Sub-Doppler spectroscopy of ^{39}K for magnetic field measurements

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Abstract

^{39}K atoms have the smallest ground state ($^2S_{1/2}$) hyperfine splitting of all the most naturally abundant alkali isotopes and therefore only a moderate applied magnetic field is needed for the establishment of the hyperfine Paschen-Back regime (around 400 G). In this regime, only 8 Zeeman transitions are visible in the absorption spectrum of the D_1 line of ^{39}K, while the probabilities of the 16 Zeeman transitions tend to zero. For each circular polarization (σ^+, σ^-), 4 spectrally resolved atomic transitions having a sub-Doppler width are recorded using a nanometric-thin cell, the thickness varying between 120 and 390 nm. We present a method that allows to measure the magnetic field in the 0.1 - 10 kG with micrometric spatial resolution, which is relevant in particular for the determination of magnetic field with a large gradient (up to 3.5 G/µm). The theory is in good agreement with the experimental measurements.

Zeeman transitions

The magnetic Hamiltonian of an alkali atom interacting with a longitudinal magnetic field $\mathbf{B} \equiv B_z$ along the z-axis (chosen as the quantization axis) reads:

$$H_m = -\frac{\mu_B}{\hbar}(g_L L_z + g_S S_z + g_I I_z)B_z \,.$$

Under the influence of the magnetic field, the atomic hyperfine states F split into magnetic sublevels. The probability A_{eg} of a transition between two Zeeman states can be shown to be proportional to

$$A_{eg} \propto \sum_{F'_g, F'_e} C_{F_e,F'_e} a(F'_e, m_e; F'_g, m_g, q) C_{F_g,F'_g} \,,$$

where C are mixing coefficients obtained by diagonalizing H_m. The expression of a is given in [1]. We can then compute transition probabilities as shown below.

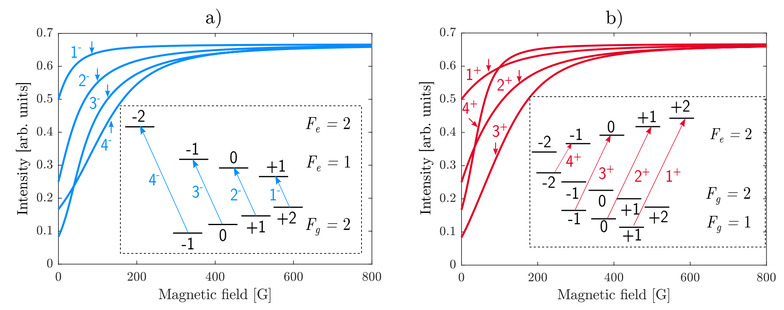

Figure 1: Magnetic field dependence of the Zeeman transitions of the D_1 line of ^{39}K. a) σ^- transitions. b) σ^+ transitions. The labels are described in the insets. Transitions having a probability close to zero for $B > 100$ G are omitted.

Experimental setup

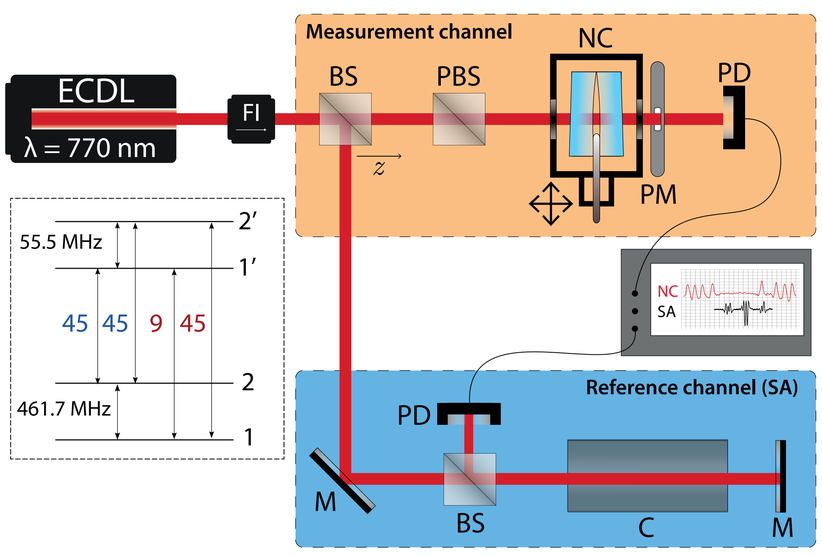

Figure 2: Scheme of the experimental setup. The orange channel allows to measure absorption spectra using a nanometric-cell, and the blue channel is used to measure the saturated absorption (SA) of a usual long cell. Inset: relative transition strengths.

Nanometric-thin cell spectroscopy

Our nanometric thin-cells (left panel) allow to obtain spectra with sub-Doppler resolution (right panel), since the only atoms participating in the absorption, reflection or fluorescence signals experience almost no Doppler shift. It behaves as a low-finesse Fabry-Perot interferometer of quality factor F (center panel). The transmitted intensity S_t is a function of integrals of the polarization of the atomic medium [2]:

$$S_t = 2t_{10}t_{02}^2 E_i \mathrm{Re}(I_f - r_1 I_b)/|F|^2$$

with

$$I_f = \frac{ik}{2\epsilon_0}\int_0^L P_0(z,\omega)\mathrm{d}z \quad \text{and} \quad I_b = \frac{ik}{2\epsilon_0}\int_0^L P_0(z,\omega)\exp(2ikz)\mathrm{d}z \,.$$

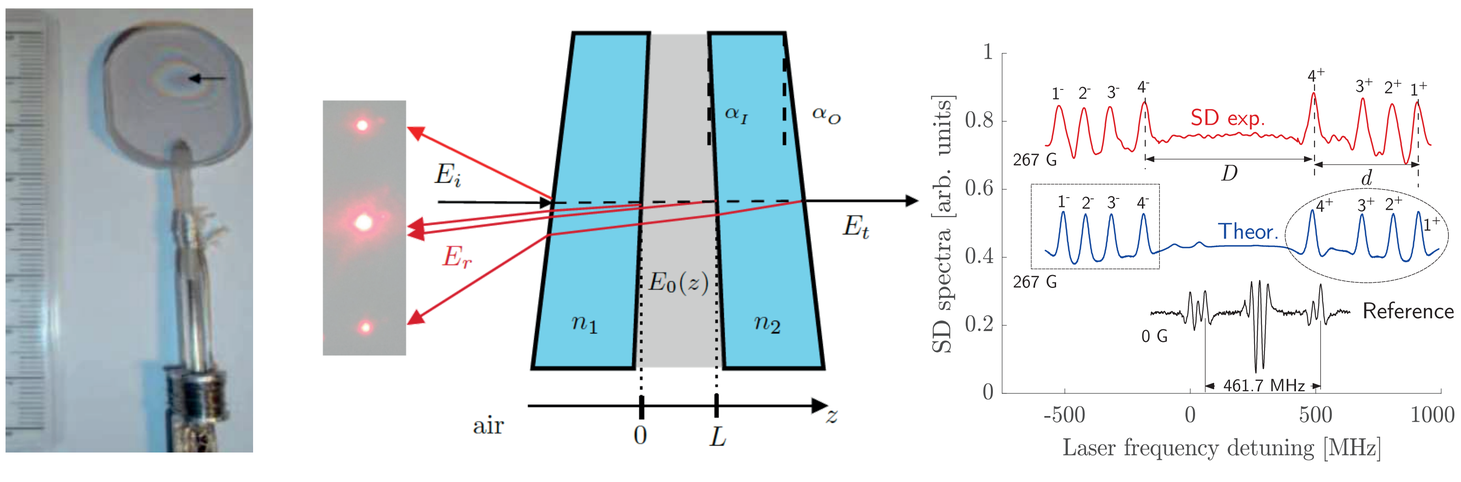

Figure 3: Left panel: Picture of the nanocell. Center panel: scheme of the nanocell with the incident, reflected and transmitted fields. Several reflections are visible. Right panel: reference SA spectum, second derivative) and second derivative (SD) of an experimental spectrum.

Experimental results

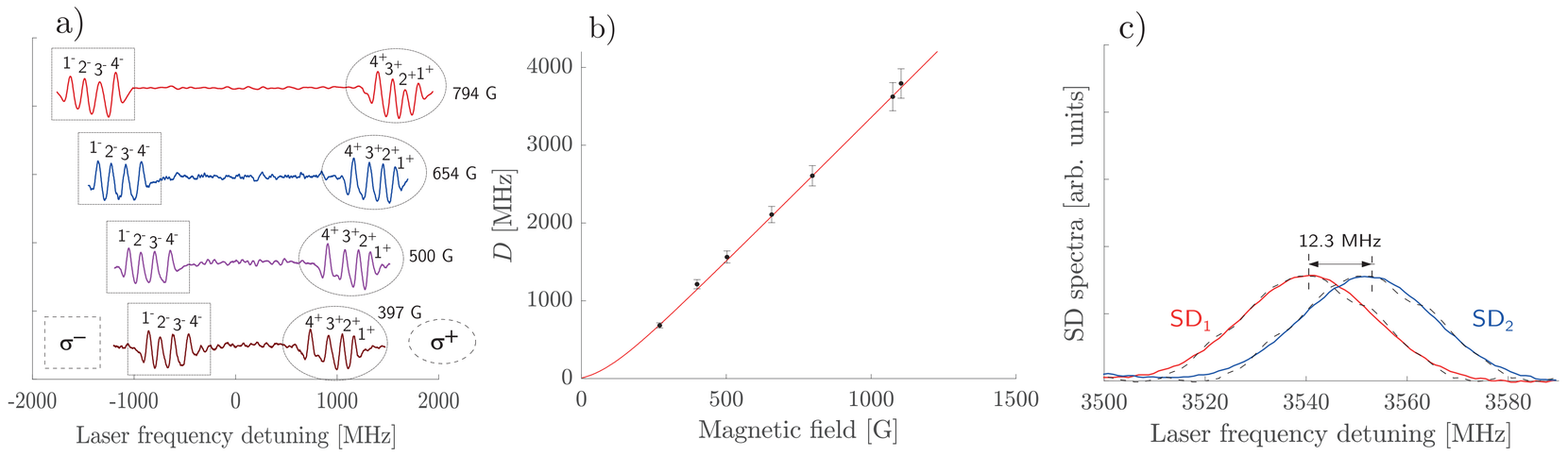

Figure 4: a) Experimental SD spectra for 397, 500, 654 and 794 G. The labels correspond to the ones given in Fig. 1. b) Distance D between transitions 4^+ and 4^-. Red line: theoretical prediction, black dots with error bars: experimental measurements. c) Single resonance recorded for 2000 (SD_1) and 2006.6 G (SD_2). Dashed lines: experiment, solid lines: theory.

We measure experimentally the distance D between transitions 4^+ and 4^- (see inset of Fig. 1) in order to determine the magnetic field. The results are compared with the theoretical prediction on the center panel. The curves on the right panel show the good spatial resolution of the magnetometer: SD_1 (resp. SD_2) were computed for $B_1 = 2000$ G (resp. $B_2 = 2006.6$ G). The shift is 12.3 MHz, which can be well measured experimentally and corresponds to a displacement of the nanocell (thickness 120 ± 5 nm) of 2 µm, allowing to measure magnetic fields with a strong gradient (here 3.5 G/µm) [3,4].

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Conclusion

The use of a nanocell is convenient for high spectral resolution table-top magnetometry in the hyperfine Paschen-Back regime. The sensitivity is not the best (around 5%), but the spatial resolution is the strongest asset of this magnetometer since large gradients of magnetic fields can be determined. Such fields are used in Stern-Gerlach-type experiments. Similar results can be obtained with a micrometer-sized cell, which are easier to fabricate [5].

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