A relation between electromagnetically induced absorption resonances and nonlinear magneto-optics in Λ-systems

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Recent work on Λ-resonances in alkali metal vapors (E. Mikhailov, I. Novikova, Yu. Rostovtsev, and G. R. Welch, quant-ph/0309171, and references therein) investigated a type of electromagnetically induced absorption resonance that occurs in three-level systems under specific conditions normally associated with electromagnetically induced transparency. In this note, we show that these resonances have a direct analog in nonlinear magneto-optics, and support this conclusion with a calculation for a J = 1 → J′ = 0 system interacting with a single nearly circularly polarized light field in the presence of a weak longitudinal magnetic field.

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Electromagnetically induced transparency (EIT, see, for example, Ref. [1] and references therein) is a phenomenon in which absorption of a light field by a resonant system is inhibited by the presence of an additional electromagnetic field. There is a close connection, discussed in detail in Ref. [2], between EIT and resonant nonlinear magneto- and electro-optical effects (NMOE), e.g., nonlinear Faraday rotation. Recently, a counterpart to EIT, electromagnetically induced absorption (EIA), has also garnered significant experimental and theoretical attention (see, for example, Refs. [3, 4, 5] and references therein). This effect is also closely related to NMOE. For example, consider optical pumping on a F → F′ = F + 1 transition, a situation in which EIA may occur [4]. In studies of nonlinear magneto-optical rotation (NMOR) on the Rb D2-line, the sign of optical rotation was seen to change as the light frequency is scanned across an F → F′ transition group [see Fig. 15(a) in the review paper [2]]. This dependence results from the fact that, because of EIA, rotation due to a F → F + 1 transition is opposite in sign to that due to F → F′ = F − 1, F transitions, for which EIA does not occur [2, 3, 5].

A type of EIA resonance exhibited by a three-level Λ-system [Fig. 1(a)] interacting with a bichromatic light field was recently investigated both experimentally and theoretically [3, 4, 5]. Experiments were carried out with 87Rb atoms contained in vapor cells with and without buffer gas. The two ground-state hyperfine components of 87Rb were used as the two lower states |b⟩ and |c⟩. Two phase-coherent copropagating laser fields tuned near the D1 transition were used as the drive and the probe fields.

The intensity of the probe field was analyzed at the output of the cell as a function of the two-photon (Raman) detuning δ. For a buffer-gas-free cell, EIT, manifesting itself as a peak in the output probe-field intensity at near-zero two-photon detuning, was observed at all one-photon detunings Δ. However, for cells with buffer gas (for example, 30 torr of Ne), very different behavior was seen. For small one-photon detuning Δ, EIT was observed, as in the buffer-gas-free case. At larger values of Δ, the resonance in two-photon detuning became asymmetric, eventually turning into an EIA resonance. A rather striking feature of the EIA resonance is that it leads to a significant reduction of the transmitted probe-field intensity on the two-photon resonance under conditions where there is very little absorption of the probe field in the absence of the drive. The au-
authors of Refs. [4, 10] found that, for the EIA effect to occur, the buffer-gas collisions must broaden the optical transition to the point that the homogeneous width is comparable to or exceeds the Doppler width.

The EIT resonance observed for small one-photon detuning is the standard coherent population trapping effect: at zero two-photon detuning the drive and probe fields combine coherently to optically pump the atoms into a state that does not couple to the combined field. The EIA resonance, in contrast, is observed when the light is far detuned from the one-photon resonance. Under two-photon (Raman) resonance conditions (when the two-photon detuning equals the differential ac Stark shift), atoms are transferred from the state that interacts with the drive light to the state that interacts with the probe light. This causes increased absorption on the probe transition [11, 12].

In this note, we point out the connection between these EIA resonances and a nonlinear magneto-optical effect arising when a single elliptically polarized light field interacts with atoms in the presence of a weak magnetic field applied along the light propagation direction. We consider a \( J = 1 \rightarrow J = 0 \) transition [Fig. 1(b)] and associate the states \( |b\) and \( |c\) with the \( M = -1 \) and \( M = 1 \) Zeeman sublevels of the \( J = 1 \) ground state, and the two components of the incident light field with the left- and right-circular polarizations of a monochromatic light field with wavelength \( \lambda \). The resultant light field corresponds to elliptically polarized light. Since one circular component, say the right circular one, is much weaker than the other, the light deviates only slightly from pure circular polarization. In other words, the angle of ellipticity \( \epsilon \), equal to the arctangent of the ratio of the minor to the major axis of the polarization ellipse, is close to \( \pi/4 \). The relative phase of the two circular components, which defines the angle of orientation \( \varphi \) of the major axis of the polarization ellipse, can have any value. In order to complete the analogy between the two problems, we need to introduce the analog of the two-photon detuning \( \delta \). This is done by applying a longitudinal magnetic field that splits the Zeeman sublevels by the Larmor frequency \( \Omega_L \) [Fig. 1(b)].

Studies of magneto-optical effects are commonly done by measuring output polarization rather than transmission of a field component. To relate the two in this case, we write the total complex optical field \( \hat{E} \) (assumed to be propagating in the \( \hat{z} \) direction) as

\[
\hat{E} = E_0 \left( (\cos \epsilon \cos \varphi - i \sin \epsilon \sin \varphi) \hat{x} + (\cos \epsilon \sin \varphi + i \sin \epsilon \cos \varphi) \hat{y} \right) e^{i(\omega t - kz - \phi)},
\]

where \( E_0 \) is the electric field amplitude and \( \phi \) is the overall phase. In the spherical tensor basis, \( \hat{e}_\pm = \mp (\hat{x} \pm i\hat{y})/\sqrt{2} \),

\[
\hat{E} = -E_0 \left( e^{i\varphi} \sin \epsilon \hat{e}_- + e^{-i\varphi} \cos \epsilon \hat{e}_+ \right) e^{-i(\omega t - kz - \phi)} = \left( E_- \hat{e}_- + E_+ \hat{e}_+ \right) e^{-i(\omega t - kz)},
\]

where we have defined \( \epsilon' = \epsilon - \pi/4 \). The intensity \( I_- \) of the right circular component is given by

\[
I_- = \frac{c}{8\pi} E_- E_-^* = \frac{c}{8\pi} E_0^2 \sin^2 \epsilon',
\]

and a differential change in intensity over a distance \( dz \) is given by

\[
\frac{1}{I_-} \frac{dI_-}{dz} = \frac{2 \epsilon'}{\epsilon'} \frac{dE_0}{dz} + \frac{2}{E_0} \frac{dE_0}{dz},
\]

for small \( \epsilon' \). Under conditions of saturated absorption, such as considered here, the term containing \( dE_0/dz \) in Eq. 4 can be neglected. The original problem is thus analogous to the determination of the magnetically induced change of ellipticity of nearly circularly polarized input light.

The effect on the input light polarization can be found using standard density matrix techniques (a description of our approach is given in Ref. 2). In order to reproduce the basic phenomenon—the change from EIT to EIA with the increase of the one-photon detuning—it is sufficient to consider the Doppler-free case. In fact, as pointed out in Ref. [10] and as discussed below, Doppler broadening leads to a suppression of the effect of interest. (This is the reason that buffer gas is required to observe the effect in the Doppler-broadened case: by increasing the homogeneous width of the optical transition so it becomes comparable to the Doppler width, it effectively “turns off” the suppression.)

The atomic Hamiltonian is

\[
H \simeq \begin{pmatrix}
-\Omega_L & 0 & -\Omega_R \\
0 & 0 & 0 \\
-\Omega_R & -\epsilon'\Omega_R & -\Delta
\end{pmatrix},
\]

under the rotating wave approximation, where \( \Omega_L \) is the Larmor frequency (Fig. 1), and \( \Omega_R = \|d\||E_0|/(2\sqrt{6}) \) is the Rabi frequency, where \( \|d\| \) is the reduced dipole matrix element. We find the steady-state density matrix for a medium of atomic density \( N_0 \) evolving according to \( H \), assuming radiative decay of the upper state to the ground state at rate \( \gamma_0 \), and much slower relaxation and incoherent repopulation of the ground state, due to atoms entering and leaving the interaction volume, at rate \( \gamma \). From
Figure 2: Change in ellipticity [Eq. (4)] of almost completely circularly polarized (|\epsilon'| \ll \pi/4) light as a function of normalized Larmor frequency $x = \Omega_L/\gamma$ at various normalized light detunings $D = \Delta/\gamma_0$. The value of the saturation parameter is $\kappa = 10$ and we assume $\gamma \ll \gamma_0$. In the bottom plot, at zero detuning, the EIT feature is seen inside the broad absorption line that would exist in the absence of the drive field. As the detuning is increased, the EIA feature appears.

This figure shows the change in the sign of the two-photon resonance as the one-photon detuning is increased (analogous to the transition from EIT to EIA). As in the experiment presented in Ref. [10], the EIA resonance peak is shifted with respect to the EIT peak because of the ac-Stark shift produced at nonzero one-photon detuning. Also, the EIT peak is broader than the EIA peak due to larger power broadening at one-photon resonance.

Figure 2 illustrates why Doppler broadening suppresses the EIA effect: since the nonzero magnetic field strength (two-photon detuning) at which the EIA feature occurs depends on the light (one-photon) detuning, the feature is washed out by Doppler averaging. Note that in Fig. 2 the change in ellipticity is always zero at zero magnetic field. This is because of the fact that, assuming ground-state relaxation due to the transit of atoms through the light beam, as we have here, a $1 \rightarrow 0$ transition has the unusual property of producing no change in light polarization in the absence of a magnetic field [12, 14]. (This is the same reason that, in a standard EIT experiment, the “dark resonance” always occurs at zero two-photon detuning no matter the relative power of the drive and probe fields [11].)

The analogy presented here underscores the fact that despite the remarkable feature of the EIA resonances observed in Refs. [9, 10], namely that there is significant reduction of the transmitted probe-field intensity on the two-photon resonance under conditions where there is very little absorption of the probe field in the absence of the drive, the EIA resonance is not actually associated with increased overall absorption. Rather, a change in ellipticity is caused by the transfer of the field between the circular polarizations. A similar interaction between strong and weak (actually, vacuum) polarization modes is discussed in Ref. [15].

We hope that the analogy between Λ-resonances with a bichromatic light field and the nonlinear magneto-optical effects will prove to be fruitful for qualitative understanding of both phenomena and serve as a guide to further experimental and theoretical work. Such a scenario has already been played out in the study of light-propagation dynamics, in which a similar analogy [16] led to light-propagation experiments with monochromatic light and Zeeman sublevels that were more straightforward than their counterparts involving bichromatic light fields and hyperfine sublevels (see Refs. [17, 18] for reviews).

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