DETECTION OF THE STATIC MAGNETIC FIELD PRODUCED BY THE ORIENTED NUCLEI OF OPTICALLY PUMPED ^{3}He GAS

C. Cohen-Tannoudji, J. DuPont-Roc, S. Haroche, and F. Laloë
Faculté des Sciences, Laboratoire de Spectroscopie hertzienne de l'Ecole Normale Supérieure, associé au Centre National de la Recherche Scentifique, Paris, France
(Received 10 March 1969)

A new type of very sensitive low-field magnetometer is used to detect the static magnetic field produced by optically pumped ^{3}He nuclei in a vapor. Various signals (pumping and relaxation transients) are obtained in this way. This magnetostatic detection allows a direct study of ^{3}He nuclear polarization without perturbing the spins.

Several methods can be used for the detection of nuclear magnetism: measurement of the induced voltage in rf detection coils in a NMR experiment,[1] detection of various optical signals in an optical pumping experiment,[2] etc. A very direct method would be the detection of the static magnetic field produced by oriented nuclei. For solid samples, the density of spins is large but the polarization at thermal equilibrium is generally very small. For gases, the low density of spins can, in some cases, be compensated by the large polarization provided by optical-pumping methods. Furthermore, in this case, the experiment can be performed at room temperature and in low external magnetic fields. Let us take for example the case of ^{3}He gas: The magnetic field outside a spherical cell containing oriented ^{3}He nuclei is the same as if all the nuclei were located at the center of the cell. If the cell contains N atoms with a polarization P, the field at a distance r from its center, in a direction parallel to the oriented spins, is radial and has a value (in mksA units)

$$\Delta H = 10^{-7}(g\mu_n/r^3)NP, \qquad (1)$$

where $g\mu_n$ is the nuclear magnetic moment of ^{3}He. With a 6-cm-diam cell, a pressure of 3 Torr, and a polarization of 5% (which is currently available[3]), the field at a distance $r = 6$ cm is $\Delta H = 6\times10^{-12}$ T $= 6\times10^{-8}$ G. The order of magnitude of this static field explains why, to our knowledge, it had never been used to detect nuclear polarizations. A new type of very sensitive low-field ^{87}Rb magnetometer has recently been set up[4]; its sensitivity, 10^{-9} G with a 3-sec detection time constant, has made it possible to measure ΔH and to perform the following experiments.

The experimental setup is shown schematically in Fig. 1. A 6-cm-diam cell contains the ^{3}He nuclei; the magnetic field they produce is detected by ^{87}Rb atoms contained in the second cell. Both cells are placed in a magnetic shield which considerably reduces (by a factor 10^5) the external magnetic noise, much larger than ΔH. The shield also lessens considerably the magnetic field inhomogeneities, so that we can observe, as we will see below, very long relaxation times in zero field, no longer limited by field inhomogeneities. The residual stray static fields inside the shield (about 10^{-6} G) are compensated by sets of Helmholtz coils. The ^{3}He atoms are optically pumped by a circularly polarized light beam B_2 ($\lambda = 10\,830$ Å) to achieve the orientation of the $^1S_0$ ground state by the classical technique.[3] The nuclear spins are oriented along the direction of B_2, and as long as there is no applied field, they remain in this direction.

The ^{87}Rb magnetometer[4] makes use of a new type of detection of the zero-field level-crossing resonances appearing in the ground state of optically pumped atoms.[5] The 6-cm-diam ^{87}Rb cell (without buffer gas), with paraffin-coated wall, is the magnetic probe of the magnetometer; it is placed close to the ^{3}He cell and optically pumped by the circularly polarized light beam B_1 (D_1 component of the resonance line) perpendicular to B_2. A rf field $\vec{H}_1\cos\omega t$ is applied in the direction of B_2 ($\omega/2\pi = 400$ Hz). The transmitted light of B_1, measured by a photomultiplier, is modulated at various harmonics $p\omega$ of ω. The modulation ($p = 1$) is proportional to the component par-

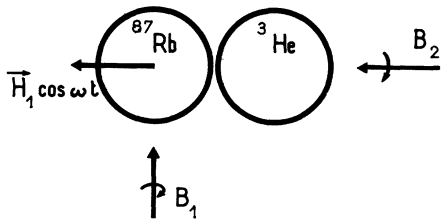

FIG. 1. Schematic diagram of the experimental arrangement.

allel to $\vec{H}_1$ of the field produced[6] (and insensitive to first order to the other components). Furthermore, the field of the ^{3}He nuclei detected by the probe is averaged by the motion of the ^{87}Rb atoms in the cell so that the magnetometer measures in fact the mean value of the field in the spherical volume of the ^{87}Rb cell (i.e., its value at the center). Figure 2 shows the variation of the detected field during the buildup of the ^{3}He polarization by optical pumping: Formula (1) (where $r = 6.3$ cm is the distance between the centers of the two cells) allows a direct measurement of the obtained polarization as a function of time.

Once the optical orientation has been obtained it is possible to cut off the discharge and the pumping beam B_2 and to record the evolution of the orientation of the ground state which is no longer coupled to the metastable state. One could get in this way a relaxation curve corresponding to the decay of the orientation of the ^{3}He ground state. The relaxation time T_γ is very long (several hours). During this long time, it is very difficult to avoid the magnetic drifts due to the evolution of the magnetization of the shield. Hence we have improved the experiment in the following way: We add a very weak magnetic field $\vec{h}$ (2 μG) perpendicular to the ^{3}He pumping direction B_2.[7] The nuclear spins precess around $\vec{h}$ at a very low Larmor frequency ν ($\nu \simeq 6\times 10^{-3}$ Hz) and the radial field produced at the center of the ^{87}Rb cell varies as $\Delta H \cos 2\pi\nu t$. The field-modulation amplitude is $2\Delta H$ and can be recorded for several hours [Figs. 3(a) and 3(b)]. One can study in this way with good precision the decay of the nuclear polarization. Figure 3(c) shows the modulation signal remaining 11 h after the optical pumping has been stopped and gives an idea of the sensitivity of this procedure for the detection of low polarizations.

The magnetostatic method described above may be interesting for the study of various problems connected with polarization of ^{3}He nuclei in the zero-field region. Both radioelectric and optical detections generally perturb the measured polarization of ^{3}He (for example, energy absorption by the induction coils and field inhomogeneities in the first case, strong relaxation of the nuclear orientation due to the discharge in the second one). On the contrary, the magnetostatic detection creates no detectable perturbation of the nuclear spins: The magnetic field of the very low-density ^{87}Rb paramagnetic vapor is too weak to perturb the ^{3}He gas; the rf field $\vec{H}_1 \cos\omega t$ is nonresonant for ^{3}He atoms and it can be shown (by changing its intensity for example) that it has no effect on the nuclear polarization. The magnetostatic detection seems to be the obvious method for continuous recording of the orientation of free ^{3}He nuclei. This method provides also a direct measurement of the number NP of oriented spins and, knowing N, of the polarization P. If the pressure is large (several Torr), N is large and it becomes possible, as one measures the product NP, the detect very weak val-

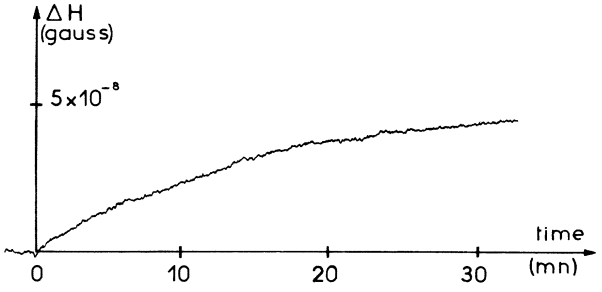

FIG. 2. Plot of the magnetic field ΔH during the optical pumping of ^{3}He (detection time constant: 3 sec). ^{3}He pressure: 3 Torr.

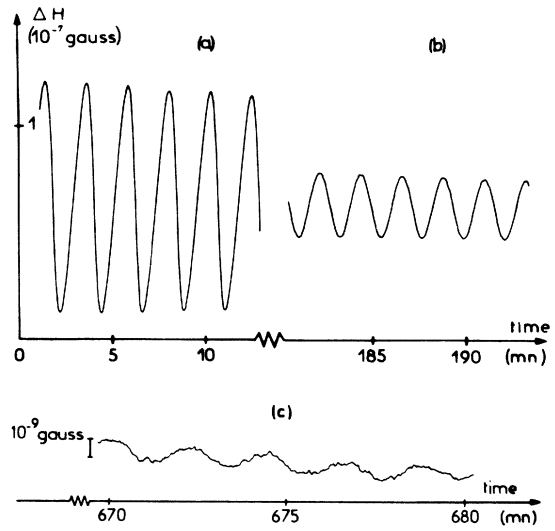

FIG. 3. Plot of the modulation of the magnetic field due to the free precession of the ^{3}He nuclear spins (^{3}He pressure: 3 Torr). (a) Just after optical pumping has been stopped (polarization $P \simeq 5\%$). (b) 3 h later. The measured nuclear relaxation time is 2 h, 20 min. [Detection time constant for (a) and (b): 3 sec.] (c) The free precession signal 11 h after optical pumping has been stopped. The polarization is now $P \simeq 5 \times 10^{-4}$ corresponding to 5.3×10^{13} oriented nuclei per cm^3; detection time constant: 10 sec. The scales are different from those of (a) and (b). In addition to the signal, one can see a small magnetic drift due to the imperfections of the shield.

ues of P which would be difficult to measure optically. Finally, various applications of this method might be used to set up magnetometers or gyrometers.

---

[1]See, for example, A. Abragam, The Principles of Nuclear Magnetism (Oxford University Press, London, England, 1961).

[2]See, for example, references in C. Cohen-Tannoudji and A. Kastler, Progress in Optics (North-Holland Publishing Co., Amsterdam, The Netherlands, 1966), Vol. V.

[3]F. D. Colegrove, L. D. Schearer, and G. K. Walters, Phys. Rev. 132, 2561 (1963).

[4]J. DuPont-Roc, S. Haroche, and C. Cohen-Tannoudji, Phys. Letters 28A, 638 (1969).

[5]N. Polonsky and C. Cohen-Tannoudji, Compt. Rend. 260, 5231 (1965). For excited states, see C. J. Favre and E. Geneux, Phys. Letters 8, 190 (1964), and E. B. Alexandrov, O. V. Konstantinov, V. T. Perel', and V. A. Khodovoĭ, Zh. Eksperim. i Teor. Fiz. 45, 503 (1963) [translation: Soviet Phys.-JETP 18, 346 (1964)].

[6]As long as this field is much smaller than the width (about 5 μG) of the level-crossing dispersion resonance curve.

[7]Since $\vec{h}$ is perpendicular to $\vec{H}_1\cos\omega t$, it does not affect the signal detected by the ^{87}Rb atoms.

OPTICAL PULSE AND PULSE-TRAIN PROPAGATION IN A RESONANT MEDIUM*

Joseph H. Eberly
Department of Physics and Astronomy, University of Rochester, Rochester, New York 14627
(Received 19 February 1969)

We derive analytic pulse and pulse-train solutions to the nonlinear coupled Maxwell-Schrödinger equations describing the propagation of shape-preserving ultrashort optical pulses in a resonant medium.

A great deal of attention has been given recently to the generation of ultrashort optical pulses[1] and their interaction with atomic systems. The special cases in which the atomic system is either an attenuator[2] or an amplifier[3] (resonant atoms asymptotically in the ground state or excited state, respectively) have been treated in some detail, principally by computer solution of the coupled Maxwell-Schrödinger equations in the quasimonochromatic-field approximation.

We describe here a method which permits analytic solution of this resonant energy-transport problem, regardless of the asymptotic preparation of the medium. The atomic system is assumed to consist of two-level atoms continuously distributed in a nondispersive host medium. The resonant interaction is between the atomic dipole moments and a quasimonochromatic plane-wave electric field. The field center frequency is equal to the center frequency of the symmetric, inhomogeneously broadened atomic line. The relation between atomic polarization and electric field is found to be highly nonlinear, as expected. In addition, the experimental breakup of large pulses into smaller ones is predictable.

The electric field is assumed to be a circularly polarized plane wave modulated by a slowly varying envelope which is a function of the single parameter $\zeta = t - z/v$, $\vec{E}(z,t) = \mathcal{E}(\zeta)[\hat{i}\cos\beta + \hat{j}\sin\beta]$ where $\beta = \omega(t - \eta z/c)$, and η is the refractive index of whatever host medium contains the resonant, interacting, two-level, atomic dipoles. Then, in the usual rotating reference frame,[4] the coupled and nonlinear Maxwell and Schrödinger equations for a particular interacting atom may be written in terms of the components (u, v, w) of a unit vector $\vec{r}$. We look for shape-preserving pulse solutions by assuming that u, v, and w also depend only on ζ. Then after writing all relevant space and time derivatives in terms of ζ derivatives we have[5]

$$\dot{u} = -\gamma v, \tag{1}$$

$$\dot{v} = \gamma u + \kappa \mathcal{E} w, \tag{2}$$

$$\dot{w} = -\kappa \mathcal{E} v, \tag{3}$$

$$\dot{\mathcal{E}} = \frac{-2\pi\kappa}{\eta c \Delta} \mathfrak{N} \frac{\hbar\omega}{2} \int v(\zeta, \gamma) g(\gamma) d\gamma. \tag{4}$$

The physical interpretation of u, v, and w is the standard one for $\Delta m = \pm 1$ electric dipole transitions: u and $-v$ are the dimensionless dispersion and absorption components of the dipole moments, and w is the atom energy divided by $\frac{1}{2}\hbar\omega$. $\mathfrak{N}$ is the number of interacting atoms per unit volume, γ is the amount by which the individual atom is off resonance with the field center frequency, $g(\gamma)$ is the atomic line-shape function,