Quadrupole splitting of ^{131}Xe in MEMS vapour cells

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Topic(s)

quantum sensing

Background

We present measurements of the coherence times and investigate quadrupole resonances of nuclear spins of an atomic gas confined in MEMS vapour cells – a key element of an atomic gyroscope. Long coherence times are essential for a low-noise performance whereas the quadrupole frequency splitting has a strong impact on the frequency readout and electronic feedback of the sensor.

Precise positioning is essential for modern mobility solutions. High performance inertial sensors, i.e. accelerometers and gyroscopes, are a key component of navigation systems, especially in the case when GPS signals and other systems are temporarily unavailable.

A nuclear magnetic resonance gyroscope (NMRG) is a rotation rate sensor that detects the angular rate $\vec{\omega}_R$ by measuring a shift in the Larmor precession frequency $\vec{\omega}_L$ of nuclear spins of an atomic gas in an applied magnetic field $\vec{B}$: $\vec{\omega}_L = \gamma\vec{B} + \omega_R$. Here γ is the gyromagnetic ratio of the nucleus. Sensitivities reported in literature [1] outperform other types of gyroscopes by several orders of magnitude. The high potential for miniaturization in particular in connection with MEMS (Micro Electro Mechanical System) fabrication technology is a second advantage of an NMRG.

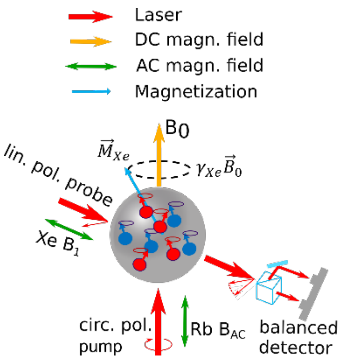

Figure 1: Vapour cell filled with Rb and Xe atoms - a key element of an atomic gyroscope.

The key element of an NMRG is a vapour cell filled with an alkali vapour and a noble gas. The nuclear spins of the noble gas with their long coherence times T_2* are used for rotation detection, whereas the alkali vapour is an auxiliary gas used for optical pumping and readout via pump and probe laser beams. The DC magnetic field B_0 determines the precession and thereby the gyroscope's measurement axis and AC magnetic fields B_1 are applied to drive the spin precession (c.f. Figure 1).

For the NMRG developed within macQsimal, we fabricate vapour cells using MEMS technology that are filled with rubidium (Rb) and two isotopes of xenon ^{129}Xe and ^{131}Xe. The usage of two noble gas isotopes allows us to deduce the angular rate and to correct for magnetic field inhomogeneity across the cell, simultaneously. The nuclear spins of ^{129}Xe and ^{131}Xe are I = 1/2 and I = 3/2, respectively. Due to its nuclear spin I = 3/2, the ^{131}Xe isotope has a nuclear electric quadrupole moment, whose interaction with electric field gradients can cause shifts of the nuclear magnetic energy levels, referred as quadrupole splitting.

For a cylindrical cell with diameter d and height h, the frequency splitting $\Delta\Omega$ for atoms with a nuclear spin I = 3/2 is given by [2]:

$$\Delta\Omega = \pm\Delta\Omega_0\, P_2(\cos\psi), \text{ with } \Delta\Omega_0 = \langle\theta\rangle\, \nu\, (h^{-1} - d^{-1})/2 \quad (1)$$

The parameter $\Delta\Omega_0$ describes the impact of the cell geometry, where ν is the mean thermal velocity and $\langle\theta\rangle$ is the mean twist angle per wall interaction of a ^{131}Xe atoms. The term $P_2(\cos\psi)$ accounts for the dependency of the magnetic field orientation, where $P_2(x) = \frac{1}{2}(3x^2 - 1)$ is the second-order Legendre polynominal, and ψ is the angle between the cell symmetry axis and the direction of the magnetic field. For glass blown vapor cells, there have been extensive studies on the dependence of the quadrupole splitting [2, 3]. For MEMS vapor cells fabricated of glass and silicon, we are aware of one paper [4] investigating the influence of the magnetic field orientation but not taken into account the impact of the cell geometry.

In our conference contribution, we present measurements of the coherence times T_2* of ^{129}Xe and ^{131}Xe nuclei and we investigate the dependence of the ^{131}Xe quadrupole splitting on the cell geometry and orientation of the magnetic field with respect to the cell symmetry axis.

Presentation

The MEMS vapor cells are fabricated at CSEM [5]. They consist of a glass-silicon-glass stack and are filled with isotopically enriched Xe gas with a mixture of ^{129}Xe:^{131}Xe of 1:1 (50 mBar @ 20°C), Rb of natural abundance and N_2 buffer gas (188 mBar @ 20°C). Figure 2(a) displays the fabricated cells of different diameter d = 1, 2, 3, and 4 mm and a cell height h = 1 mm.

Free-induction decay (FID) measurements of the Xe nuclei are performed at Bosch. The MEMS vapour cell is placed at the center of a 4-layer magnetic shielding with a triaxial coils system inside. We use a circularly polarized 795 nm laser for optical pumping and readout and a field switching technique [4] to initialize the Xe nuclear spin precession around a static magnetic field of 1 µT.

Figure 2(b,c) displays the FID measurements of the Xe nuclear spin precession for the cell with a diameter d = 4 mm. The Fourier spectrum (c.f. Figure 2(c)) clearly reveals a narrow ^{129}Xe peak at 11.9 Hz and a ^{131}Xe spin triplet at 3.5 Hz. From the peak widths, we extract T_2* times of 2.39 ± 0.06 s and 5.5 ± 0.5 s for ^{129}Xe and ^{131}Xe, respectively. The results are comparable to literature values [4,5] reported for MEMS cells.

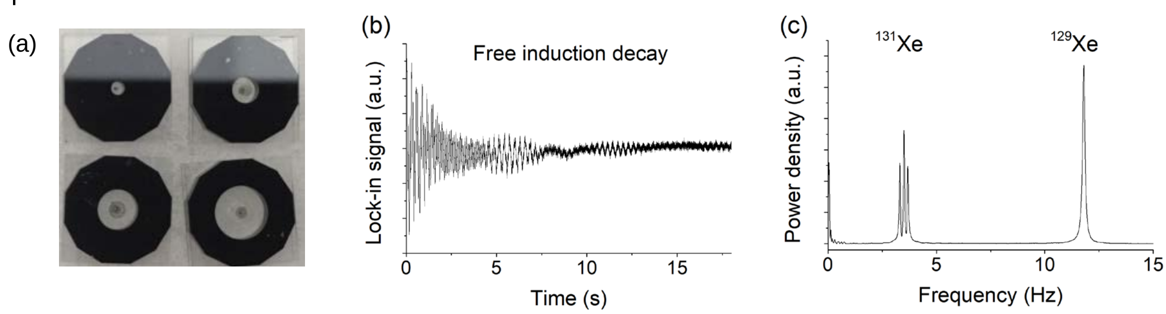

Figure 2: (a) MEMS vapour cells with diameters of 1, 2, 3 and 4 mm. (b) Free induction decay and (c) its Fourier transform taken for a cell with a diameter of d = 4 mm and height h = 1 mm.

Next, we investigate the ^{131}Xe nuclear quadrupole splitting as a function of the cell geometry. Figure 3 (a) shows that the sideband splitting decreases with decreasing cell diameter. According to eq. (1), the frequency splitting $\Delta\Omega/2\pi$ depends linearly on the geometry parameter $h^{-1} - d^{-1}$ (c.f. Figure 3(b)) with the slope $|\langle\theta\rangle\nu/4\pi|$. Taking into account the mean thermal velocity $\nu = 252\ m/s$ of the atoms at 120°C, we find a mean twist angle per wall adhesion of $\langle\theta\rangle = 24\ \mu rad$. This value is in good agreement with $29\ \mu rad$ [4] reported for silicon and significantly smaller than twist angles reported for pyrex and duran glass $\langle\theta\rangle_{pyrex} = 38\ \mu rad$ [2] and $\langle\theta\rangle_{duran} = 46\ \mu rad$ [3], respectively.

Finally, we study the dependence of the frequency splitting on the angle ψ between the magnetic field and the cell symmetry axis. As suggested by eq. (1), the quadrupole splitting quadratically depends on $\cos\psi$ (c.f. Figure 3(c)) and vanishes at an angle 54.7°.

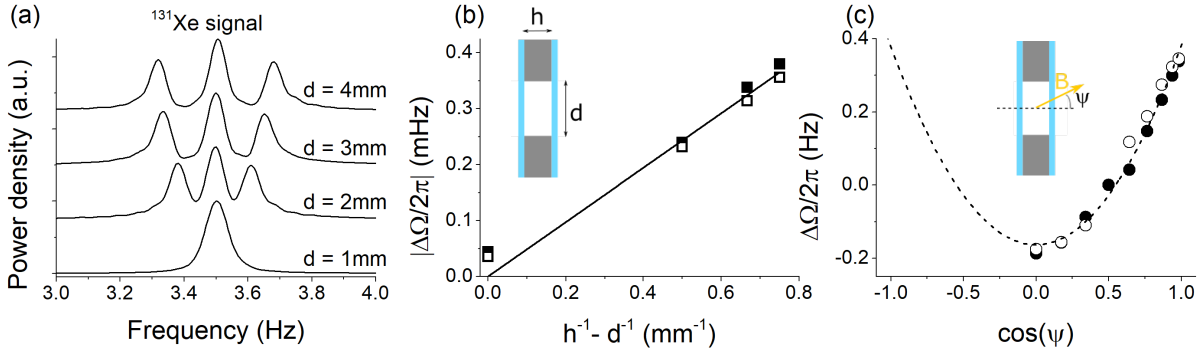

Figure 3: Investigation of the ^{131}Xe quadrupole splitting as a function of the (a,b) cell geometry (at $\psi = 90°$) and the (c) orientation angle ψ of the B-field w.r.t the cell symmetry axis (for d = 4 mm, h = 1 mm).

The MEMS vapour cells presented here with coherence times up to 5.5 s are well suited for the realization of an NMRG within macQsimal. The investigation of the ^{131}Xe quadrupole splitting and its dependency on the cell geometry needs to be considered when designing the electronic readout and feedback of the sensor.

References

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