Parametric relaxation resonance of optically oriented atoms in a transverse magnetic field

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(Submitted November 23, 1974)
Zh. Eksp. Teor. Fiz. **66**, 1578–1580 (May 1974)

It is shown that relaxation modulation of optically oriented atoms in a transverse magnetic field leads to resonance variation of the macroscopic magnetic moment, provided that the modulation frequency is identical with the Larmor frequency or its subharmonics.

The resonance effects which arise in optical orientation of atoms in a transverse magnetic field, due to modulation of the intensity of the pumping light[1] and the value of the transverse field[2], have been recently studied in detail, both theoretically and experimentally. Similar effects have also been discovered for optically oriented atoms in an effective magnetic field.[3,4]. A common feature of these researches has been the modulation of the nonisotropic action on the spin system. In the present work, we consider the effect of modulation of an isotropic factor—the collisional relaxation--under conditions of transverse pumping, and also under conditions of ordinary magnetic resonance.

We assume that the optically oriented atoms possess an angular momentum $J = 1/2$ in the ground state. Orientation of the atoms in the ground state is brought about by absorption of circularly polarized light, which propagates along the z axis. We shall assume that the longitudinal relaxation time T_1 is equal to the transverse relaxation time T_2: $T_1 = T_2 = T$ (the case of isotropic relaxation), and that the relaxation rate is modulated according to the law

$$\Gamma=1/T=\bar{\Gamma}(1+\mu\cos\Omega t). \tag{1}$$

We first consider the case of transverse pumping: the constant magnetic field H_0 is directed perpendicular to the beam of light along the x axis. In this case, the Bloch equations for the macroscopic magnetic moment **M** of atoms in the ground state have the form

$$\frac{dM_x}{dt}=-gM_x,\quad \frac{dM_y}{dt}=\omega_0M_z-gM_y,\quad \frac{dM_z}{dt}=-gM_z-\omega_0M_y+\Gamma_p\bar{M}_0. \tag{2}$$

In Eqs. (2), $\omega_0 = \gamma H_0$ is the Larmor frequency, $\Gamma_p = 1/T_p$ (T_p is the pumping time), $g = \Gamma + \Gamma_p$, $\bar{M}_0 = \text{const}$ is the maximum possible value of the projection of the moment **M** on the z axis. At $t \gg 1/g$, the solution of Eqs. (2) with account of (1) has the form

$$M_x(\omega_0)=0,\quad M_y(\omega_0)=-\bar{M}_0\Gamma_p\,\mathrm{Im}\,B(\omega_0),\quad M_z(\omega_0)=\bar{M}_0\Gamma_p\,\mathrm{Re}\,B(\omega_0), \tag{3}$$

$$B(\omega_0)=\sum_{k,n=-\infty}^{\infty}(-1)^kI_n(\varkappa)I_k(\varkappa)\frac{\exp[i(n-k)(\Omega t+\pi/2)]}{\bar{\Gamma}+\Gamma_p+i(\omega_0-k\Omega)}, \tag{4}$$

$$\varkappa=\mu\bar{\Gamma}/\Omega. \tag{5}$$

Here $I_n(\kappa)$ and $I_k(\kappa)$ are Bessel functions of imaginary argument.

It follows from Eqs. (3) and (4) that the magnetic moment rotates in the yz plane and changes in resonant fashion when the modulation frequency Ω equals the Larmor frequency ω_0 or its subharmonics ω_0/k. The resonant change of M_z and M_y can be observed experimentally as usual from the change in the absorption of the light propagating along the z axis (the pumping beam) or along the y axis (the auxiliary beam). It follows from (4) that the resonance signals that are generated here will not be saturated. The absence of saturation is a common property of parametric resonances[1-4] and is due to the fact that the motion of the magnetic moment takes place in a plane perpendicular to the magnetic field, and is therefore not accompanied by a change in the energy of the spin system in the magnetic field.

We now consider the effect of modulation of the relaxation under the conditions of ordinary magnetic resonance: a constant magnetic field H_0 is directed along the light beam along the z axis, the projections of the magnetic field H_1 (which rotates with the frequency ω) on the x and y axes are respectively equal to $H_1 \cos \omega t$ and $-H_1 \sin \omega t$. We limit our discussion to consideration of the case of zero detuning: $\Delta\omega = \omega - \omega_0 = 0$. In this case, the Bloch equations in a set of coordinates that rotate with angular velocity ω about the z axis are identical with Eqs. (2) upon replacement of ω_0 by $\omega_1 = \gamma H_1$ (ω_1 is the nutation frequency). Consequently, the expressions for the moment projections in the rotating coordinate system will be the same as those obtained above (with the substitution $\omega_0 \to \omega_1$). Changing to laboratory coordinates, we obtain expressions for the moment components $\tilde{M}_x$, $\tilde{M}_y$ and $\tilde{M}_z$ in the case of modulation of the relaxation under conditions of magnetic resonance:

$$\tilde{M}_x=M_y(\omega_1)\sin\omega_0t,\quad \tilde{M}_y=M_y(\omega_1)\cos\omega_0t,\quad \tilde{M}_z=M_z(\omega_1). \tag{6}$$

The quantities in (6) are given by the relations (3), (4) and (5). It follows from Eqs. (6), (3) and (4) that the modulation relaxation under conditions of magnetic resonance (for zero detuning) leads to the appearance of parametric resonances at the nutation frequency and its subharmonics.

Thus, both in the case of transverse pumping and under conditions of magnetic resonance, the relaxation modulation leads to the appearance of parametric resonances. The nature of this phenomenon is the same in the two cases considered since the second case reduces to the first. In fact, under conditions of magnetic resonance, transverse pumping actually takes place: the role of the transverse field is played here by the effective magnetic field, which is identical with the field H_1 in the case $\omega = \omega_0$, and is therefore perpendicular to the beam of the pumping light.

We now discuss the possibility of excitation and observation of parametric relaxation resonances. For the existence of relaxation modulation, we can make use of the fact that the relaxation rate depends on the concentration and velocity of the atoms of the buffer gas, which is usually employed in experiments on optical pumping, and in certain cases on the strength of the electric discharge (for example, in the case of He^4 and He^3). To modulate the concentration and velocity of the atoms of the buffer gas, we can use acoustic oscillations. It is easy to modulate the strength of the discharge by changing the electric potential which maintains the discharge; a significant modulation depth is achieved in this case. Thus, on the basis of the data of[5], we obtain $\mu = 0.1$ for He^4 in the 2^3S_1 state.

The expected value of the optical signals of relaxation resonance can be compared with the value S_H of the optical Hanle signal, observed in the case of transverse pumping: $S_H = AM_z(\mu = 0, \omega_0 = 0)$. We find from Eqs. (3) and (4) that $S_H = A\overline{M}_0\Gamma_p/\overline{\Gamma} + \Gamma_p)$. We now estimate the amplitude $S_{pl}(\Omega)$ of the signal of the first relaxation resonance ($k = 0$), observed from the absorption of the pumping light at the frequency Ω ($|n - k| = 1$). For the case $\Omega = 5\overline{\Gamma}$ (for good resolution of the neighboring resonances, it is necessary to take $\Omega \gg \Gamma$) and $\mu = 0.1$, with the use of Eqs. (3) and (4), we obtain $S_{pl}(\Omega) = AM_z(\Omega = \omega_0) = 10^{-2}S_H$. Consequently, observation of the relaxation resonance signal (at $\mu = 0.1$) is possible if the Hanle signal is observed with a signal-to-noise ratio of more than 100, which is frequently the case in experiments on optical orientation.

The author expresses his gratitude to V. I. Perel' for arousing his interest in the problem, and to R. A. Zhitnikov and B. N. Sevast'yanov for useful discussions.

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Translated by R. T. Beyer
162