Electromagnetically induced absorption resonances in Hanle-configuration prepared in a paraffin coated $^{87}$Rb cell

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Abstract. We present an experimental investigation of electromagnetically-induced absorption (EIA) at the D$_1$ line of $^{87}$Rb contained in an anti-relaxation coated vacuum optical cell. The configuration includes a pump and a probe beam propagating in opposite directions and having mutually orthogonal linear polarizations; the probe beam absorption is registered depending on the value of a magnetic field scanned around zero and applied collinearly to the laser beams. The advantages of this scheme have been recently evidenced in vapor cells filled with a buffer gas. In the present work we studied the width and the contrast of the EIA resonances obtained in a coated cell for different values of the pump power. The results are compared with those obtained in a buffer gas cell for the same transition of $^{87}$Rb. The theoretical calculations are in good agreement with the experiment.

1. Introduction

The interaction of two coherent light fields with degenerate atomic energy levels can lead to the observation of different nonlinear interference effects [1]. When the degeneracy is lifted by applying a dc magnetic field scanned around zero, magneto-optical resonances are observed (the so-called Hanle configuration). Depending on the experimental conditions and the observation geometry, when the resonant light field propagates through the atomic medium, different phenomena are manifested around the degeneracy condition: coherent population trapping (CPT) [2], electromagnetically-induced transparency (EIT) [3] or electromagnetically-induced absorption (EIA) [4].

The magneto-optical resonances are often realized on a single ground-state hyperfine level of an alkali atom (Rb, Cs, K). Since the ground states are long-lived, the magneto-optical resonances can be ultra-narrow. This fact, together with the good signal-to-noise ratio of the resonances, attracts increasing attention due to the possibility of their application in various fields of quantum physics, such as magnetometry, optical communications, etc. A standard way to increase the lifetime of the coherent states, and thus reduce the resonance linewidth, is to use vapor cells with additional buffer gas or antirelaxation coating of the walls. The EIA signals were first registered on optical transitions with $F_e=F_g+1$ ($F_e>0$), where $F_e$ and $F_g$ are the total angular momenta of the ground and excited states, respectively [4]. The EIA effect was attributed to a spontaneous transfer of population or Zeeman coherences from the excited state to the ground state [5, 6]. For such kind of transitions (increased

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absorption, or "bright" transitions), it is difficult to produce narrow-width and high-contrast EIA resonances in buffer gas cells due to the collisional depolarization of the excited state. Later, different geometries for realization of EIA in buffer gas cells were proposed, both for "bright" and "dark" \( (F_e = F_g - 1, F_g) \) types of dipole transitions, requiring the application of microwave radiation, additional transverse magnetic fields, etc.

A novel scheme for observation of magneto-optical EIA resonances has been proposed in [7]. The scheme exploits counter-propagating pump and probe light beams with mutually orthogonal linear polarizations. The light field should be in resonance with an open dipole transition in the \( D_1 \) line of Rb or Cs. The experiments have already demonstrated that very high-contrast and narrow-width EIA resonances can be registered in buffer-gas-filled vapor cells \([8, 9]\). The present work aims to investigate the EIA resonances in the same scheme but in a coated vacuum cell and to compare the resonance parameters with those obtained in a buffer-gas Rb cell.

2. Experiment

The experimental setup is shown schematically in figure 1. A single-mode diode laser (DL) is used, oscillating at \( \lambda = 794.76 \) nm, with a linewidth of 50 MHz. A \( \lambda/2 \) plate is used to control the laser polarization. Two polarization beam splitters (PBS) and a system of mirrors are used to form two counter-propagating laser beams with orthogonal polarizations, which propagate through the Rb cell. The ratio of the laser power of the beams is varied by means of grey filters and measured by a power meter. The vacuum cell containing \( ^{87}\text{Rb} \) is paraffin-coated, 25 mm long, with a diameter of 20 mm and is enclosed in a 3-layer magnetic shield, which isolates the stray magnetic field. The laser frequency is controlled by monitoring the fluorescence from a second Rb vapor cell. A dc magnetic field \( B_{\text{scan}} \), created by a solenoid, is applied collinearly to the laser beams. The cell temperature is kept at 50°C.

![Figure 1. Scheme of the experimental setup. DL – diode laser, I – optical isolator, PBS – polarization beam-splitter.](image)

Our experiment was performed at the \( 5^2S_{1/2} \rightarrow 5^2P_{1/2} \) transition \( (F_g = 2 \rightarrow F_e = 1) \) of the \( ^{87}\text{Rb} \) \( D_1 \) line. The beam diameters were 5 mm. The absorption of the counter-propagating probe beam was registered in dependence on the dc magnetic field scanned with a frequency 0.33 Hz around zero value with amplitude 40 mG. The signal is an EIA resonance centered at zero magnetic field.

3. Experimental results and discussion

The EIA resonances were registered for a pump beam power from \( P_{\text{pump}} = 50 \mu\text{W} \) to 7 mW and probe beam power \( P_{\text{probe}} = 5 \mu\text{W} \). A typical experimental resonance profile obtained using the presented scheme is shown by a black line in figure 2; a Lorentzian fit is shown in red. As can be seen, the lineshape of the resonance is complex. It consists of a narrower part superimposed on a broader pedestal. Such complex lineshape has been registered in other works where CPT, EIT or EIA effects were studied in coated cells (for instance, see [10, 11]). The broad pedestal is attributed to the
relaxation of the atoms interacting only once with the laser beam, while the narrower part is due to the relaxation of atoms with multiple crossing of the beam after spin-preserving collisions with the cell walls.

Figure 3 shows the dependence of the resonance full width at half maximum (FWHM) on the pump beam power. Because of the complex resonance shape, the linewdths were determined based on the full resonance amplitude, therefore they are higher than those obtained under the same conditions but in a cell with a buffer gas [8]. The linewdths have similar values only if the Lorentzian profile is considered (for the case presented in figure 2, the width of the Lorentzian part is 2 mG).

\[ C_{rel} = \left( \frac{A}{A_{ped}} \right) \times 100\% , \]
\[ C_{tech} = \left( \frac{A}{A_T} \right) \times 100\% , \]

where \( C_{rel} \) defines the relative, and \( C_{tech} \), the technical contrast. \( A \) and \( A_T \) are denoted in figure 2. \( A_{ped} \) is the Doppler profile amplitude. The dependences of these two parameters on the pump beam power are presented in figure 4. It is seen that the technical contrast (figure 4b) approaches some kind of saturation with the pump power. In the case of the buffer-gas-filled rubidium vapor cell [8], the behavior is different, namely, the contrast starts decreasing at high pump power levels.

\[ C_{rel} \]
\[ C_{tech} \]

Figure 4. Dependence of the relative (a) and technical (b) contrast of the EIA resonance on the pump beam power; \( P_{probe} = 5 \) µW.
4. Theoretical lineshape

For shortness, we show here only the main equations that should be solved to obtain a theoretical lineshape of the resonance. We use a standard approach based on the density matrix formalism [9]:

\[
(\Gamma + \gamma + \gamma_c)\hat{\rho}^\alpha = \frac{\gamma_c f(\nu)}{2F_0 + 1} \text{Tr}\left\{\hat{\rho}^\alpha\right\} + \sum_{j=p,\bar{p}} R_j^2 \left[ L_j (\hat{V}_j\hat{\rho}^\alpha\hat{V}^\dagger_j - \hat{\rho}^\alpha\hat{V}^\dagger_j) + H.c.\right],
\]

\[
(\Gamma + \gamma_c)\hat{\rho}^{ee} = \Gamma \hat{\rho}_0^{ee} + \gamma_c f(\nu)\left\{\hat{\rho}^{ee}\right\} + \beta \gamma(2F_0 + 1) \sum_{q=0,1} \hat{T}_q^\dagger \hat{T}_q + i\Omega \left[\hat{\rho}^{ee}, \hat{F}_z\right]
- \sum_{j=p,\bar{p}} R_j^2 \left[ L_j (\hat{V}_j\hat{\rho}^{ee}\hat{V}^\dagger_j - \hat{V}^\dagger_j\hat{\rho}^{ee}\hat{V}_j) + H.c.\right].
\]

The matrices \(\hat{\rho}^{ee}\) and \(\hat{\rho}^\alpha\) correspond to the ground and excited states, respectively. The angular brackets \(\langle ... \rangle\) denote integration over all atom velocities in the gas, \(f(\nu)\) is the Maxwell velocity distribution, \(\beta\) is the branching ratio (\(\beta=1\) for a closed transition). \(\hat{\rho}_0^{ee}\) describes the isotropic ground state when the light field is absent. \(\hat{F}_z\) is the operator of the \(z\)-projection of the total angular momentum of the ground state, \(\hat{i}^\dagger\) is the identity matrix. The operators \(\hat{T}_q\) and \(\hat{V}_j\) are proportional to the \(3jm\)-symbols and can be found in [9] with \(j=c,p\) for the pump (\(c\)) and probe (\(p\)) waves.

At small magnetic fields, we can consider the energy level splitting over the magnetic sublevels \(m\) only for the ground state. Therefore, the Larmor frequency \(\Omega=\mu_B g B/\hbar\) stands only in equation (4) with \(\mu_B\) the Bohr magneton, \(g\) the Landé \(g\)-factor of the ground state, \(B\) the magnetic field directed along the wave vectors. \(\text{Tr}\{...\}\) denotes the trace operation, while \([......]\) is the operation of commutation of two matrices. "H.c." means the Hermitian conjugate terms. \(L_j = (\gamma_{eg} - \delta_j)^{-1}\) are the Lorentzians with \(\gamma_{eg} = \Gamma + \gamma_c + \gamma/2\) being the relaxation rate of the optical coherences, \(\delta_c = \delta - k\nu\) and \(\delta_p = \delta + k\nu\) are the frequency detunings for the pump (control) and probe beams, respectively, taking into account the linear Doppler frequency shift \(k\nu\) for a moving atom, and \(\delta = \omega - \omega_0\) is the optical frequency detuning of the laser radiation frequency \(\omega\) from the optical transition frequency \(\omega_0\) for an atom at rest. \(R_{c,p}\) are the Rabi frequencies. The relaxation rate \(\gamma\) causes the narrowest spectral feature in the resonance lineshape (see figure 2), while the rate \(\gamma_c\) is responsible for the observation of a broad pedestal. The rate \(\gamma\) in equation (4) corresponds to the excited-state spontaneous relaxation.

Figure 5. (a) The calculated probe wave intensity after the cell, normalized to the input intensity. (b) The same with a zoom. Parameters: \(R_c=\gamma, R_p=0.1\gamma, \Gamma = 10^{-5}\gamma, \gamma=10^{-2}\gamma, T_{\text{cell}}=50^\circ\text{C}, L_{\text{cell}}=25\text{ mm}.

Figure 5 shows the results of the numerical calculation of equations (3, 4). It is seen that the theory reproduces the complex lineshape of the EIA resonance: a narrow transmission dip in the center accompanied by a broader pedestal. The increased absorption at zero magnetic field is due to the fact that atoms are prepared into the special state within the level \(F_p=2\). This state is a "dark" state for the
pump wave due to CPT. At the same time, this state is a “bright” state for the probe beam, leading to increased absorption. When the magnetic field $B$ is far from zero value, the CPT state is destroyed and most of the atoms are pumped out from the level $F_{g}=2$ towards $F_{g}=1$. Being in $F_{g}=1$ level, atoms do not scatter photons from the pump and probe waves, leading to increase in the atomic transparency.

5. Conclusions
In this work we studied the EIA resonances obtained in the counter-propagating pump and probe light beams configuration using a paraffin-coated optical cell. Comparing the lineshape of the signals obtained by us in a coated cell with those reported for a buffer gas cell, significant differences are seen. Unlike the complex shape of the resonance in the coated cell, in the buffer gas cell it has a Lorentzian profile. Regarding the contrast, in our case it is lower according to both definitions. The difference can be attributed to the ambiguity in determining the background level due to the complex resonance lineshape. Additional reason could be the laser linewidth, which in our case is 50 MHz, while the experiments in a buffer gas cell are performed with a DFB laser of less than a 1 MHz linewidth. The parameters of the EIA resonance can be also improved using a laser beam with a larger diameter, together with further compensation of residual small transverse magnetic fields inside the shielding and increasing the cell temperature. Additional experimental and theoretical work is planned to realize the full potential of the proposed method of EIA registration in anti-relaxation coated cells.

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