Conditions for Spin Squeezing in Laser-Cooled Rubidium

S. R. de Echaniz, M. W. Mitchell, M. Kubasik, M. Koschorreck, H. Crepaz, J. Eschner, and E. S. Polzik

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

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. Some have been realised experimentally. Spin squeezing is the hallmark 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 78Rb atoms using the 1s(F=1) hyperfine ground state. In this system we expect to have a much higher coupling than in previous work. Suitable Zeeman sublevels and operations 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 \( F \) and a probe pulse in a coherent polarisation state \( \pm \) 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 effect). At the quantum level, light and atoms exchange quantum fluctuations according to:

\[ \hat{H}_{\text{coup}} = \hat{F} \hat{\chi} \]

After the interaction, \( \hat{\chi} \) can be QND measured by measuring the quantum fluctuations on \( \hat{F} \), inducing squeezing on the atomic spin.

Ideal spin-1/2 vs. 87Rb system

Most theoretical studies consider an ideal spin-1/2 system, whereas the atomic spin is polarised in the \( y \) direction (coherent superposition of \( |1,1\rangle \) 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 introduces a phase shift which produces no signal on the polarimeter. In the case of a real \( 87\text{Rb} \) system, the lower \( F \)-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 \( \ket{+1} + \ket{-1} \), and defining the pseudo-spin \( \hat{F} \) on the right.

Simplification of Hamiltonian

Decomposing the dipole interaction Hamiltonian into three different terms corresponding to the ranks of the tensor polarisability, we can rewrite it for 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 \( \alpha = \beta = \gamma = 0 \).

Degree of squeezing and scattering

- **Lossless degree of squeezing**:
  \[ S^2 = \frac{1}{2} \left( 1 - \frac{1}{\eta^2} \right) \]
  - Coherent state: \( \eta = 1 \)
  - Squeezed state: \( \eta > 1 \)

- **Spin-1/2 system with decay**:
  - Scattering induces decoherence as atoms decay back to the initial states:
  \[ S^2 = \frac{1}{2} \left( 1 - \frac{1}{\eta^2} \right) \frac{1}{1 + \frac{1}{\eta^2}} \]

Optical density of a standard MOT (\( \mu = 25 \))

Optical density of a standard FORT (\( \mu = 100 \))

Experiments coming soon!

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

References