Transformation of the coherent population trapping resonance into enhanced fluorescence in a paraffin coated Rb vacuum cell

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Abstract. The ultra-narrow resonances achieved in coherent spectroscopy of alkali atoms originate from the destruction of the laser-induced coherence in the ground state. An anti-relaxation cell coating preserves the coherence created and, consequently, the resonance narrows by almost two orders of magnitude. Coherence resonances are used in magnetic field sensors, atomic clocks, quantum informatics, etc. In this work, we investigate the features of the CPT resonance on the D1 87 Rb line obtained in fluorescence in paraffin coated cells. The transformation from a black to a bright resonance is found to depend on the laser power and the experimental geometry.

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 hyperfine transition is excited by linearly polarized single frequency laser light which connects the Zeeman sub-levels in \(\Lambda\)-systems through its \(\sigma^+\) and \(\sigma^-\) components. The coherent fields connect the lower levels of the system in a new, non-absorbing state. 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.

Alkali atoms in vapor phase depolarize after collision with the cell walls thus limiting the coherence lifetime of the non-absorbing state. In order to prevent such depolarization, vapor cells are covered with an anti-relaxation coating. The most popular is a paraffin coating which has been shown to allow up to 10 000 collisions before destroying the atom coherence [2]. In a Hanle configuration experiment the signal is very sensitive to a stray magnetic field. An advantage of the covered cells is that magnetic field gradients are reduced which narrows the resonance.

The CPT resonances in coated cells have some new features with respect to the uncoated ones. The long lifetime of the coherent state makes possible the transfer of coherence by multi-photon processes because of mixing of the contributions of polarization moments with different ranks. The competition

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between processes with different rates leads to new structures in the signal observed. They cannot be connected with one definite polarization moment [3] and may change in sign. Additional “bright” resonances appear in the Λ-level system, where only dark resonances are registered in an uncoated cell [4].

CPT in a coated cell has been investigated mainly in absorption [5]. In this work we investigate the coherent population trapping in a paraffin covered cell by means of the fluorescence signal.

2. Experimental

2.1. The set up

The experimental set-up is shown in figure 1(a). It consists of a single-mode diode laser oscillating at \( \lambda = 794.76 \, \text{nm} \), a Rb cell and a system for registration and control of the experiment. The laser beam passes through an optical isolator to avoid the optical feedback and a polarization rotator to change the laser polarization direction when necessary. The laser power is attenuated by means of grey filters. Then the laser beam passes through the vapor cell enclosed in a 3-layer magnetic shield which screens the laboratory magnetic field. The cell is paraffin coated, containing \(^{87}\text{Rb}\). The frequency of the laser 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 \( B \), created by a solenoid, is applied collinearly to the laser beam. The current through the solenoid is controlled by a PC.

![Figure 1. The experimental set-up (a); Λ-system in 5S1/2 \( \rightarrow \) 5P1/2 87Rb D1 formed by a linear polarized laser (b).](image)

The fluorescence from the cell is detected by a photodiode. Its dependence on the dc magnetic field \( B \) is stored in a two channel digital oscilloscope. Our experiment was performed on the \( 5S_{1/2} \rightarrow 5P_{1/2} \) transition (\( F_g=2 \rightarrow F_e=1 \)) of the \(^{87}\text{Rb} \) D1 line shown in figure 1(b). The linearly polarized laser beam through its \( \sigma^+ \) and \( \sigma^- \) components connects all sub-levels of the transition investigated into 3 Λ-systems, creating CPT resonance when the levels are degenerate, i.e. at zero magnetic field.

2.2. Experimental results

The CPT resonance in coated cells has a dual structure – a narrow resonance superimposed on a broad pedestal [5]. The pedestal is due to the time of flight and is determined by the laser beam radius. Interesting in view of applications is the narrow resonance part whose width is determined by the relaxation of the laser-created coherent state. Due to a difference of two orders of magnitude in the two widths they are recorded separately. In this work we investigate the narrow resonance. The magnetic field was scanned from -1 mG to +1 mG. The laser power \( P_{\text{las}} \) was varied from 5 \( \mu \text{W} \) to 500 \( \mu \text{W} \). The fluorescence signal was detected in two orthogonal directions. The resonance detected in the direction parallel to the \( E \) preserves its sign. At low \( P_{\text{las}} \) (less than 100 \( \mu \text{W} \)), the resonance detected in a direction orthogonal to \( E \) is “bright” indicating enhanced fluorescence around the zero point of the
scanned magnetic field. Above this value, the resonance sign changes and a “dark” resonance is detected in both directions. The CPT resonance sign and width in an uncoated cell does not depend on the observation direction and the laser power and is “dark” [6]. The width of the CPT resonance in fluorescence detected along the $E_{\text{int}}$ is twice as narrow. The resonances obtained in the orthogonal directions are shown in figure 2.

The possibility of controlling the transformation of CPT resonances in $\Lambda$-systems from “dark” to “bright” have been recently investigated theoretically [7,8]. Experimental results have been reported using two counter-propagating laser beams [9] in the presence of a magnetic field applied in a transverse direction.

![Figure 2](image1.png)

**Figure 2.** CPT resonance detected in direction perpendicular to $E$ (a); CPT resonance detected in direction parallel to $E$ (b).

3. Theoretical
The theoretical analysis of the CPT resonances obtained by means of a Hanle effect configuration and observed in fluorescence is based on the standard semiclassical description of the atomic system by the statistical operator $\hat{\rho}$ in density matrix representation. The irreducible tensor operator (ITO) formalism is used. The numerical calculations are based on the model presented in [10]. The task is to estimate the influence of the relaxation constants of the tensor components with different ranks on the shape and sign of the resonance detected in two directions, namely, parallel and orthogonal to the laser polarization vector.

The relaxation constants of the ground state $\gamma_g(\kappa)$ and the Raby frequency were varied taking into account that in cells with an anti-relaxation coating the transverse relaxation rate is much higher than the longitudinal relaxation rate $\gamma_g(2) >> \gamma_g(0)$. Figure 3 shows the signals in fluorescence for two orthogonal directions of observation – along and perpendicular to the vector of laser polarization $E$. They show qualitative agreement with the experiment. The resonance obtained in a direction perpendicular to $E$ is twice as narrow as the one obtained parallel to $E$. The sign of this resonance changes as the laser power is increases, while the resonance in a collinear observation preserves its...
sign. These predictions were experimentally confirmed in our experiment. The numerical calculations will be improved by taking into account the velocity distribution of the atoms, the Gaussian shape of the laser beam and the stray magnetic fields.

Conclusions
The features were investigated of the CPT resonance of the D1 $^{87}$Rb line obtained in fluorescence in a paraffin-coated cell. Transformation from black to bright resonance was observed depending on laser the power and the experimental geometry. The resonances obtained in fluorescence in two directions – parallel and perpendicular to the laser polarization vector, differ by a factor of two. The numerical calculations show qualitative agreement with the experiment.

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References
[1] Arimondo E 1996 Prog. Opt. 35 257-354
[2] Bouchiat M A and Brossel J 1966 Phys. Rev. 147 41
[3] Balabas M V et al 1999 JETP Lett. 70 198-202
[4] Gateva S, Alipieva E, Taskova E and Todorov G 2011 Proc. SPIE 7747 77470G
[5] Klein M, Novikova I, Phillips D F and Walsworth R L 2006 J. Mod. Opt. 53/16-17 2583-91
[6] Alipieva E, Gateva S, Taskova E and Cartaleva S 2003 Opt. Lett. 28/19 1817-9
[7] Chou H-S and Evers J 2010 Phys. Rev. Lett. 104 213602
[8] Braznikov A, Taichanachev and Yudin V 2011 Eur. Phys. J. D 10.1140/epjd/e2011-20112-6
[9] Kim S K, Moon H S, Kim K and Kim J B 2003 Phys. Rev. A 68 063813
[10] Huss A, Lammegger R, Windholz L, Alipieva E, Gateva S, Petrov L, Taskova E and Todorov G 2006 JOSA B 23/9 1729-36