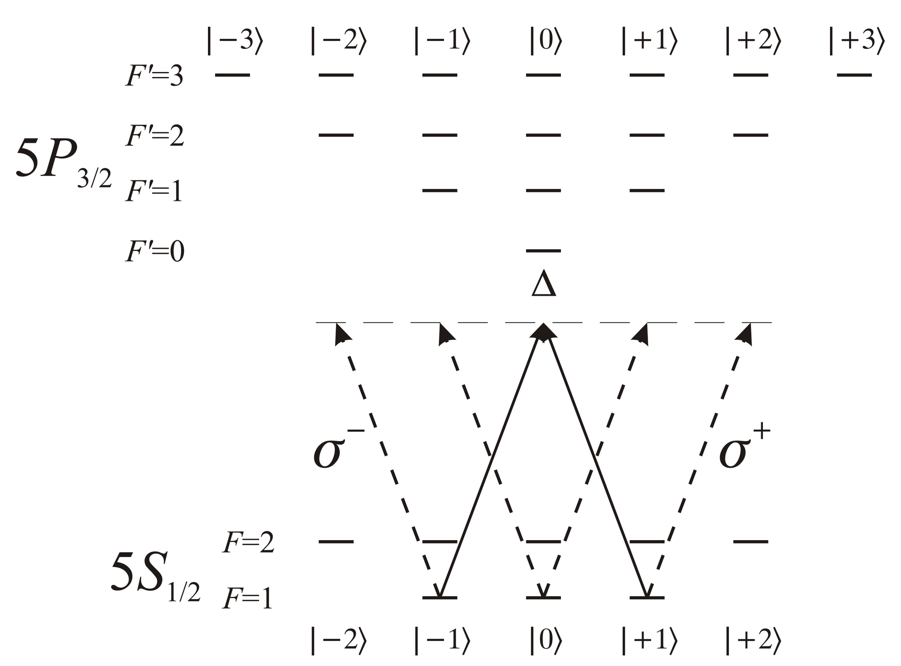
$$\hat H_{int} = \hbar\Omega\left(\hat S_z \hat F_z + \frac{1}{4}\hat n\hat N\right)$$

Phase shift

Most theoretical studies consider an ideal spin-1/2 system, where the atomic spin is polarised in the x direction (coherent superposition of $|-1/2\rangle$ and $|+1/2\rangle$). In this case, the effective Hamiltonian is easily obtained, and corresponds to the one on the left. The first term is the one responsible for the interaction described above, while the second one only introduces a phase shift which produces no signal on the polarimeter.

In the case of a real ^{87}Rb system, the lowest F-value accessible is $F=1$ and the Zeeman sublevels complicate the interaction between atoms and light. The system can be reduced to an equivalent spin-1/2 system by preparing the atoms in a superposition $|-1\rangle + |+1\rangle$, and defining the pseudo-spin $\hat{\mathbf{J}}$ on the right.

Rubidium scheme



- Polarise atoms into one component of the alignment tensor:

$$\hat T_x \propto |-1\rangle\langle+1| + |+1\rangle\langle-1|$$

- Commutation relation:

$$[\hat F_z, \hat T_y] = -2i\hat T_x$$

- Definition of pseudo-spin:

$$\left.\begin{aligned} \hat J_x &\equiv \tfrac{1}{2}\hat T_x \\ \hat J_y &\equiv \tfrac{1}{2}\hat T_y \\ \hat J_z &\equiv \tfrac{1}{2}\hat F_z \end{aligned}\right\} \Rightarrow [\hat J_z, \hat J_y] = -i\hat J_x$$

Simplification of Hamiltonian

- Full dipole interaction Hamiltonian:

$$\hat H_{int} = \hat{\mathbf{E}}^{(-)}(\mathbf{r},t)\,\frac{\alpha}{\hbar\Delta}\,\hat{\mathbf{E}}^{(+)}(\mathbf{r},t)$$

- α is a rank-2 spherical tensor:

$$\alpha = \alpha^{(0)} + \alpha^{(1)} + \alpha^{(2)} \quad \longrightarrow \quad \hat H_{int} = \hat H^{(0)}_{int} + \hat H^{(1)}_{int} + \hat H^{(2)}_{int}$$

scalar — vector — tensor

$$\hat H^{(0)}_{int} \propto \hat n\hat N \qquad \hat H^{(1)}_{int} \propto \sum_{F'} \frac{\alpha^{(1)}_{F,F'}}{\Delta_{F,F'}}\hat S_z \hat J_z \qquad \hat H^{(2)}_{int} \propto \sum_{F'} \frac{\alpha^{(2)}_{F,F'}}{\Delta_{F,F'}}\left(\hat S_+\hat J_- - \hat S_-\hat J_+ + \frac{\hat n}{\sqrt{6}}\left(6\hat J_z^2 - \hat N\right)\right)$$

Phase shift — Phase shift

Light shifts:

$$a_+^\dagger a_+|+1\rangle\langle+1| + a_-^\dagger a_-|-1\rangle\langle-1| - a_+^\dagger a_+|-1\rangle\langle-1| - a_-^\dagger a_-|+1\rangle\langle+1|$$

Raman transitions:

$$a_+^\dagger a_-|+1\rangle\langle-1| + a_-^\dagger a_+|-1\rangle\langle+1|$$

Decomposing the dipole interaction Hamiltonian into three different terms corresponding to the ranks of the tensor polarisability, we can reduce it to the same Hamiltonian as for a spin-1/2 system.

The rank-zero contributions don't produce any signal. All second-rank polarisability contributions and some of the first-rank contributions cancel out for $\Delta \gg \Delta_{hfs}$, leaving only the ones from $F'=0$.

After all simplifications, the interaction Hamiltonian reduces to:

$$\hat H_{int} \propto \frac{\alpha^{(1)}_{1,0}}{\Delta_{1,0}}\hat S_z \hat J_z$$

Degree of squeezing and scattering

- Lossless degree of squeezing:

$$\xi^2 = \frac{1}{1+\rho_0\eta}$$

  - Coherent state: $\xi^2 = 1$
  - Squeezed state: $\xi^2 < 1$
  - Want high OD (ρ_0) and scattering (η).

- Spin-1/2 system with decay:
  - Scattering induces decoherence as atoms decay back to the initial states.

$$\tilde\xi^2 = \xi^2 + \frac{\eta}{1-\eta} + \frac{\eta}{(1-\eta)^2}$$

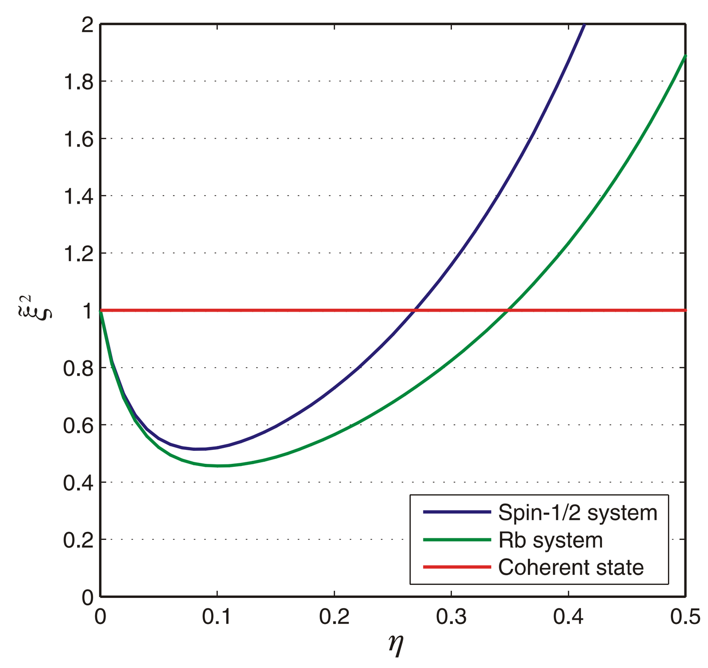
- Rb system:
  - Scattering may induce decoherence (γ), when atoms decay into the initial substates, or atom loss (β), when they decay into other substates out of the system.

$$\tilde\xi^2 = (1-\beta)\,\xi^2 + \eta\frac{1-\beta}{1-\eta} + \gamma\frac{1-\beta}{(1-\eta)^2}$$

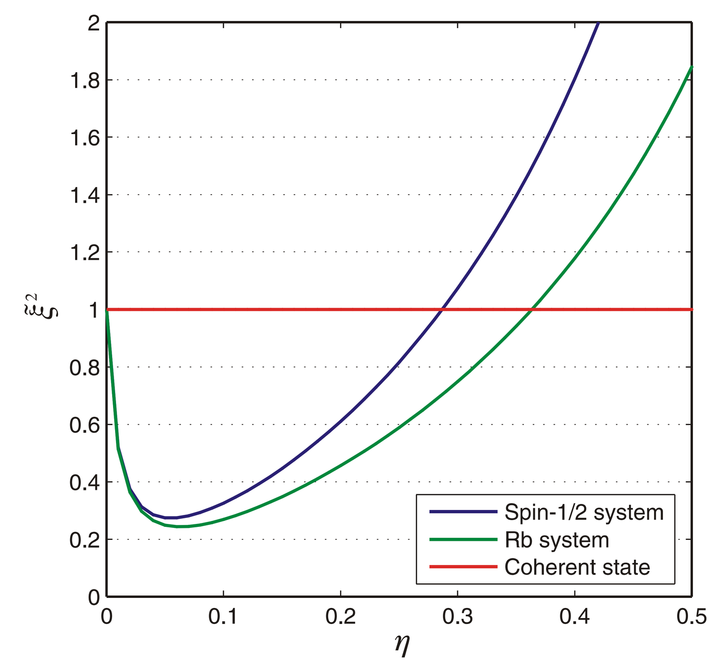
$$\eta = \gamma + \beta, \quad \gamma = \tfrac{5}{3}\beta$$

Achieving high coupling between the atoms and light means also high scattering rates, which induce decoherence and losses. Therefore, the degree of squeezing exhibits an optimum value at a particular scattering rate for a given OD.

Optical density of a standard MOT ($\rho_0=25$)

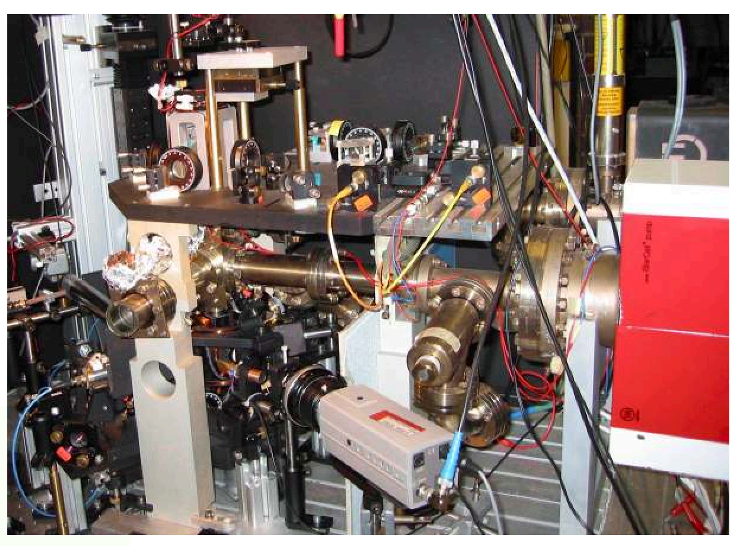


Optical density of a standard FORT ($\rho_0=100$)

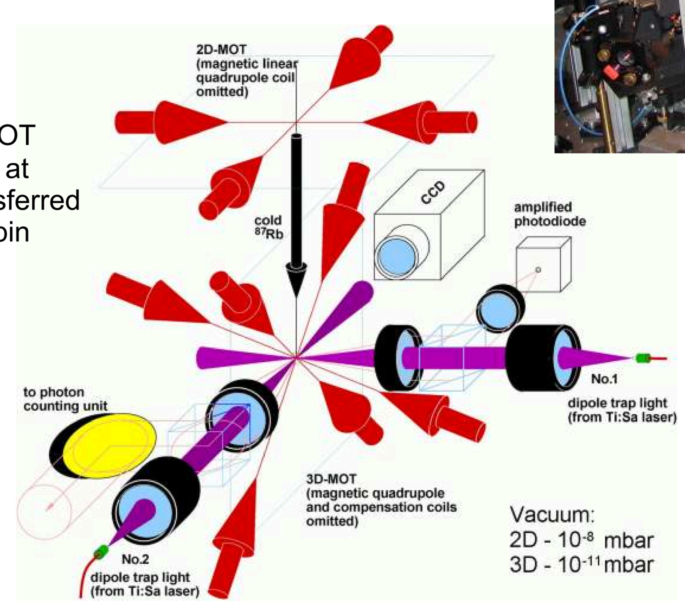


Experiments coming soon!

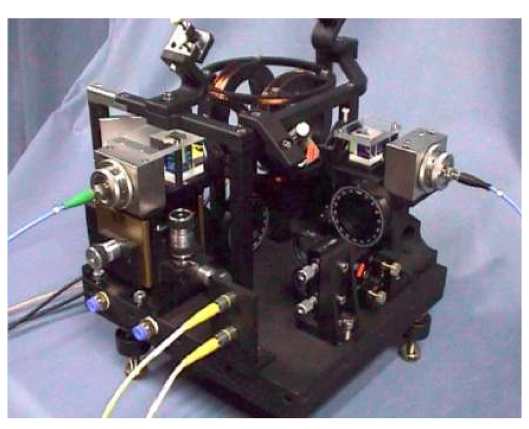
- Consider diffraction effects in FORT and add them to the model.
- Finish experimental setup and achieve spin squeezing.
- Towards quantum memories…



Double stage MOT with ~10^8 atoms at 70μK to be transferred to a FORT for spin squeezing



Vacuum:
2D - 10^{-8} mbar
3D - 10^{-11} mbar



References

- A. Kuzmich, N. P. Bigelow, and L. Mandel, Europhys. Lett. **42**, 481 (1998).
- J. M. Geremia, J. K. Stockton, and H. Mabuchi, quant-ph/0501033 (2005).
- B. Julsgaard, J. Sherson, J. I. Cirac, J. Fiurášek, and E. S. Polzik, Nature **432**, 482 (2004).
- J. H. Müller, P. Petrov, D. Oblak, C. L. Garrido Alzar, S. R. de Echaniz, and E. S. Polzik, Phys. Rev. A **71**, 033803 (2005).