Electromagnetically induced transparency in a V-system with $^{87}\text{Rb}$ vapour in the hyperfine Paschen-Back regime

Clare R Higgins* and Ifan G Hughes

Department of Physics, Durham University, South Road, Durham, DH1 3LE, United Kingdom

E-mail: clare.r.higgins@durham.ac.uk

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Abstract

We observe electromagnetically induced transparency (EIT) in a V-system in a thermal rubidium-$^{87}$ vapour in the hyperfine Paschen-Back regime, realised with a 0.6 T axial magnetic field. In this regime energy levels are no longer degenerate and EIT features from different initial states are distinct, which we show produces a much cleaner feature than without a magnetic field. We compare our results to a model using the time-dependent Lindblad master equation, and having averaged over a distribution of interaction times, see good qualitative agreement for a range of pump Rabi frequencies. Excited state decay into both ground states is shown to play a prominent role in the generation of the transparency feature, which arises mainly due to transfer of population into the ground state not coupled by the probe beam. We use the model to investigate the importance of coherence in this feature, showing that its contribution is more significant at smaller pump Rabi frequencies.

Keywords: V-systems, $^{87}$Rb, thermal vapours, electromagnetically induced transparency

(Some figures may appear in colour only in the online journal)

1. Introduction

Electromagnetically induced transparency (EIT) is an optical phenomenon involving three quantum states coupled by two optical fields (laser beams). In an absorbing medium, a transparency window in the transmission of a weak probe beam on one transition is induced by the presence of a strong pump beam on another transition [1]. Throughout the text we refer to these beams as ‘pump’ and ‘probe’. EIT has been widely studied and has potential applications in precision magnetometers [2–4], slow light generation [5, 6], quantum information [7, 8], and atomic clocks [9]. There are three possible configurations of EIT: V; lambda; and ladder [10]. V-EIT is the least studied of these because there is no stable dark state [11], as both of the singly coupled states are excited states and can decay to the ground state. Nevertheless, V-EIT has been extensively studied [6, 12–25], and provides an interesting testing ground for ascertaining the relative importance of coherent and incoherent mechanisms in the generation of the transparency window [16, 26, 27].

One of the main obstacles to overcome in modelling and understanding V-EIT in thermal vapours is the complexity introduced by the overlapping spectral lines, as a consequence of the degeneracies of the magnetic sub-levels and the excited-state hyperfine splitting being less than the Doppler width of the probed transition. To circumvent these difficulties, we use the hyperfine Paschen-Back regime [28–35] where the energy levels are non-degenerate. A 0.6 T magnetic field used with $^{87}$Rb vapour on the D1 and D2 lines leads to isolated transitions separated by more than their Doppler width. Previous work has shown that operating in this regime allows simplified energy-level schemes and theoretical models, leading to good agreement between theory and experiment [36–39].
The natural linewidths (linear) of states 2 and 3 are 6.0 MHz and 5.7 MHz, respectively. These are split along the direction of propagation of the laser beams. The experimental setup is shown in figure 2. We use a 2 mm long 98\% $^{87}$Rb vapour cell in a magnetic field, parallel to the laser propagation direction, of 0.6 T, produced by two cylindrical ‘top hat’ magnets. The orthogonally linearly polarised 795 nm and 780 nm beams are combined on a polarising beam splitter (PBS). A quarter waveplate transforms the polarisation to left-hand circular and right-hand circular respectively. A lens of focal length 200 mm focusses the beams to waists of $(100 \pm 5) \mu m \times (78 \pm 5) \mu m (780 nm)$ and $(65 \pm 5) \mu m \times (90 \pm 5) \mu m (795 nm)$ inside the cell. We aim to overlap the beams as completely as possible inside the cell by optimising the EIT feature, however due to the slight shape difference a perfect overlap is not possible. After the cell an interference filter removes pump light, and the probe transmission spectrum is measured on a photodiode (PD). We have a strong, resonant 795 nm pump, and a weak 780 nm scanning probe. We use a vapour temperature of 80 °C; at lower temperatures the signals are smaller, and at higher temperatures the absorption saturates and the features are distorted.

4. Experimental results

Figure 3 shows the advantage gained by using the hyperfine Paschen-Back regime. The top panels show theoretical D2 line spectra without a magnetic field (red) and with a 0.6 T field (blue). The two peaks used in the lower panels are shown highlighted. In the lower panels dotted lines are probe beam only; solid lines are when the pump beam is introduced. The probe only features have a Voigt profile with FWHM of $\sim 550$ MHz at 80 °C. The profile is dominated by its Gaussian component, which is due to the Doppler effect; atoms at finite temperature travel at a range of velocities which each absorb at a frequency displaced from resonance, given by $\omega = \omega_0 + kv$. Here $\omega$ is angular frequency, $\omega_0$ is resonance angular frequency, $k$ is wavenumber and $v$ is the velocity component along the direction of propagation of the laser beams. The left panel shows experimental EIT features with no magnetic field, which shows contributions from several transitions. The right
Figure 3. Upper panels: theoretical scans over D2 features without magnetic field (top, red), and with 0.6 T magnetic field (second panel, blue). Shaded rectangles show where the experimental spectra in the lower panels fit in the spectra. In the lower panels dotted lines are probe beam only, solid lines are when the pump beam is introduced. Left: experimental V-EIT feature with no magnetic field. Many hyperfine sublevels contribute producing a messy feature. Right: experimental feature in 0.6 T magnetic field. Energy levels are separated by more than the Doppler width so a single clean feature is seen.

shows the feature in a 0.6 T field, where one clean feature is visible. Both features are produced in the same cell, with the same laser powers.

Figure 4 shows a scan over the two \( m_I = 3/2 \) D2 \( \sigma_+ \) absorption lines in a 0.6 T magnetic field. The black trace is a probe only scan, and the red traces shows the effect of adding a 20 \( \mu \)W pump beam. Here, and throughout, we use a probe power of 0.1 \( \mu \)W. All the optical power values reported throughout this work are measured before the vapour cell, and have an error of \( \pm 5\% \). We see that two different features appear; on the \( m_J = -1/2 \) \( \rightarrow \) \( m_J = +1/2 \) peak (left) we see a narrow transmission feature, characteristic of EIT. The states coupled at this point in the scan are shown in the diagram above. Notably the probe is coupling out of \( |1\rangle \), the upper ground state. On the \( m_J = -1/2 \) \( \rightarrow \) \( m_J = +1/2 \) peak (right) there is an enhanced absorption feature. In this case, as shown in the lower diagram, the probe couples out of \( |0\rangle \), the lower ground state. This state is populated by spontanteous decay from \( |3\rangle \), which is itself populated by the strong pump beam.

Following on from figures 4 and 5 shows the effect of tuning the pump beam to different \( m_I \) transitions. The black trace in (a) shows a scan of the 780 nm probe over the D2 absorption lines at 0.6 T, with no pump. At 0.6 T, \( m_J \) and \( m_I \) are good quantum numbers. For \( ^{87}\text{Rb} \), \( I = 3/2 \), therefore there are four possible values for \( m_I \). The spectrum shows two sets of four transitions; in set 1 (set 2) all four transitions are between states with initial \( m_J = +1/2 \) (\( -1/2 \)) and final \( m_J = +3/2 \) (\( +1/2 \)). Inside each set, each transition has a different \( m_I \) value, as labelled in the figure. The four coloured traces show the probe transmission when the pump is tuned to the correspondingly coloured transition in (b). It is evident that when the pump is coupled to a particular \( m_I \) level in the upper ground state, \( |1\rangle \), there is a transmission window in the probe absorption peak coupling out of that level (set 1 transitions). There is also a corresponding enhanced-absorption feature when the probe instead couples out of the lower ground state with the same \( m_I \) value, \( |0\rangle \) (set 2 transitions). The EIT features shown in figure 5 have an FWHM of \( (39 \pm 3) \text{ MHz} \).

5. Model

Atomic systems can be modelled using the Lindblad-master equation [10],

\[
\frac{d\rho}{dt} = -\frac{i}{\hbar}[H, \rho] + L,
\]  

(1)
which describes the evolution of the density matrix, $\rho$,

$$
\rho = \left( \begin{array}{cccc}
\rho_{00} & \rho_{01} & \rho_{02} & \rho_{03} \\
\rho_{10} & \rho_{11} & \rho_{12} & \rho_{13} \\
\rho_{20} & \rho_{21} & \rho_{22} & \rho_{23} \\
\rho_{30} & \rho_{31} & \rho_{32} & \rho_{33}
\end{array} \right),
$$

of the system. The diagonal elements, $\rho_{n n}$, are the population in each state, and the off-diagonal elements, $\rho_{ab}$, are the coherences between states. The system Hamiltonian, $H$, in the rotating wave approximation, has state detunings, $\Delta_{ab}$, on the diagonals, and Rabi frequencies, $\Omega_{ab}$, coupling the states on the off-diagonals. The Hamiltonian corresponding to the system in figure 1(a) is

$$
H = \frac{\hbar}{2} \left( \begin{array}{cccc}
0 & 0 & 0 & 0 \\
0 & 0 & \Omega_{12} & \Omega_{13} \\
0 & \Omega_{12} & -2\Delta_{12} & 0 \\
0 & \Omega_{13} & 0 & -2\Delta_{13}
\end{array} \right),
$$

while the Hamiltonian for figure 1(b) is

$$
H = \frac{\hbar}{2} \left( \begin{array}{cccc}
0 & 0 & 0 & 0 \\
0 & 0 & 0 & \Omega_{02} \\
0 & \Omega_{02} & 0 & \Omega_{13} \\
\Omega_{13} & 0 & -2\Delta_{02} & 0 \\
0 & \Omega_{13} & 0 & -2\Delta_{13}
\end{array} \right).
$$

As we use a $V$ system in a co-propagating geometry, we incorporate the Doppler effect into the model by setting $\Delta_{\text{pump}} \rightarrow k_{\text{pump}} \omega$ and $\Delta_{\text{probe}} \rightarrow k_{\text{probe}} \omega$. Prominent EIT features are observed with velocity groups where the residual two-photon doppler broadening ($k_{\text{pump}} - k_{\text{probe}} \omega < \Omega_{\text{pump}}$) have been and they in particular coherent states. The Hamiltonian for figure 1(b) is

$$
H = \frac{\hbar}{2} \left( \begin{array}{cccc}
0 & 0 & 0 & 0 \\
0 & 0 & 0 & \Omega_{02} \\
0 & \Omega_{02} & 0 & \Omega_{13} \\
\Omega_{13} & 0 & -2\Delta_{02} & 0 \\
0 & \Omega_{13} & 0 & -2\Delta_{13}
\end{array} \right).
$$

Decays between states are included in the Lindblad dissipator term, $L$, given by

$$
L = \sum_n \frac{1}{2} [2C_n \rho C_n^\dagger - (\rho C_n^\dagger C_n + C_n C_n^\dagger \rho)],
$$

which is a sum over all decay modes, $n$, where $C_n = \sqrt{\gamma_n} A_n$ are collapse operators and $A_n$ are operators which couple the environment to the system with rate $\gamma_n$. For our system this means $C_{ab} = \sqrt{\gamma_n} \rho_{ab} \langle b | [a] | n \rangle$.

We solve the Lindblad master equation numerically for our four-level system. We model with a probe beam Rabi frequency of 0.96 MHz on the $m_J = +1/2 \rightarrow m_J = +3/2$, and, due to the differing dipole matrix elements of the transitions, a Rabi frequency of 0.55 MHz on the $m_J = -1/2 \rightarrow m_J = +1/2$ transitions. This puts us in the weak probe regime. We use a range of pump Rabi frequencies to produce a range of features which span those seen experimentally. This range is 2 MHz–100 MHz. The pumping transition we use is open, as the excited state, $|3\rangle$, can decay to both $m_J$ ground states, $|0\rangle$ and $|1\rangle$, as depicted in figure 1(a). The pump and probe only couple to $|1\rangle$ so in the steady-state solution all the population ends up in the uncoupled ground state, $|0\rangle$, resulting in no absorption. We therefore have to use the time-dependent solutions. We have beams with an average $1/\epsilon^2$ radius of $(83 \pm 5) \mu$m, from which we calculate the in-beam time-of-flight distribution, using the transverse velocity distribution [41–43]. For a given probe detuning the solutions are summed over all longitudinal velocity contributions [44]. The absorption profile is calculated from the imaginary part of the relevant coherence, which is a suitably weighted average of the result at each time step, and we use the Elescu code [45] to calculate the linestrengths.

6. Comparison with experiment

Figure 6 shows the effect of changing pump power/Rabi frequency on the transmission and absorption features, with experimental results in the upper panels and model predictions in the lower panels. Optical power is related to Rabi frequency by the area of the beam and the dipole matrix element of the transition. Here, as we are not plotting theory and experiment on the same axis we use optical power for experiment, and Rabi frequency for theory. We see good qualitative agreement, with both the narrow transmission and the extra absorption feature correctly predicted, though the features are slightly narrower in theory than in experiment. We attribute the
Figure 6. The effect of changing the 795 nm pump power on the induced transparency and enhanced absorption features on the $m_I = +3/2$ transitions of the D2 (780 nm, 0.1 μW) spectrum. Upper: experimental transmission spectra with changing pump powers, with values of in μW of 1 (dark), 5, 10, 50, 100, 500, 1000 (light). These correspond to Rabi frequencies in the range 2 MHz–100 MHz. The EIT features shown in the top left panel have FWHM ranging from $(21 \pm 3)$ MHz (lowest pump power) to $(247 \pm 5)$ MHz (highest pump power). Lower: modelled transmission spectra with pump Rabi frequencies in MHz of 1 (dark), 3, 10, 20, 50, 100, 300 (light). The range of Rabi frequencies was chosen to straddle the range of features seen in the experimental data; they are not calculated equivalents.

Figure 7. A comparison of experimental and modelled results. Black dashed line is experimental with 10 μW pump, which converts to an average linear Rabi frequency in the beam of 15 MHz. Two theory traces are plotted, chosen to fit the tip of the transparency feature (red) and the bottom of the absorption feature (blue). They have linear Rabi frequencies of 5.5 MHz and 12.0 MHz respectively, which are close to our experimental value. It is clear that for this model a pump Rabi-frequency cannot be chosen which fits well to all aspects of the feature; we must choose one or the other.

Figure 8. Plot showing the absolute value of the coherence between excited states $|\rho_{23}|$, as extracted from the model, and the corresponding probe transmission. On each plot we compare a closed system (dashed lines), and the open system of our experiment (solid lines), for linear pump Rabi frequencies as shown in the legend.

7. How significant is the coherent effect?

A relevant question in three-level-systems is whether the spectral features are caused by coherent or incoherent effects [11, 16, 26]. The presence of a prominent enhanced absorption
feature on the transition out of the non-pump-coupled ground state, \( |0\rangle \), is evidence that a significant part of the transmission feature does not arise from a coherent EIT effect, but instead from population transfer to a different (and uncoupled) ground state via velocity-selective optical pumping. However, the coherent process is still present, and we can use the model to see this. The density matrix element \( \rho_{23} \) is the coherence between \([2]\) and \([3]\), the excited states of our system. Figure 8 compares the transmission (lower panel) and corresponding coherence (upper) for a closed system—meaning no decays into \( |0\rangle \)—(dotted lines) and our open system (solid lines). A range of pump Rabi frequencies are plotted and coloured according to the legend. We see that as pump Rabi frequency increases, the difference between the coherences in the closed and open systems increases, and that in our system, coherence increases as Rabi frequency increases up to a point (approx. 20 MHz), above which coherence decreases. We also note that for a given pump Rabi frequency the closed system coherence is greater than the open system coherence, while the open system transmission is greater than the closed system transmission. This shows that in our open system the coherence is a small, but present, cause of the feature and that as the pump Rabi frequency increases, its proportional contribution decreases.

8. Conclusions and outlook

In conclusion, we have observed a clean, narrow EIT feature in a V-system and the concomitant enhanced absorption. We see that the EIT feature has contributions from a coherent process, and an incoherent optical pumping process. The incoherent contribution occurs because of the allowed decay from the excited states to both ground states, and is the cause of the enhanced absorption feature. Our theoretical model captures all of the relevant processes, and gives insight into the role of coherence in explaining the observed narrow spectral features. The theoretical treatment is greatly simplified because the experiment was conducted in the hyperfine Paschen-Back regime, leading to distinct non-overlapping resonances.

In this work the Doppler mismatch is small, however the clean system presented here would easily allow investigation of the effect of large mismatches, for example the 5S–5P S5–6P V-system in rubidium [15, 25], and could be the subject of further study. Another interesting aspect of this work is the sensitivity of the V-EIT spectra to collisional linewidths. Indeed, the study of isolated resonances in the hyperfine Paschen-Back regime could provide a more sensitive spectral measurement of alkali metal–noble gas collisions, and will be the subject of future work.

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Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI: doi:10.15128/r2t148fh16h.

ORCID IDs

Clare R Higgins https://orcid.org/0000-0002-9835-8478
Ifan G Hughes https://orcid.org/0000-0001-6322-6435

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