N94-10565

A PHASEONIUM MAGNETOMETER: A NEW OPTICAL MAGNETOMETER BASED ON INDEX ENHANCED MEDIA

Marlan O. Scully
Department of Physics, Texas A & M University
College Station, Texas 77843

Michael Fleischhauer, and Martin Graf
Sektion Physik, Universität München
W-8000 München, Germany

Abstract

An optical magnetometer based on quantum coherence and interference effects in atoms is proposed whose sensitivity is potentially superior to the present state-of-the-art devices. Optimum operation conditions are derived and a comparision to standard optical pumping magnetometers is made.

1 Optical Pumping Magnetometer

The detection of magnetic fields via optical pumping techniques was first discovered by Franken and Colegrove in helium [1]. An atomic system with three lower magnetic sublevels say, $m_J = +1, 0, -1$ and one upper level, is driven by resonant unpolarized light. A magnetic field, which for simplicity we take to be parallel to the propagation direction, splits the energies by an amount $\hbar aB$, where $a \approx 10^7$ s^{-1}/Gauss and B is the magnetic field strength.

Due to optical pumping, the population of the $m_J = \pm 1$ states is driven into the $m_J = 0$ level and the pump light will be transmitted through the otherwise absorbing gas.

Now, if there is a RF signal applied to the gas which is resonant to the sublevel transition, the atoms will be driven back to the $m_J = \pm 1$ states and the gas will again absorb the optical radiation. Thus by monitoring the transmitted pumping light while varying the RF frequency one has a sensitive measure of the spacing of the magnetic sublevels. That is, the pumping light will be "shut off" when

$$\omega_{RF} = aB \tag{1}$$

This is summarized in Fig.1.

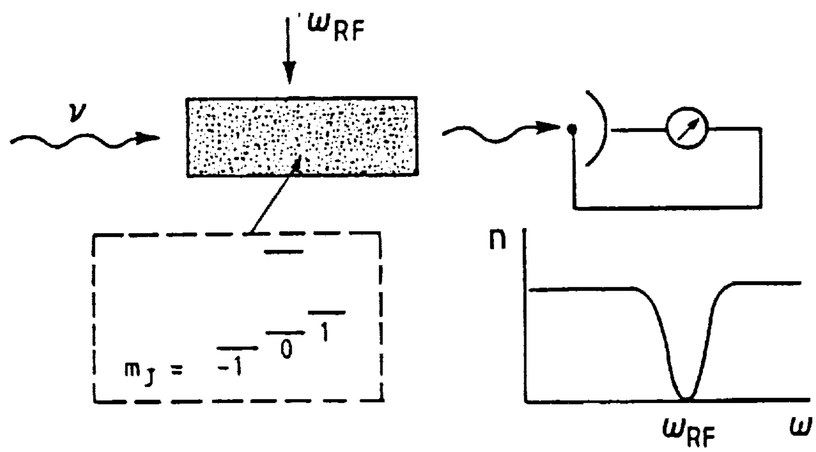

FIG.1. Optical Pumping Magnetometer Concept

The ultimate precision to which we can measure this frequency and the strength of the magnetic field is determined by intensity fluctuations in the transmitted light beam, i.e. fluctuations in the number m of observed photoelectrons. To obtain the resonance frequency, one determines the position of the half maxima. The intensity fluctuations at this point lead to an error

$$\Delta\omega_{error} = \left|\frac{\partial\omega}{\partial m}\right| \Delta m, \tag{2}$$

where $\partial m/\partial\omega$ is the slope of the transmission curve at the half maximum.

Assuming shot noise in the number of observed photoelectrons, i.e. $\Delta m = \sqrt{m}$, and 100% detection efficiency, so that $m = P_{in}t_m/\hbar\nu$, we obtain under optimum conditions for the frequency error

$$\Delta\omega_{error} = \gamma_{mag}\sqrt{\frac{\hbar\nu}{P_{in}t_m}}. \tag{3}$$

Here P_{in} is the optical input power, ν the frequency of the pump field, and t_m is the measurement time. γ_{mag} is the width of the transmission line, which in the absence of power broadening is the transverse decay rate γ_c of the RF transition. Equating the signal frequency (1) to the error (3) we arrive at the minimum detectable change in the magnetic field for the optically pumped magnetometer

$$B_{min} = \frac{\gamma_{mag}}{a}\sqrt{\frac{\hbar\nu}{P_{in}t_m}}. \tag{4}$$

Increasing the power of the pump radiation obviously increases the sensitivity. However, as P_{in} grows the transmission line will get power broadened and γ_{mag} will eventually increase. In order to optimize the parameters, we calculated the width of the transmission line by solving the density matrix equations within a second order perturbation approach in the RF field. We thereby consider the level configuration shown in Fig.2.

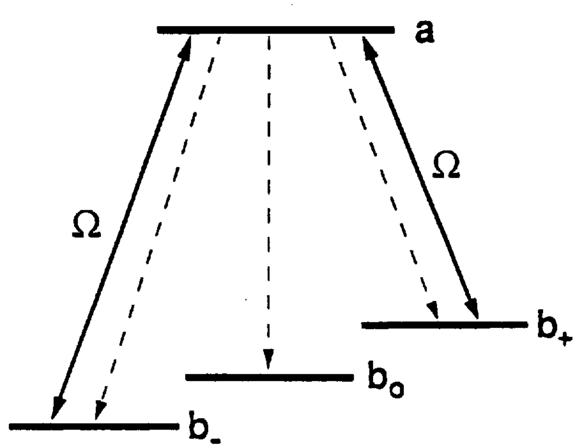

FIG.2. 4-level scheme for the optical pumping magnetometer. Since the magnetic field is parallel to the propagation axis, the unpolarized pump field drives the $m_J = \pm 1$ lower levels to the $m_J = 0$ upper state.

In the interaction picture we have the equations of motion for the populations

$$\dot{\rho}_{b_+b_+} = \gamma_+\rho_{aa} + i\left(\Omega^*\rho_{ab_+} - c.c.\right) - i\left(\Omega^*_{RF}\rho_{b_+b_0} - c.c.\right), \tag{5a}$$

$$\dot{\rho}_{b_0b_0} = \gamma_0\rho_{aa} + i\left(\Omega^*_{RF}\rho_{b_+b_0} - c.c\right) - i\left(\Omega^*_{RF}\rho_{b_0b_-} - c.c.\right), \tag{5b}$$

$$\dot{\rho}_{b_-b_-} = \gamma_-\rho_{aa} + i\left(\Omega^*\rho_{ab_-} - c.c\right) + i\left(\Omega^*_{RF}\rho_{b_0b_-} - c.c\right), \tag{5c}$$

for the RF polarizations

$$\dot{\rho}_{b_+b_0} = -(i\Delta + \gamma_c)\rho_{b_+b_0} - i\Omega_{RF}\left(\rho_{b_+b_+} - \rho_{b_0b_0}\right) + i\Omega^*\rho_{ab_0}, \tag{6a}$$

$$\dot{\rho}_{b_0b_-} = -(i\Delta + \gamma_c)\rho_{b_0b_-} - i\Omega_{RF}\left(\rho_{b_0b_0} - \rho_{b_-b_-}\right) - i\Omega\rho^*_{ab_0}, \tag{6b}$$

and for the optical polarization

$$\dot{\rho}_{ab_0} = -\frac{\Gamma}{2}\rho_{ab_0} - i\Omega^*_{RF}\rho_{ab_-} - i\Omega_{RF}\rho_{ab_+} + i\Omega\rho_{b_+b_0} + i\Omega\rho_{b_-b_0}, \tag{7}$$

Here $\gamma_+, \gamma_-, \gamma_0$ are the longitudinal decay rates of the optical transitions, $\Gamma = \gamma_+ + \gamma_- + \gamma_0$, Ω_{RF} and Ω are the Rabi-frequencies of the RF and optical field, and Δ is the detuning of the RF-frequency from the magnetic transition frequency. In the absence of the RF-field all population is optically pumped into level b_0. Hence, in zeroth order the only non-vanishing matrix element is $\rho^{(0)}_{b_0b_0} = 1$, and the medium is totally transparent with respect to the optical field. In first order of the RF-coupling, low-frequency coherences build up. Solving Eqs. (6) and (7) we find

$$\rho^{(1)}_{b_+b_0} = -\rho^{(1)}_{b_0b_-} = \frac{\Omega_{RF}(\Delta + i\gamma_c)}{\Delta^2 + \gamma_c^2 + \dfrac{4|\Omega|^2\gamma_c}{\Gamma}}, \tag{8}$$

where we have assumed $\Omega^*_{RF} = \Omega_{RF}$. In second order of the RF-field, population in the $b_\pm$ ground levels is created and the optical field will be absorbed. Noting that $\rho^{(2)}_{aa} = 0$, we find from Eqs. (5a) and (5c) the imaginary part of the $a - b_\pm$ susceptibilities, which determine the absorption of the pump field radiation

$$\chi'' = \frac{\wp^2 N}{\hbar\epsilon_0}\frac{\Omega^2_{RF}}{\Delta^2 + \gamma_c^2 + \dfrac{4|\Omega|^2\gamma_c}{\Gamma}}\left(\gamma_c + \frac{2|\Omega|^2}{\Gamma}\right). \tag{9}$$

As can be seen from this equation and Fig. 3, an increasing Rabi-frequency Ω leads to a power broadened transmission line with width

$$\gamma_{mag} = \gamma_c \left(1 + \frac{4|\Omega|^2}{\gamma_c \Gamma}\right)^{1/2} \tag{10}$$

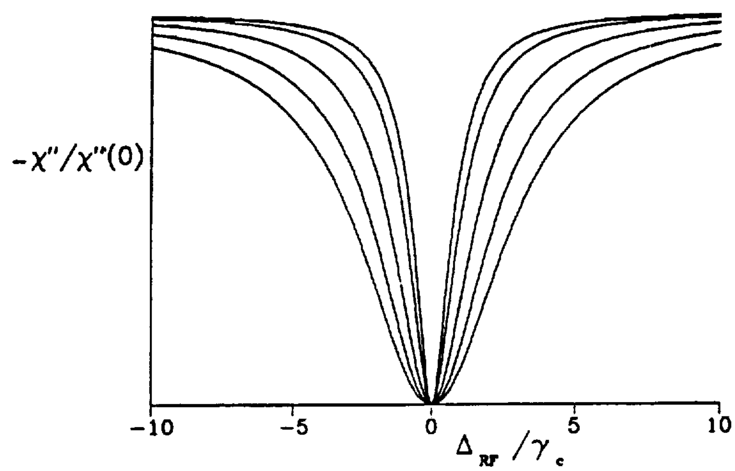

FIG.3. Normalized imaginary part of optical susceptibility as function of RF detuning Δ. The Ràbi-frequency of the pump field is (from top to bottom) 0.1 , 0.5, 1, 1.5, 2 $\times$ $\gamma_c\Gamma/4$.

For a sufficiently small input power, such that $\gamma_{mag} \approx \gamma_c$, the minimum detectable magnetic field, Eq. (4), decreases with increasing input power P_{in}. However, above a certain value P_{in}^c, corresponding to the critical value of the optical Rabi-frequency

$$\Omega^c = \sqrt{\frac{\gamma_c \Gamma}{4}}. \tag{11}$$

B_{min} attains a constant value

$$B_{min} \rightarrow \frac{1}{a}\sqrt{\frac{\gamma_c}{t_m}}\sqrt{\frac{3\lambda^2}{2\pi A}}, \tag{12}$$

where A is the pump laser cross section. For a measurement time of 1 s, $\lambda = 500$ nm, $\gamma_c = 10^3$ s^{-1}, and $A = 1$ cm^2, the rhs of Eq. (12) is of order 10^{-10} Gauss. The highest sensitivity obtained experimentally so far with an optical pumping magnetometer is of the order of 10^{-9} Gauss [2].

2 Interferometric Measurements of Magnetic Level Shifts

An alternative way of determining magnetic level shifts is to detect the change of the index of refraction near an atomic resonance.

Let us consider a simple two-level atomic absorber. If we ignore the absorption for the moment, the dispersion of such a medium near resonance is given by

$$n \approx 1 + \frac{\chi'}{2} \approx 1 + \lambda^3 N \frac{\Delta}{\gamma}, \tag{13}$$

where λ is the wavelength of the atomic transition, N the number density of atoms, $\Delta = \omega_{ab} - \nu$ is the detuning between the atomic transition frequency ω_{ab} and the probe field frequency ν. An applied magnetic field which shifts the atomic transition frequency will thus lead to a change of the index of refraction

$$\Delta n \approx \lambda^3 N \frac{a \cdot B}{\gamma}. \tag{14}$$

A probe beam transmitted through a sample of these atoms over a distance L will hence acquire a phase shift due to the magnetic field

$$\Delta\phi = \frac{2\pi}{\lambda}\Delta n L \approx \frac{2\pi}{\lambda}\lambda^3 N L \frac{a \cdot B}{\gamma}. \tag{15}$$

Detecting this phase shift by interferometric means, for instance in a Mach-Zehnder interferometer, thus gives a sensitive measure for the magnetic level shift. The phase measurement error is found from $\Delta\phi_{error}\Delta m \approx 1$. Assuming again shot noise, i.e. $\Delta m = \sqrt{m}$ and equating the signal and error expressions, yields the minimum detectable magnetic field

$$B_{min} = 2\pi \frac{\gamma}{a} \frac{1}{\lambda^2 LN} \sqrt{\frac{\hbar\nu}{P_{in} t_m}}. \tag{16}$$

Naturally, however, such a gaseous medium will not be useful because of the large absorption as indicated in Fig.4.

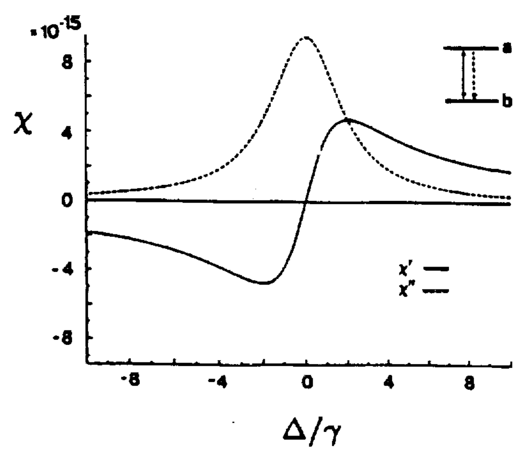

FIG.4. Real (χ') and imaginary part (χ'') of the susceptibility of a two level atom, determining the index of refraction and the absorption.

This is the point where the idea of quantum interference in atomic systems comes in. If the upper level a of an optical transition is driven by a strong driving field to an auxiliary level c, the absorption from the ground state b is essentially cancelled [3], while the index of refraction displays a large dispersion, due to quantum interference of different absorption pathways.

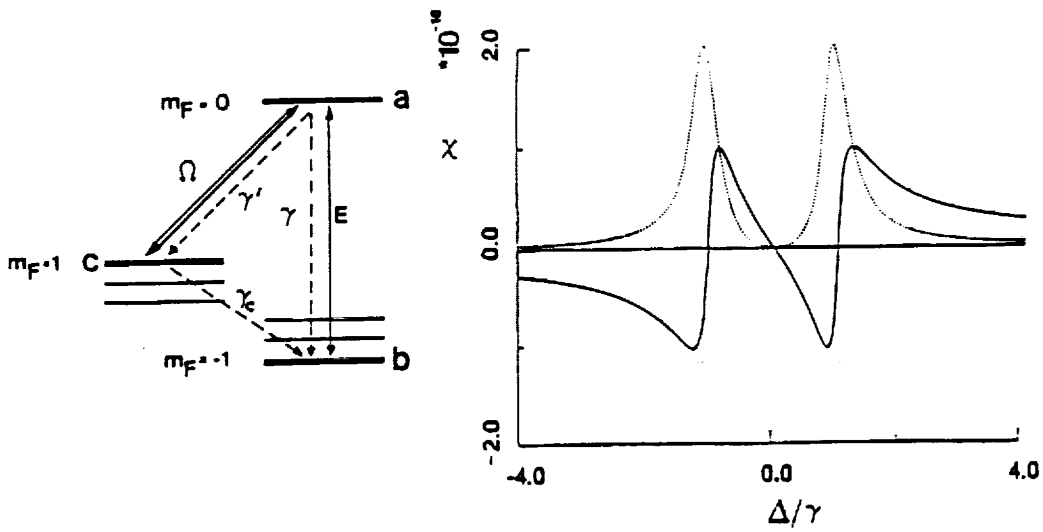

FIG.5. Left: Λ configuration in which strong driving field with Rabi-frequency Ω' on a-c transition generates transparency on the a-b transition. Right: corresponding susceptibility spectrum.

3 Optical Magnetometer Based on Electromagnetically Induced Transparency

Near a resonance of the coherent medium we have a large dispersion of the index of refraction. A probe field propagating a distance L through the phaseonium medium will acquire a phase shift

$$\Delta\phi_{sig} = -\frac{3}{4\pi}\lambda^2 N L \frac{\gamma}{|\Omega'|^2} aB \tag{17}$$

due to the magnetic field. The induced transparency is not perfect due to collisional dephasing of the c-b polarization (γ_c) and the amplitude of the transmitted field will be reduced by a factor κ

$$\kappa = \exp\left\{-\frac{3}{8\pi}\lambda^2 L N \frac{\gamma\gamma_c}{|\Omega'|^2}\right\}. \tag{18}$$

κ is, however, close to unity for sufficiently strong driving fields.

Putting a phaseonium gas cell in one arm of a Mach-Zehnder interferometer as per Fig.6, the signal phase shift (17) can be measured by a balanced detection of the intensities at the two outputs. As shown in Ref.[4], the operation of such a phaseonium magnetometer is again shot noise limited. Equating the signal and noise expressions one finds for the minimum detectable magnetic field in a phaseonium magnetometer

$$B_{min} = \frac{1}{a}\frac{4\pi}{3}\frac{1}{\lambda^2 LN}\frac{|\Omega'|^2}{\gamma}\left[\frac{1+\kappa^2}{2\kappa^2}\right]^{1/2}\left[\frac{\hbar\nu}{P_{in}t_m}\right]^{1/2} \tag{19}$$

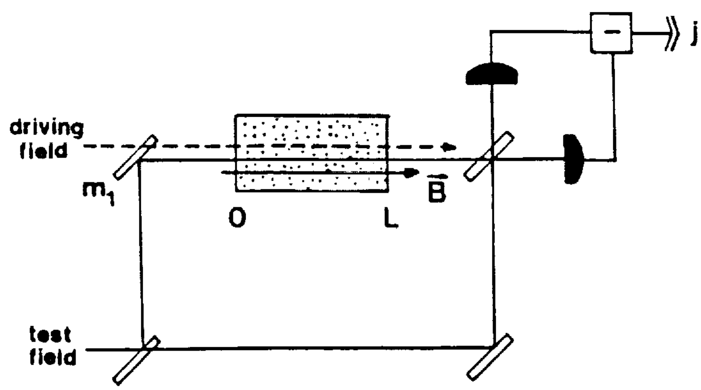

FIG.6. Mach-Zehnder interferometer

Increasing the number density N or the interaction length L enhances the signal phase shift. On the other hand the transmittivity κ decreases. An optimum value is found when

$$\frac{4\pi}{3}\frac{1}{\lambda^2 LN}\frac{|\Omega'|^2}{\gamma} \approx \gamma_c. \tag{20}$$

This gives for the minimum detectable field under optimum parameter conditions

$$B_{min} = \frac{\gamma_c}{a}\left[\frac{\hbar\nu}{P_{in}t_m}\right]^{1/2} \tag{21}$$

which is identical to the expression found for the standard optical magnetometer for the case of small input power. However, if in the optical pumping magnetometer the input power exceeds a critical value determined by the critical Rabi-frequency (10), the sensitivity remains constant, whereas in the case of the phaseonium magnetometer much higher sensitivities are possible as can be seen in Fig. 7. Here the Rabi-frequency of the probe field, Ω, is limited only by the condition of linearity

$$\Omega \leq \gamma. \tag{22}$$

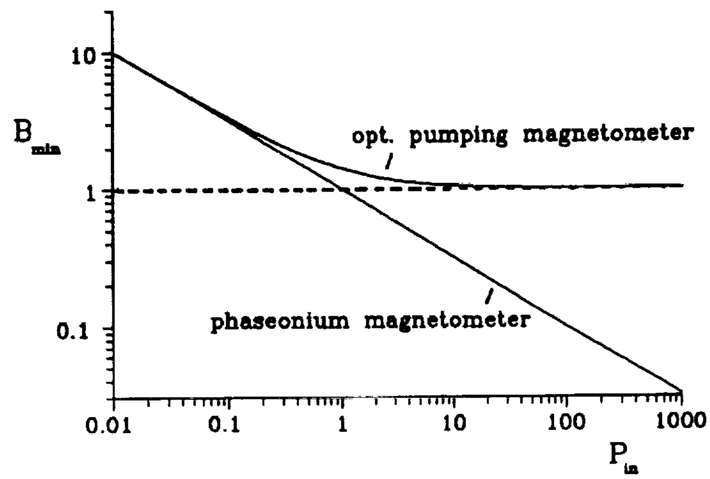

FIG.7. Minimum detectable magnetic field for the optical pumping and phaseonium magnetometers as functions of the input intensity in units of P_{in}^c

To see the potentially enhanced sensitivity, let us consider a special numerical example. Reasonable values are: $\gamma = 10^7$ s^{-1}, $\gamma_c = 10^3$ s^{-1}, $|\Omega'| = \gamma$, $\lambda = 500$ nm, $L = 10$ cm, $t_m = 1$ s, $P_{in} = 1$ mW, $a = 10^7$ s^{-1}/gauss, $N = 2 \times 10^{12}$ cm^{-3} (10^{-4} torr at room temperature). This gives a minimum detectable magnetic field strength of

$$B_{min} \rightarrow 10^{-12} \text{ Gauss}$$

which is smaller by one or two orders of magnitude than that of existing magnetometers. Thus, the phaseonium magnetometer potentially leads to much higher sensitivities than existing state-of-the-art devices.

4 Acknowledgments

This work was supported by the Office of Naval Research.

References

[1] P.A. Franken and F.D. Colegrove, Phys.Rev.Lett. **1**, 316, (1958)

[2] C. Cohen-Tannoudji, J. DuPont-Roc, S. Haroche, and F. Laloë, Phys.Rev.Lett. **15**, 758, (1969); A. Kastler, Nuc.Instr.and Methods **110**, 259, (1973)

[3] S. Harris, Phys. Rev. Lett. **62** 1022 (1989); A. Imamoğlu and S. Harris, Opt. Lett. **14**, 1344 (1989); S. Harris, et al., Phys. Rev. Lett. **66**, 2593, (1991).

[4] M.O. Scully and M. Fleischhauer, *High Sensitivity Magnetometer based on Index Enhanced Media*, (unpublished); M. Fleischhauer and M.O. Scully, *Quantum Sensitivity Limits of an Optical Magnetometer Based on Atomic Phase Coherence*, (unpublished)