Spin Squeezing in Cold Atomic Ensembles

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Abstract

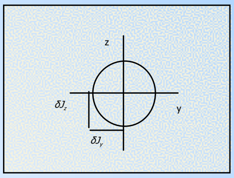
Mapping of a squeezed state of light onto an ensemble of about 10^9 cold Cs atoms confined in a MOT, by means of complete absorption of a resonant beam, was reported in 1999(1). In 2000 a highly squeezed spin state was created in a cell of room-temperature Cs atoms by a non-demolition measurement(2).
In this project we are going to create a long-lived spin squeezed state in a cloud of cold ^{87}Rb atoms via off-resonant light-atom interaction and a projective measurement(3). First the atoms will be confined and cooled down to μK temperatures in a MOT. Then they will be loaded into a far-off-resonant optical dipole trap and pumped to a coherent spin state. Spin-squeezing will be achieved by measurement of polarisation of a probe pulse prepared in a coherent polarisation state and sent through the atoms.

Spin squeezing

Heisenberg uncertainty relation for spin

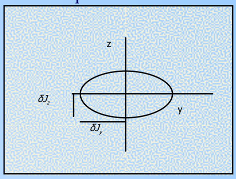
$$\delta J_y^2 \, \delta J_z^2 \geq \frac{1}{4} \left| \langle J_x \rangle \right|^2$$

Coherent state



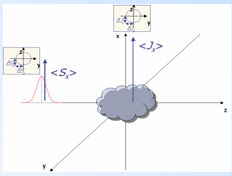
$$\delta J_z = \delta J_y$$

Squeezed state

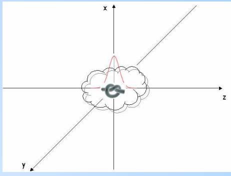


$$\delta J_z < \delta J_y \, (or \, \delta J_y < \delta J_z)$$

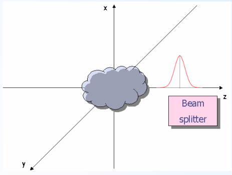
Experiment



A coherent spin state is prepared in an optically dense cloud of 10^8 cold ^{87}Rb atoms by means of optical pumping.



Then a pulse of light in a coherent polarisation state is sent. As a result of mutual interaction atoms and light become entangled.

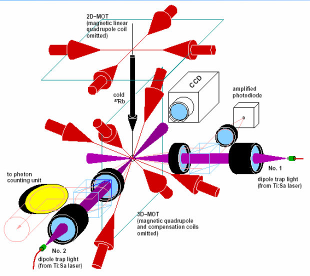


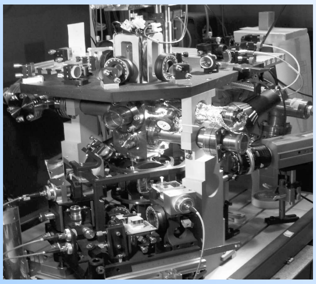
$$S_y^{out} = S_y^{in} + \kappa J_z, \quad \kappa = \kappa(J_x)$$
$$S_z^{out} = S_z^{in}$$
$$J_y^{out} = J_y^{in} + k S_z, \quad k = k(S_x)$$
$$J_z^{out} = J_z^{in}$$

A non-demolition polarisation measurement performed on the light pulse squeezes the atomic spin.

Cooling and trapping

Magneto-optical trap





First, the atoms are pre-cooled and confined to the axis of the upper 2-dimensional MOT stage. The 2-D MOT acts as a filter allowing only slow atoms to move through a differential pumping stage to the lower 3-dimensional MOT stage (black arrow). There the atoms are captured and cooled in all 3 spatial directions.

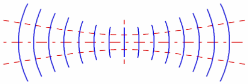
MOT parameters:

- 2D – 10^{-8} mbar
- 3D – 10^{-11} mbar

- N ≈ 10^8 ^{87}Rb
- n ≈ 10^{10} cm^{-3}
- r ≈ 1 mm
- T ≈ 50 μK

Optical dipole trap

After cooling, the MOT is switched off and the atoms are transferred to an optical dipole trap. Our far off-resonant laser will ensure a long coherence time of the atomic spins. Its high power will supply a sufficient force to effectively trap the atoms.



$$\vec{F}(\vec{r}) \propto -\frac{\vec{\nabla} I(\vec{r})}{\Delta}$$

Dipole trap parameters:

- Yb:YAG
- 1030 nm, far off-resonant, no scatter losses
- 20 W CW, single-mode

- U ≈ 1 mK (trap depth)
- T ≈ 100 μK

Applications

- Continuous variables quantum information processing
- Higher resolution atomic clocks
- High precision magnetometry

References

1. J. Hald, J. L. Sørensen, C. Schori, E. S. Polzik, Phys. Rev. Lett. **83**, 1319 (1999).
2. A. Kuzmich, L. Mandel, N. P. Bigelow, Phys. Rev. Lett. **85**, 1594 (2000).
3. A. Kuzmich, E. S. Polzik, in *Quantum information with continuous variables*, S. L. Braunstein, A. K. Pati, (Eds.), Kluwer Academic Publishers, (2003).