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macQsimal

Miniature Atomic vapor-Cell Quantum devices for SensIng and Metrology AppLications

Deliverable D6.4

Quantum-enhanced gyroscope study report

WP6 – Miniature atomic gyroscope

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Abbreviations

NMR	Nuclear magnetic resonance
QND	Quantum non demolition
WP	Work package

Partner short names

accelCH	Accelopment Schweiz AG, CH
CNRS	Centre National de la Recherche Scientifiques CNRS, FR (LKB – Laboratoire Kastler Brossel)
CSEM	CSEM SA – Centre Suisse d'Électronique et de Microtechnique, CH

Contents

Executive Summary

This deliverable is a theoretical study on quantum-enhancement in atomic sensors such as gyroscopes, using nuclear spins in atomic vapours.

Need for the deliverable

Nuclear magnetic resonance atomic gyroscopes presently work in the classical regime. The aim of our study is to explore quantum enhancement strategies to improve performances of these sensors in the future.

Objectives of the Deliverable

With the help of this deliverable, we will be able to:

- Demonstrate theoretically the possibility of quantum enhancement
- Propose a strategy using metastable atoms in a pure helium-3 vapour
- Prepare the ground for a first experimental demonstration

Outcomes

- Theoretical demonstration of the possibility of quantum enhancement (nuclear spin squeezing) in a pure helium-3 vapour
- Detailed study using a cavity mode that performs a quantum non demolition continuous measurement, inspired by the techniques successfully used in alkali
- Calculations of the maximum gain in presence of decoherence

Next steps (in view of an experimental realisation)

- Evaluation of the requirements on the magnetic field stability
- Full modelling of the atomic level structure for a more realistic description of the Faraday interaction

1 Introduction

An atom having two relevant levels of $E_\uparrow$ and $E_\downarrow$ with energy difference $E_\uparrow - E_\downarrow = \hbar\omega$, can be seen as an equivalent spin 1/2. When the spin is prepared in a superposition of the two states, it precesses at the Lamor frequency ω, that is the quantity we want to measure in an atomic sensor such as a clock or a magnetometer. In an atomic clock, $E_\uparrow - E_\downarrow = \hbar\omega$ is typically the ground state hyperfine splitting in an alkali atom of a given species, while in a magnetometer it is the Zeeman splitting due to a magnetic field.

In all kinds of spectroscopic measurements based on the precession of a spin, as in the atomic clocks and magnetometers mentioned above, or in atomic gyroscopes, a fundamental source of noise in the measured precession frequency is *atomic projection noise*.

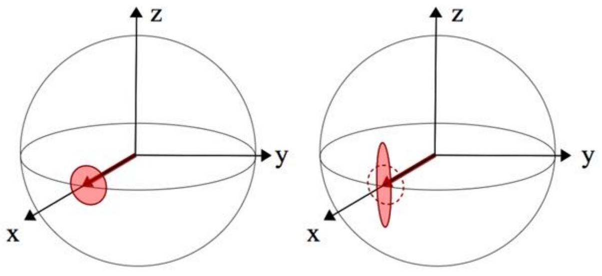
Let S be a collective spin formed by the sum of N individual spins ½, with components:

$$\hat{S}_x = \sum_{i=1}^{N} \frac{|\uparrow\rangle\langle\downarrow|_i + |\downarrow\rangle\langle\uparrow|_i}{2} \;; \qquad \hat{S}_y = \sum_{i=1}^{N} \frac{|\uparrow\rangle\langle\downarrow|_i - |\downarrow\rangle\langle\uparrow|_i}{2i} \;; \qquad \hat{S}_z = \sum_{i=1}^{N} \frac{|\uparrow\rangle\langle\downarrow|_i - |\downarrow\rangle\langle\uparrow|_i}{2} \;;$$

and let us consider a situation in which the individual spins are non-correlated, each of them being in the superposition of the two states ↑ and ↓. In such a state, the collective spin is in an eigenstate of the operator S_x with eigenvalue $N/2$, and the two transverse components S_y and S_z (orthogonal to the mean spin) have evenly distributed fluctuations imposed by the Heisenberg uncertainty principle: $\Delta S_y = \Delta S_z = \sqrt{N}/2$. For a given precession time T, the quantum uncertainty in S_y introduces an angular uncertainty $\delta\varphi$ on the spin position, that is immediately translated into an uncertainty on the precession frequency ω:

$$\delta\varphi = \frac{\Delta S_y}{\langle S_x\rangle} = \frac{\frac{\sqrt{N}}{2}}{\frac{N}{2}} = \frac{1}{\sqrt{N}} \quad ; \quad \delta\omega = \frac{\delta\varphi}{T} = \frac{1}{T\sqrt{N}}$$

The uncertainty $\Delta S_y = \sqrt{N}/2$ is the quantum projection noise, and $\delta\omega$ in the above equation gives the atomic projection noise limit for a frequency measurement in its simplest form. By introducing correlations among the atoms, it is possible to reduce the fluctuations in S_y thus reducing the angular uncertainty on the spin position. As shown schematically in Figure 1, this is done at the cost of increasing the fluctuations in S_z as the Heisenberg uncertainty principle imposes that $\Delta S_y\, \Delta S_z \geq N/4$.



uncorrelated atoms

squeezed

Figure 1. *Angular uncertainty on the collective spin position on the Bloch sphere due to quantum fluctuations, for uncorrelated atoms (left) and spin-squeezed atoms (right).*

The atomic projection noise has been measured since 1999 in atomic fountains [1], and several experiments demonstrated spin squeezing, both with cold atoms and atomic vapours [2].

The Task 6.4 of WP6 of the macQsimal project has the goal to study theoretically possible quantum enhancement strategies for NMR gyroscopes. Although fundamental limits due to the spins' quantum noise have not yet been reached in such devices, the joint progress of miniaturisation technology and more efficient spin squeezing techniques, make it that quantum noise in a high precision NMR gyroscope could become one day a relevant issue.

2 Quantum manipulation of the nuclear spins

Nuclear spins in noble gases, such as Helium-3 and Xenon-129, have the property of being very well isolated from the environment which ensures for theses spins extremely long coherence times. As an example, a coherence time T_2 exceeding 60 hours was measured in a helium-3 vapour [3], itself limited by the longitudinal T_1 decay time due to collisions with the walls (larger T_1 of order several hundreds hours have otherwise been obtained in these systems [4]). On the one hand these values allow for long precession times T and consequently very small fundamental uncertainties on the precession frequencies. On the other hand, they make the macroscopic nuclear spin in a vapour a unique system for the generation and study of long-lived quantum states at room temperature. Already in 2005, we suggested that the nuclear spins of Helium-3 could serve as a long-lived quantum memory [5], and to generate long-lived non-local quantum states [6]. Since then, major experimental progress has been accomplished in the domain of spin squeezing, in particular via quantum non demolition (QND) measurements, in systems of alkali atoms interacting with one mode of the electromagnetic field [2][7].

The challenge of transposing the technique of spin squeezing via QND measurement from alkali to noble gases nuclear spins, lies in the same property that constitutes the peculiarity of the nuclear spin system, that is its isolation from the environment. The idea that we follow is that we can rely on the same physical processes that are currently used to orient the nuclear spins in conjunction with optical pumping (metastability exchange collisions or spin exchange collisions) to transfer or manipulate quantum fluctuations of the nuclear spins.

2.1 Via metastability exchange collisions in helium-3

The singlet ground state of helium-3, separated by about 20 eV from all the excited states, is not directly accessible with optical laser light. However, by means of an oscillating discharge, a small fraction of the atoms of the vapour, typically 10^{-6}, can be promoted to a triplet metastable state that can be taken as the starting point for laser transitions in the near infrared. The orientation of the nuclear spins is then obtained via an indirect process called metastability exchange optical pumping [4]. In a first step, angular momentum is transferred via light-atom interaction, from the laser to the metastable atoms and hence to their nuclear spin via hyperfine coupling. In a second step, one relies on metastability exchange collisions between metastable and ground state atoms to obtain oriented nuclear spins in the ground state. The time scale for this process, limited by the relative small density of atoms in the metastable state, is typically of the order of the second. Even if metastability exchange collision can transfer quantum correlations [6],[5] we find that that a single measurement on a small fraction of the atoms (10^{-6}) cannot project the whole system into a squeezed state. The solution we found is a continuous QND measurement of the Faraday type enhanced by a resonant cavity.

In our study we show that, although the single metastable atoms have a relatively short lifetime as they are quenched by reaching the cell walls, a continuous measurement of the light that leaves the cavity after interaction with the metastable atoms performs a QND measurement on the nuclear spin projecting it onto a long lived spin-squeezed state [9],[10]. The typical time scale for squeezing is of the order the second and it is limited by the density of metastable atoms in the cell. A scheme of the setup is shown in Figure 2, taken from [9].

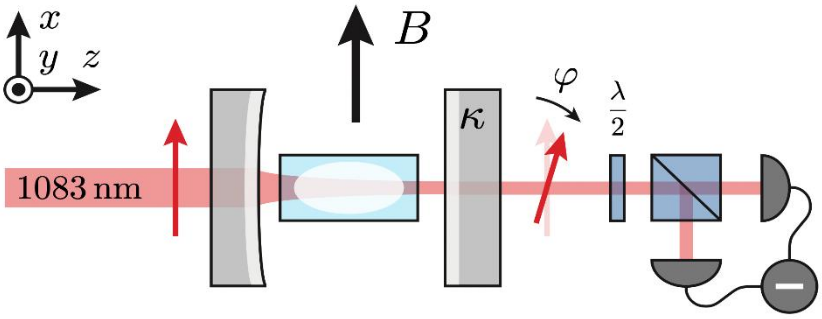


Figure 2. *Illustration of the proposed setup to generate nuclear spin squeezing by continuous measurement. A Helium-3 vapour cell is placed inside an asymmetric optical cavity, ensuring that photons leave the cavity at rate κ predominantly through the out-coupling mirror. A (switchable) discharge maintains a small fraction of the atoms in a metastable state. The atomic metastable and nuclear spins are oriented in the x-direction beforehand by optical pumping. The light polarisation, initially along x, is rotated by an angle φ due to the Faraday effect, performing a quantum non-demolition measurement of the nuclear spin fluctuations along the light propagation direction. This polarisation rotation is continuously monitored via homodyne measurement.*

2.2 Via spin exchange in alkali-noble gas mixtures

In the case of alkali-noble gas mixtures, for example Rubidium-Xenon, the alkali (instead of the metastable atoms for helium) serve as intermediary species to address the nuclear spins.

A short time after the beginning of our project, in June 2019, a paper was submitted that was precisely addressing one of our objectives, that is to adapt our previous works [5] and [6] (that were done for Helium) to the case of alkali-noble gas mixtures using spin exchange collision and quantum non-demolition measurements [8]. The authors find that 3 dB of squeezing for ^{129}Xe-^{87}Rb mixtures can be obtained with this method with a squeezing preparation time of the order of hundreds of milliseconds.

3 Perspectives

A detailed paper for nuclear spin squeezing generation in Helium-3 vapours via Faraday-based quantum non demolition measurement has been submitted for publication. We have presently finished the purely theoretical part and we collaborate with the group of Philipp Treutlein in Basel to identify the optimal configuration and the optimal parameters in view of a possible experimental demonstration.

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