Stray magnetic field influence on the CPT resonance in a coated Rb vacuum cell

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Abstract. Interaction of a resonant laser beam with an atomic absorption medium creates population redistribution and interference between atomic levels. This anisotropy of the medium is experimentally observed as coherent population trapping (CPT) or electromagnetically induced transparency (EIT). Due to the small sub-natural width of the CPT and EIT resonances, they find wide applications in metrology, quantum optics, atom cooling. A non-compensated stray magnetic field (SMF) can change the shape and sign of the resonance or destroy it completely. In this work, we present an experimental and theoretical investigation of the influence of a stray magnetic field on the CPT resonances obtained on Zeeman sublevels of the D1 line of 87Rb in a paraffin-coated vacuum cell. The role is clarified of the polarization moments with different rank in creating the integral registered fluorescent signal in the presence of a stray magnetic field. It is shown that a transverse magnetic field plays an important role in changing the shape of the signal.

1. Introduction
Coherent population trapping (CPT) is an interference effect arising in a three-level atomic system after interaction with two coherent fields which connect the ground levels to a common upper level [1]. In a Hanle-configuration, the CPT resonance is due to the interference between the Zeeman sub-levels of a single hyperfine level. The effect manifests itself as a dark resonance (lack of fluorescence), or as a peak of transmission. The resonance width is determined by the lifetime of the coherent state. As the ground states are long-lived, the CPT resonances are ultra narrow. Widths of 1-10 Hz have been measured [2].

The narrow resonance and good signal/noise ratio attracts the attention of the scientists and the CPT phenomena find many applications – in magnetometry, quantum optics, atom cooling. The role of the factors which change the shape and width of the resonance is increasing respectively. As our signal is obtained through a controlled scanning of a magnetic field around its zero value, a stray magnetic field can change the shape and sign of the resonance or destroy it completely. Earlier, the influence of the stray magnetic field on Hanle CPT was investigated in an uncoated vacuum cell [3].

In a coated cell, the long lifetime of the coherent state makes possible the transfer of coherence by multi-photon processes because of mixing of the contribution of polarization moments with different ranks. They have different relaxation constants and are influenced in a different way by the laser

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power and the stray magnetic field [4]. In a previous work [5], we investigated the CPT resonance
dependence on the laser power and the experimental geometry in a coated cell when a polarized
fluorescence is registered. A satisfying agreement between the experiment and the theoretical
modeling was achieved when an additional dc magnetic field was added to the computation model.

In the present work, we studied the connections of the polarization moments having different ranks
with the tensor components, which form the observable integral fluorescence, in the presence of a
stray magnetic field.

2. Experiment

2.1. The set-up

The experimental set-up is shown in figure 1(a). It consists of a single-mode diode laser (DL)
oscillating at $\lambda = 794.76$ nm, a Rb cell and a system of registration and control of the experiment. The
laser beam with diameter 1.5 mm passes through an optical isolator (I) to avoid the optical feedback
and a polarization rotator to change the laser polarization direction when necessary. An additional
linear polarizer is inserted in order to obtain pure linear light polarization. The laser power is
attenuated by means of grey filters and measured by a Thorlabs power meter. Then the laser beam
passes through the vapor cell enclosed in a 3-layer magnetic shield which isolates the stray magnetic
field. Additional Helmholtz coils (not shown in figure 1) are mounted in the magnetic shield  to
compensate the residuum magnetic field. The vacuum cell is paraffin-coated, containing $^{87}$Rb, 25 mm
long with diameter 20 mm. The laser frequency is controlled by monitoring the fluorescence from a
second Rb vapor cell. All measurements are performed at room temperature (25 °C). A dc magnetic
field $B_{\text{scan}}$, created by a solenoid, is applied collinearly to the laser beam. The current through the
solenoid is controlled by a digital function generator Rigol.

![Figure 1. (a) the experimental set-up; (b) geometry of the experiment.](image)

Our experiment was performed on the $^5S_{1/2} \rightarrow ^5P_{1/2}$ transition ($F = 2 \rightarrow F = 1$) of the $^{87}$Rb D$_1$ line.
The ground state coherence was created by a linearly polarized laser beam. The fluorescence from
the cell was detected by a photodiode mounted so as to gather the light emitted in the $0z$
direction (figure 1(b)). The fluorescence dependence on the dc magnetic field $B_{\text{scan}} = \pm 60$ mG was stored in a
Tektronix oscilloscope. The resonance is centered at zero magnetic field where the levels of the
$^5S_{1/2} \rightarrow ^5P_{1/2}$ transition are degenerated. The fluorescence signal shape dependence on the laser
power and the transverse magnetic field was studied.

In figure 2, the CPT resonances are shown obtained at different laser power excitation, from $P_{\text{ins}}=5$ μW to $P_{\text{ins}}=19$ mW. The shape and sign of the resonance change as the laser power is increased. Two resonances were chosen for theoretical modeling – at low and high power, having opposite signs.
3. Theoretical modeling

The theoretical model in the present work used a basic system of equations for the component of the statistical operator, $\hat{\rho}$, adapted to describe the interaction of an atomic system with a static (scanned) magnetic field $B_{\text{scan}}$, an additional arbitrarily oriented magnetic field $B'$ and a linearly polarized strong laser field $E_{\text{laser}}(\omega_0,t)$ resonant to the atomic transition with total quantum number $F_\phi, F_f$.

Using the irreducible tensor operator (ITO) formalism and the adopted calculation scheme [6], solutions for arbitrary polarization moments (PM) $\rho_\phi^f$ can be obtained, depending on the scanned magnetic field, for different parameters: – Rabi frequency, relaxation constants, including spontaneous emission transfer, and stray magnetic field $B'$.

As the quantization axis $0z$ is chosen along the electrical vector of the laser light $E_{\text{laser}}$ and the magnetic field $B_{\text{scan}}$ is scanned along the laser beam propagation $0x$, only two components of the stray magnetic field $B'$ are of importance: – $B'_y$ and $B'_z$.

A stray magnetic field $B'_y$, orthogonal to the scanned magnetic field $B_{\text{scan}}$ and $E_{\text{laser}}$ is equivalent to introducing a variable with the $B_{\text{scan}}$ ellipticity in the laser field. As a result, orientation moments $\rho_\phi^f$, $\rho = f, \varphi$ are created. The dynamics of the tensor components describing the modification of the orientation of the upper $f_\phi^1$ and lower $\phi_\phi^1 \pm \frac{1}{2}$ level is shown in figure 3. It is seen that only the component of the transverse magnetic field directed along the $0y$ is of importance.

Figure 3. Dependence of the orientation moment on the scanned magnetic field in the presence of a transverse magnetic field: a) directed along the $0y$ axis; b) directed along the $0z$ axis.
Detailed analyses of the numerical solutions for all tensor components with rank 0 and 2 of the upper and lower state allow the visualization of the dynamics of their behavior depending on the laboratory magnetic field (figure 4).

![Figure 4](image)

**Figure 4.** Behavior of population $f_{00}$, longitudinal $f_{02}$ and transverse $f_{22}$ alignment in the presence of a transverse magnetic field.

It is seen that as the transverse magnetic field is increased, the amplitude of the population $f_{00}$ and the narrow resonance in the longitudinal alignment $f_{02}$ of the upper state decrease. As a result, the sign of the resonance in the non-polarized fluorescence changes. The behavior of the population and the longitudinal alignment of the lower level is similar. The transverse alignment $f_{22}$ dependence on the stray magnetic field is non-monotonic. The physical reason for this behavior is clear. The transverse magnetic field creates orientation and at the same time destroys the lower level alignment. This leads to a decrease in the amplitudes of the longitudinal and transverse alignment resonances of the upper level. This process competes with the spontaneous transfers of coherency and population; with the increase of the laser power, its efficacy decreases.

The non-polarized spontaneous emission intensity $I_{f\phi}(\vec{e}_n)$ in a chosen direction $\vec{e}_n$ from the upper $(f, F_f)$ to the lower $(\phi, F_\phi)$ level is described by

$$I_{f\phi}(\vec{e}_n) = C_0 (-1)^{F_f + F_{\phi}} (2F_f + 1)^{-1/2} \sum_q (2\kappa + 1) \sum_q (-1)^q f_q \kappa T^\kappa_{-q}(\vec{e}_n),$$

where $T^\kappa_{-q}(\vec{e}_n)$ is the observation tensor [7].

The integral fluorescent signal was obtained using the formula for the non-polarized fluorescence. Two atomic sub-ensembles were included in the theoretical model. The first is responsible for the wide pedestal. The lifetime of these atoms is determined by the time of flight. The second ensemble of atoms forms the narrow resonance and their lifetime is determined by the relaxation of the laser-created coherent state. The Rabi frequency and the value of the transverse magnetic field were varied. To examine the transverse magnetic field influence on the resonance shape, two cases were chosen – at a laser power $P_{\text{las}} \sim 30 \mu W$ and at $P_{\text{las}} \sim 700 \mu W$. The experimental records of the signal are shown in figure 5: a) – in the presence of a transverse magnetic field; b) with a compensated transverse magnetic field.

It is seen that the transverse magnetic field destroys the narrow structure centered at the zero point. Interpretations of the experimental results are made with numerical modeling of the experiment.

Computed signals are in a good agreement with the experiment.
Figure 5. a) in presence of a transverse magnetic field; b) with a compensated transverse magnetic field.

4. Conclusions
A transformation from bright to black CPT resonance, depending on the laser power and a transverse magnetic field, was registered on the D$_1$ $^{87}$Rb line in a paraffin-coated cell. A model for numerical calculation of the CPT in Hanle-configuration was applied, which uses the ITO formalism and takes into account the influence of a stray magnetic field. The role was clarified of the orientation in creating the integral experimentally observed signal in the presence of a stray magnetic field. The comparison of the theoretical shape of the resonances with the experiment shows a good agreement.

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