⁴He OPTICAL PUMPING WITH POLARIZATION MODULATED LIGHT AND MAGNETOMETRY APPLICATION

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Abstract :

In optical pumping experiments using a laser, beam polarization can be modulated with the help of an electrooptic modulator device. This technique has been applied to pump ⁴He(2³S₁) metastable atoms. New resonances, never observed before, has been studied theoretically and experimentally versus geometric and modulation parameters and an application to high sensitivity magnetometer is presented.

Introduction :

The recent development of an infrared diode pumped laser using a LNA crystal (1) allows for optical pumping of metastable (2³S₁)He atoms for such applications as construction of a source of polarized electrons (2), to prepare ³He nuclei (3), to polarize ions via Penning collisions (4) and construction of high sensitivity magnetometers (5).

In the last application, the magnetic resonance technique is mainly used. With the use of a laser, other techniques using an intensity or polarization modulated pumping beam are now possible (6), (7).

We present here some results obtained when the polarization of the pumping beam is modulated at a frequency Ω close to the Larmor frequency (ω_L) or its second harmonic of the metastable (2³S₁)He atoms in a static magnetic field. This method has never been studied before mainly because of experimental limitations. Resonances can be detected on the transmitted beam which is modulated mainly at Ω and 2Ω frequencies and an application to magnetometry is presented.

Experiment

The experimental set-up represented on fig.1 is the same as that described in ref.(7). A helium cell is placed inside a magnetic shield to avoid magnetic laboratory perturbations where a pair of Helmholtz coils provides a controlled static magnetic field. The laser emission is tuned on the (2³S₁-2³P₀) ⁴He line.

Lasers have several advantages over lamps :

- selection of only one of the three (2³S₁-2³P_{2,1,0}) transition
- high power
- high modulation rates and modulation frequencies are possible using an electrooptic modulator device (EOM)

In the present case, the linearly polarized laser beam enters in the EOM at 45° of its neutral axes and the phase shift is modulated according to :

$$\Delta\Phi = a + b \cos \Omega t$$

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The output polarization shape depends on the value of the a and b parameters.

For example :

- $a = 0, b = \pi/2$: The polarization changes periodically from left to right circular and its mean value is linear.

- $a = b = \pi/2$: The polarization oscillates between two mutually orthogonal linear directions and its mean value is circular.

Phase detection (fig.1) has been chosen to compare theory and experiment. Main resonances are observed when $\Omega = \omega_L$ and $\Omega = 2\omega_L$ and appear as a modulation of the transmitted light.

Fig.1 : Experimental set up.

L : LNA tunable laser, P : linear polarizer, EOM : Electro-Optic Modulator, C : helium cell, b : Helmholtz coils, S : magnetic shield, PD1, PD2 : photodetectors, D : Signal amplifier, dc and ac are respectively the mean value and the modulated part of the detected signal, G1 : dc power supply, G2 : function generator, A : lock-in amplifier, R : chart recorder.

Several parameters are involved and lead to a great variety of resonance signals :

- modulations parameters (a and b)
- geometric parameters (θ, η) (fig.2) : $\vec{B}_0$ is taken in the OYZ plane ; θ represents the angle between the pumping beam direction and the static magnetic field ; η is the angle between a fixed axis and the axis of the mean polarization vector.

Figure 2

We have evaluated the expected resonance signals with the usual optical pumping theory and in the low optical power limit (see (7) and references therein).

Fig.3 represents in quadrature resonance signal amplitude observed versus η when the magnetic field is scanned over the value corresponding to a Larmor frequency $\omega_L = \Omega$. This resonance is detected at the second harmonic 2Ω with modulation parameters a and b equal $\pi/2$ and for three values of the angle θ . The calculated curves (full line) have been fitted on experiment with one point ($\theta = 90^\circ$ and $\eta = 60^\circ$).

Fig. 3 : Relative in-quadrature amplitude at 2Ω frequency at Larmor frequency $\omega_L = \Omega$ versus η .

Modulation parameters a and b are equal to $\pi/2$

theoretic : (...) $\theta = 90^\circ$ / (---) $\theta = 45^\circ$ / (—) $\theta = 0$

experimental : (x) $\theta = 90^\circ$ / (+) $\theta = 45^\circ$ / (*) $\theta = 0$

Fig4a represents the ratio between the amplitudes of the in-phase and the in-quadrature signal versus parameter b . As predicted, the in-phase amplitude vanishes when $b = 1,84$ radians (x ; experimental, full line : theoretical). Fig. 4b shows the in-phase (a) and in quadrature(s) resonance curves for three values of parameter b . This result is characteristic of polarization modulation and is not observed in the usual magnetic double resonance technique or the intensity modulated optical pumping.

Fig.4 a : Ratio s/a between the in-phase and in quadrature amplitude at Ω frequency and at Larmor frequency $\omega_L = \Omega/2$ versus b . Geometric parameter θ equals 0 (independent of η) and constant phase shift $a = \pi/4$ (x experimental, solid line : calculated)

Fig. 4b : In phase (s) and in quadrature (a) resonance curves when phase parameter b equals respectively 1,37 rad (1) ; 1,87 rad (2) ; 2,02 rad (3)

Application to magnetometry

Measurement of an unknown magnetic field is achieved by determining the position of one of the above resonances. Different procedures may be used. For example, resonance is pointed at the zero of the in-quadrature signal of fig.4b (a). The in-quadrature of the lock-in detector may be used as an error signal to control the modulation frequency of the E.O.M. However, this technique requires a very precise and stable phase setting. Moreover, solid state photodetectors introduce a phase shift which is dependant of the mean incident radiative power. Then a small laser power drift will give a phase-setting error incompatible with the precision needed.

So, the amplitude of the modulation at ω or 2ω frequency is detected (quadratic detection). It provides a symmetrical signal with respect to resonance position. In order to obtain an error signal that can be used to lock the generator frequency to the magnetic field, a small low frequency ($\approx 300\text{Hz}$) magnetic field is superimposed to the static magnetic field. The resulting modulation is then synchronously detected. Instead of magnetic field modulation, frequency modulation of the generator could be used as well.

Fig.5 shows a recording of the frequency of the HF generator locked to the magnetic field when a magnetic field step of 1nT is applied to the Helium cell. Noise level is evaluated at $10^{-2}\text{nT}/\sqrt{\text{Hz}}$. This represents at the present time, the sensitivity of our device.

Fig.5: Frequency recording of the HF generator locked to the magnetic field when 1nT field step is applied. Modulation parameters a and b equal respectively 0 and $\pi/2$. Geometric parameters θ and η equal 90° .

Conclusion

In order to apply to magnetometry we now optimize all parameters (modulation parameters, geometric parameters, optical density) and compare it with the two used techniques (magnetic resonance technique, and intensity modulated pumping technique).

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