We investigate electromagnetically induced transparency (EIT) and electromagnetically induced absorption (EIA) in rubidium vapor using a scanning magnetic field co-aligned with the laser propagation direction. Sub-natural line width features appear at zero magnetic field. Criteria for deciding whether to expect EIT or EIA are discussed. Particular attention was given to identification and suppression of spurious signals rising from polarization impurity and residual stray magnetic fields. In the presence of a second strong, coherent laser beam we observed that the EIT signal inverts into an EIA signal. We provide a simple qualitative explanation for this “sign reversal”. Our work helps us evolve a clear understanding of the intriguing physics behind coherently prepared atomic media.
A Thesis

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Dedication

To my loving husband William Wilson IV,

and my parents Allen and Cindy Day.
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Chapter 1

Introduction

1.1 Motivation

The phenomena known as electromagnetically induced transparency and absorption (EIT/EIA) has been studied for over twenty years [1]. Existing technologies such as the precision of the atomic clocks and sensitive magnetometers are being drastically improved by the use of EIT [2-4]. There are new fundamental effects such as “production of ultraslow light”, made possible by the fact that EIT is often accompanied by a million-fold increase in refractive index of the atomic vapor. [5] New technologies in the field of quantum information are currently being pursued; such as “building of quantum memory” where light may be slowed and essentially “frozen” inside the atomic medium only to be released at will. [6]

The motivation behind our current experiment is to understand the basic physics of EIT/EIA. In the literature [7] there are conditions that look at the atomic configuration and based on these conditions EIT or EIA is expected for a particular hyperfine transition. The conclusion that leads to these conditions was made using Zeeman EIT/EIA using one laser. In our data we can show that by adding a second strong laser beam which is coherent with the first, we can transform an EIT signal for that transition into EIA signal.

Below we start with an introduction to the basic terminology of EIT, EIA and sign reversal, and review the background literature.

1.2 EIT, EIA, and Sign Reversal: Basic Terminology

Electromagnetically induced transparency (EIT) is a phenomenon that occurs when two close-lying ground states $|g_1\rangle$ and $|g_2\rangle$ are excited to the same upper-energy level $|e\rangle$ as shown in fig1.1A by two lasers of frequency $\omega_{l1}$, and $\omega_{l2}$, is referred to as the probe the coupling beams which are resonant with the $|g_1\rangle \rightarrow |e\rangle$ and $|g_2\rangle \rightarrow |e\rangle$ transition respectively $|g_1\rangle$ and $|g_2\rangle$. This is known as a $\Lambda$ (or lambda) system. The simultaneous absorption probability amplitudes of the two lasers from the ground states to the common excited state may destructively interfere under certain conditions. At that point the atom
is in a “dark” state i.e. a non-absorbing superposition of the ground states. This makes the atom appear transparent to resonant the laser beams. \[8\]

The EIT signal appears as a narrow peak as seen in fig1.1C. This graph is created by keeping \(\omega_{L1}\) frequency locked (commonly referred to as the coupling) while \(\omega_{L2}\) (the probe) is swept about the frequency of the coupling laser. The probe transmission spectrum is shown. The EIT signal peaks when the probe detuning from the coupling laser is zero, because then the two excited pathways from \(|g_1\rangle\) and \(|g_2\rangle\) to \(|e\rangle\) are identical thus maximizing interference.

Electromagnetically induced absorption (EIA) is basically the opposite of EIT. In the case of EIA there are two close-lying excited states that yield two stimulated emission pathways to the same ground state as shown in fig1.1B. This is known as a V-system. A superposition of excited states is created, which is unable to emit into the ground state via stimulated emission. The atom eventually relaxes into the ground state via spontaneous emission, thus ultimately destroying the superposition of excited states. For this EIA was demonstrated by the Akulshin group in 1998 \[9\]. The spectrum for EIA is shown in fig1.1D with induced absorption peaks. EIA manifests as a peak in absorption because stimulated emission is redistributed as spontaneous emission, thus causing these photons to go “missing” when the transmitted laser beam is detected. The EIT and EIA resonances appear with sub-natural line widths when magnetic field is zero. This is because while the spontaneous emission bandwidth determines the natural line width, the EIT line width is determined by the much narrower stimulated emission bandwidth. For this reason, EIT find great application in magnetometry \[10\], and quantum information processing \[11\].


To achieve EIT (EIA) the ground (excited) states of the atom must be close-lying as seen in fig 1.1A,B. The traditional setup the probe and coupling beams emits from two separate lasers. These lasers must be perfectly co-aligned and phase locked. Without phase lock the lasers would not give rise to processes that are coherent with one another. The coupling laser has a fixed frequency and the probe beam is swept about the frequency of the coupling laser, whereas the coupling beam is a stronger. The probe transmission spectrum is observed.

Besides the traditional setup described above for demonstration of EIT and EIA, there is an alternative method which achieves the same basic goals. This method known as Zeeman EIT, utilizes a scanning B-field to generate close-lying energy levels required for EIT and EIA. In this case, one way exploit different polarizations of the same laser beam to effectively generate two phase locked, co-aligned beams for EIT/EIA. [7]
1.2.2 Criteria for EIT verses EIA: Zeeman EIT

Dancheva [7] uses Zeeman EIT to define whether one should expect an EIT or EIA when a laser is locked to a particular atomic transition. EIT is expected when the lower magnetic sublevels ($F_g$) are greater than or equal to upper magnetic sublevels ($F_e$). As for EIA, it is expected when $F_g$ is less than $F_e$.

1.2.3 Sign Reversal in EIT and EIA

What is sign reversal? In the literature, people use the phrase “sign reversal” to describe the conversion of an EIT (or EIA) signal into the other, by controlling the relative intensity of the probe and coupling lasers [11]. This is an interesting occurrence, because one expects from the criteria in section 1.2.2 that EIT or EIA occurs, solely determined by the specific transition. For example $F_g=2$ to $F_e=1$ shown in fig 1.2, clearly there are three $\Lambda$-systems and only one $V$-system. According to the criteria this should be an EIT. However, this is only true for one beam, for sign reversal there are two beams. The additional beam causes a shift in the atomic population. This creates a dominant $V$-system (shown in the atomic configuration as two red arrows) creating an EIA.

Figure (1.2): $^{85}\text{Rb } F_g=2 \rightarrow F_e=1$; EIT for one beam, with two beams a dominant $V$-system (shown in red) appears creating an EIA.
1.3 Overview of Thesis

Chapter two I will discuss in detail Zeeman EIT and EIA. I will examine in detail criteria for EIT and EIA in Zeeman EIT and EIA. I review over a three level atomic systems and then take a look at a multi-level atom. Then I will discuss the reasoning for sign reversal for orthogonal linear polarizations.

Chapter three contains a depiction of our optical layouts. I will go over procedures and precautions for alignment, polarization checks, and magnetic field detection. Then I will discuss methods for correcting polarization impurities and stray magnetic fields.

Chapter four contain data that was collected from our setup. The data is displayed to show transmission as a function of the scanned magnetic field. Each data set was taken using orthogonal linear polarization and low intensities.
Chapter 2

EIT, EIA, and Sign Reversal in Multi-Level Atoms

In chapter two I will discuss Zeeman EIT and EIA. Also discuss the criteria for Zeeman EIT and EIA in further detail than what was provide in chapter 1. This chapter I will cover the realistic case of multi-level atoms for our experiment. Lastly I will go over a preliminary argument for sign reversal in the case of orthogonal linear polarization.

2.1 Zeeman EIT/ EIA
Recall in section 1.2.1 we introduced an alternative method for producing EIT where we scanning magnetic, known as Zeeman EIT. An important advantage of Zeeman EIT is that a single laser beam without having to phase-lock or co-aligning two separate lasers. The atomic vapor is placed in an applied magnetic field propagating in the same direction as the linearly polarized laser. In the literature this particular arrangement of light and magnetic field is referred to as the Hanle configuration \[7\]. This magnetic field causes a Zeeman splitting, shown in fig 2.1C, B for the case of a simple two level system \( F_g=1 \rightarrow F_e=0 \). The applied magnetic field creates three ground states. Here \( m_f = 1 \) and \( m_f = -1 \) raise and lower by an amount that is linearly proportional to the magnitude of the magnetic field. The zero levels in the ground and excited states do not shift. The linearly polarized laser appears as a superposition of left and right circularly polarized \( \sigma^+ \) and \( \sigma^- \) beams. One of the main advantages of using the Zeeman EIT/EIA is you no longer have to phase-lock two lasers. This makes this setup more stable and simpler to use. However there are some disadvantages. The main disadvantage is the applied magnetic field sweeps the Zeeman sublevels, effectively sweeping the frequency of any laser (or lasers) that passes through, so you no longer have control over which laser is swept.
As mentioned earlier in section 1.2.2 Dancheva made three important conclusions about when to expect EIT and when to expect EIA. First, for a given hyperfine transition \( F_g \rightarrow F_e \) in the presence of a magnetic field, if the number of Zeeman ground sub-levels exceed the Zeeman excited sub-levels the system resembles the \( A \)-system shown in Fig.1A, leading us to expect EIT. Second, if the number of excited Zeeman sub-levels exceeds the ground Zeeman sub-levels we have a situation that resembles the \( V \)-system shown in Fig.1B, leading us to expect EIA. Third; when the ground and excited Zeeman sub-levels are equal we expect to see EIT, because even though this particular situation is a combination of \( \Lambda \) and \( V \)-systems, spontaneous emission destroys the excited state coherence in the \( V \)-system. However the coherence in the \( \Lambda \)-system is more robust and persists. \[7\] Note that Dancheva’s work suggests that whether EIT or EIA occurs, depends only upon the Zeeman structure of the ground and excited states of the specific transition. It is not at all obvious how an EIA is obtained in a transition where EIT is predicted using Dancheva’s criteria.
2.2 Zeeman EIT/ EIA Multi- Level Atoms

However sec 2.1 does not tell the complete story. In reality when we have our laser tuned to a particular hyperfine transition, we end up exciting other close lying hyperfine transitions. This is illustrated in fig.2.2A.

Consider, the laser tuned near resonance with the $F_g=3 \rightarrow F_e=4$ transition in $^{85}$Rb. Note that the laser is not far from resonance with the neighboring hyperfine transitions $F_g=3 \rightarrow F_e=2, 3$. The logic from the previous paragraph would predict EIT for the $F_g=3 \rightarrow F_e=2$ and $F_g=3 \rightarrow F_e=3$ transitions, and conversely EIA for the $F_g=3 \rightarrow F_e=4$ transition.

Due to the simultaneous excitation of all three hyperfine transitions $F_g=3 \rightarrow F_e=2, 3, 4$ one may ask, what is the net effect? The answer depends on the relative strengths of the $F_g=3 \rightarrow F_e=2, 3, 4$ transitions. The oscillator strengths for each transition in $^{85}$Rb and $^{87}$Rb are shown in fig.2.2B. In the case of the $F_g=3 \rightarrow F_e=2,3,4$ transition in $^{85}$Rb we see that the $F_g=3 \rightarrow F_e=4$ is stronger than the sum of $F_g=3 \rightarrow F_e=2,3$. Therefore we expect the net effect form exciting $F_g=3 \rightarrow F_e=2, 3, 4$ transition to be an EIA.

Consider another example $^{85}$Rb $F_g=2 \rightarrow F_e=1,2,3$. The $F_g=2 \rightarrow F_e=1$ transition would yield an EIT feature, as would the $F_g=2 \rightarrow F_e=2$ transition, while the $F_g=2 \rightarrow F_e=3$ transition would yield EIA. From fig.2.2 we see that the sum of the strengths of $F_g=2 \rightarrow F_e=1$ and $F_g=2 \rightarrow F_e=2$ is greater than $F_g=2 \rightarrow F_e=3$, thus yielding a net EIT for the $^{85}$Rb $F_g=2 \rightarrow F_e=1,2,3$ transitions. Shown in fig 2.3 is data collected at this transition.
Figure (2.2): (A) Atomic structure of $^{85}$Rb and $^{87}$Rb, (B) Reproduced from [3] Probability distribution of D$_2$ lines

Figure (2.3): EIT, $^{85}$Rb, $F_g = 2 \rightarrow F_e = 1,2,3$, Zeeman Detuning, FWHM 81kHz.
2.3 Sign Reversal in Multi-level Atoms

From Sec. 2.2 it is clear that when several hyperfine transitions are excited simultaneously both EIT and EIA processes occur but the net effect observed is the one that dominates. In this section we show that one can, by introducing a second resonant laser beam, turn off some of these coherent processes causing the overall net effect to convert from EIT to EIA or vice versa.

In order to elucidate how such a sign reversal may occur, first consider the simplest case of the $F_g = 1 \rightarrow F_e = 0$ transition shown in figs.1.1 and 2.1C. If the experiment described in Sec. 2.1 (Fig.1.1) is carried out, we expect to see an EIT signal as shown, for example, in fig.2.3. We now introduce a second resonant linearly polarized laser beam, in addition to the first beam shown in fig.2.1A, is incident on the atomic sample. This revised setup is shown in fig.2.4. Note that the second beam is chosen to have orthogonal polarization so that it may be conveniently separated from the first beam with the help of a polarizing beam splitter. Typically, the first beam for which the transmission is recorded as a function of the scanning B-field, is weak and is referred to as the “probe”. The second beam can be strong and is referred to as the “coupling” (or sometimes “pump”) beam. In EIT and EIA experiments it is usually the probe transmission spectrum that is observed, although the coupling transmission has also been investigated in one case [13,14,15].

Consider what happens to the probe transmission spectrum (see fig.2.3) in the scenario depicted in fig.2.5. In the region where B is not zero, the $F_g = 1$ and $F_g = -1$ ground sublevels are Zeeman shifted out of resonance with the excited state. The excited state is off-resonantly pumped by the $\sigma^+$ and $\sigma^-$ laser components of the lasers. This off-resonant pumping is dominated by the strong coupling beam. The atom absorbs the coupling light, populating the excited state. The atom then relaxes from the excited state either by stimulated/spontaneous emission back to the $F_g = +1$ and $F_g = -1$ ground levels (in which case the whole process is repeated), or by spontaneous emission into the $F_g = 0$ ground level. Once in the $F_g=0$ ground level the atom stays there because there is no pi-polarized light available to pump it back to the excited $F_e=0$ level. Owing to the presence of the strong coupling beam, almost all the atoms are very soon pumped into the $F_g=0$ ground level. All of the above happens as the magnetic field is scanning toward B = 0. By the time the B-field actually reaches zero-value, all the atoms are in the $F_g=0$ ground sublevel. Therefore at B= 0, no atoms are available in the $F_g = +1$ and $F_g = -1$ ground sublevels to form the signature superposition dark state needed for EIT. Thus no EIT signal would be observed, i.e., this EIT process has been effectively turned off by the addition of the strong coupling laser beam.

Now let’s re-consider the scenario in the previous paragraph but this time for a $F_g = 1 \rightarrow F_e = 1$ transition. The Zeeman levels and lambda-V systems leading to EIT/EIA processes are
shown in fig.2.5B, where in the usual case of just one linearly polarized laser beam, the lambda (EIT) process dominates over the more fragile V (EIA) process. However, with the addition of the strong coupling laser, the EIT process is turned off as described in the previous paragraph since most of the population is transferred to the $F_g = 0$ ground sublevel. At this point, only the V-system survives giving rise to the EIA process at $B=0$. Thus, we see how the EIT signal expected in the usual case of just one weak incident beam, has been transformed into an EIA signal with the addition of the second strong beam.

Fig.2.5C extends the above arguments to the case of a $F_g = 1 \rightarrow F_e = 2$ transition. In this situation, the usual case of one incident beam leads to an EIA signal owing to the dominance of the V over the $\Lambda$-systems. As shown in fig.2.5C, the addition of the second strong laser beam does not change the sign of the EIA signal.

The reason for presenting the three different transitions in figs.2.5A-C is that with real-life multilevel atoms (see Sec. 2.2) we may end up exciting all three transitions simultaneously, such as with the $F_g = 1 \rightarrow F_e = 0,1,2$ hyperfine levels in $^{87}\text{Rb}$. The data and results are shown in Chapter 4. Note from Sec. 2.2 that the net effect predicted for these three hyperfine transitions in the usual case of one weak incident beam is EIT. However, based on our qualitative analysis above we expect that all the EIT processes arising from $\Lambda$-systems shown in figs.2.5A-C are turned off upon the addition of the second strong laser beam, while the EIA processes arising from the V-systems survive – thus, we predict that the net effect flips from EIT to EIA.
Figure (2.4): Vapor cell with a scanning longitudinal B-field with the two laser beams of orthogonal linear polarization, co-propagating in the same z-direction. The beam passes through a polarizing beam splitter (PBS) to separate the two orthogonal beams. The transmission one of these beams (the probe) is detected with a Photodiode (PD).

Figure (2.5): $^{87}$Rb, ($F_g = 1 \rightarrow F_e = 0, 1, 2$) (A) expected EIT, population shifts to $m_e = 0$ ground state owing to large coupling intensity, effectively turning EIT off. (B) expected EIT, large coupling population shifts creating a V-system shown in blue, (C) expected EIA, large coupling also creates a V-system shown in blue.
Chapter 3

Experimental Setup and Procedures

Below I will begin briefly describe the laser used and how we set the laser to desired transitions using a rubidium vapor cell that contains a combination of 72% $^{85}$Rb and 28% $^{87}$Rb. The rubidium vapor cell is 72 mm long and 25mm wide. Then discuss the Helmholtz coil system and how we produce the scanning for the magnetic field. Finally I will describe the important procedures we use to suppress polarization impurity and stray magnetic fields.

3.1.1 External Cavity Diode Laser System /Saturated Absorption Spectroscopy

The External Cavity Diode Laser System (ECDLS) is an affordable home built laser system. Capable of providing narrow bandwidth extinction of less than or equal to 100KHz. [16] This system is contained in a mobile aluminum case that helps with temperature control. Fig.3.1 The laser diode that is used produces a diverging 780 nm beam. A lens is used to collimate the diverging beam. For our experimental purposes the laser is collimated over a distance of ten feet. Then the beam passes through a cube beam-splitter (BS). This BS is a 50/50 beam-splitter; meaning half of the beams intensity passes though the cube and the other half is reflected out the other side. The beam that passes through the BS encounters a diffraction grating. If the diffraction grating is aligned correctly the -1 order should be reflected back into the laser diode. Connected to the diffraction grating is a piezo electric transducers (PZT). The PZT helps with fine control adjustment of the laser frequency. All these pieces are assembled on an aluminum base plate that rest on a Sorbothane pad that also acts as vibration control. The final produce gives us two laser beams one that goes directly to our experiment and the other goes to saturated absorption spectroscopy (SAS). Further detail of maintenance of the ECDL can be found in ref [17].
Earlier it was stated in order to get EIT or an EIA signal we must have the laser tuned to specific hyperfine structures. The laser is tuned by an arrangement called Saturated Absorption Spectroscopy (SAS) [16] shown in fig3.2. This system considers two weak beams one of which is overlapped with a third counter-propagating strong beams. The two weak beams are allowed to fall on to the twin photodiodes, the outputs of which are subtracted. Each beam is a Doppler broadened line shape on its detector. The two beams together yield a flat line. In the presence of the strong beam fig3.3A counter-propagating overlapping week beams. Spectral hole are “burned” into the Doppler profile of the strong beam fig.3.3B. The twin photodiode output shows only the narrow spectral holes fig.3.3C. These narrow spectral features correspond to the hyperfine transitions and the laser maybe locked in resonance with these features.
3.1.2 Helmholtz Coils

The set up for the Helmholtz coils is arranged to cancel out the Earth’s magnetic field in three dimensions (x, y, and z). This is achieved by wrapping loops of wire in each of the spatial direction as shown in fig.3.4. Then we pass current though the wires to create desired magnetic fields. Traditionally thick copper wires are used to create these loops. In this experiment computer ribbon is used instead, permitting a greater number of turns in the paired loops. This allows the use of lower current. This Helmholtz coil configuration is calibrated by using a state-of-the-art Hall probe sensor 7030 Gauss/Tesla meter. This sensor detects the magnetic fields in three dimensions. The probe is positioned at the center of the Helmholtz coils in the place where the vapor cell is usually located. We then
calibrate the probe by using a shielding cover. The zero point on the sensor drifts, therefore zeroing using the shield is required before every measurement. Once that is complete we adjust the current until the probe shows zero magnetic field for the Helmholtz coil configuration. For further information on experimental and theoretical data for the Helmholtz coils in our experiment refer to Appendix (A).

![Figure (3.4): Helmholtz Coils; in the picture the axis of the dimensions are displayed.](image)

Cancelling stray magnetic fields is very important, since they can cause spurious feature. Spectral dips and peaks that resemble genuine EIT and EIA features as shown in chapter 4. Using a hall probe, magnetic field readings were taken along the Z axis fig.3.4. Each data point was taken a centimeter apart. These measurements were taken to examine the magnetic uniformity along the entire length of the 7.28cm rubidium cell. The length of the z-direction of the Helmholtz coil is 24cm and the rubidium cell is spatially centered inside the coils. The graphs in fig.3.5 show that magnetic fields that range 1-10mG. We tried to estimate the stray fields within a cylindrical volume at the ends of the vapor cell for a 3mm beam diameter. This measurement is subjected to human error and we decided to use the optical feature generated by EIT for further improvements in the magnetic field cancellation.
3.1.3 Applied Magnetic Field in z- direction

In order to have a Zeeman EIT there has to be a scanning magnetic field applied in the direction of the propagating laser beam. In this experiment the laser passes through a vapor cell with a wrapped solenoid of 121 turns fig.3.6. This solenoid provides the magnetic field needed to create the Zeeman EIT. The current that is used for this coil is about 0.99A. This current is ramped by using a function generator set to a triangle waveform to ramp the current at 3.2 Hz creating a swept magnetic field of ±20G.
3.2 Initial optical layout for Zeeman EIT: Limitations

The optical layout for our experiment is depicted in fig.37. All our EIT measurements are achieved by using linear polarization. Later circular polarization is used in chapter 4. For this setup in fig.3.7 we start right to left. The laser profile is elliptically shaped, so an anamorphic prism pair is used to correct the beam profile. An isolator is used after the prism pair to prevent retro-reflection from going back into the laser. The first set of mirrors (M1) change the height of the laser beam, so that it is centered in the Helmholtz coils. An objective and lens combination expands the beam. This allows us to pick a good spot of the beam using an iris. The half wave-plate (HWP1) controls how much of the beam is directed to the vertical and horizontal ports of the polarizing beam splitter. The mirror setup (M2) starting above the polarizing beam splitter (PBS) is the vertically polarized coupling beam (in blue), and the beam going straight through PBS is the horizontally polarized probe beam (in red) fig.3.7. We are able to adjust the intensity of the coupling beam by using half wave-plate (HWP2) and polarizer combination. The two beams are combined by a cube beam splitter (BS), and the path (shown in purple) continues through another set of mirrors (M3). After the beam passes through the center of the cell, the two lasers are slightly miss-aligned so only the probe beam can be detected with a photodiode. The coupling beam is thrown in to a beam dump (BD). We then use an external cavity diode laser. The laser is tuned to specific hyperfine structures with the aid of a Saturated Absorption Spectroscopy (SAS). With this setup we are able to achieve both EIT and EIA signals.
The polarization purity after each mirror was measured (using method describe in 3.3.2) to be 98% pure or better, which is typically acceptable. All mirrors (M2 & M3) were set at 45 degrees to minimize impurities. However there were still some impurities due to a combination of stray magnetic fields and polarization that were undetectable using standard state of the art methods. We show sub-natural line widths spectral features derived from this setup. We thought initially that any sub-natural feature must be due to EIT. However, this notion was up-ended by observation made using a single $\sigma$- polarized beam that is described in the next section.

### 3.3 Improved Optical Layout for Zeeman EIT: Reducing Polarization Impurity, and Stray Magnetic Fields

As described through the thesis, EIT is the inference in the probability amplitude of absorption of two coherent laser beams. In our case these two beams, of orthogonal circular polarization are created from a single linearly polarized laser beam. In order to check for artifacts caused polarization impurity and/or stray magnetic fields, we decided to block the one of the two laser beams. This was not possible by using linearly polarized laser. So we implemented this check by blocking the coupling laser and inserting a quarter wave-plate in the path of the probe beam immediately before the vapor cell. The proper procedure for
insertion of the quarter wave plates is described in Appendix B. The observed transmission spectrum of this single \( \sigma \)-polarized beam is shown in fig.3.8. No ultra-narrowing should have been observed.

![Graph](image.png)

**Figure (3.8):** With only one circularly polarized beam propagating through the cell, a sub-natural line width spectral feature of line width 155kHz.

Fig.3.8 shows that spurious sub-natural spectral features can be generated when there is polarization or magnetic field impurity [18,19]. In the following section methods used to reduce this signal will be discussed. It is crucial for EIT experiments to obtain extremely high polarization purity (1 in \( 10^5 \)) and extremely low residual magnetic fields (less than a few mGauss).
3.3.1 Polarization Purity

To improve polarization we made the following important improvement to the system shown in fig 3.7. The improved setup is outlined in fig. 3.9. Basically we eliminated mirrors (M3) and with the use of Glan-Thompson (G-T) polarizers, and (G-T prism). These changes were major improvements to the system. Fig. 3.9 This optical layout is similar to the initial setup. The changes begin after the PBS. G-T polarizer is set for vertical (coupling) and horizontal (probe) polarization. The intensity for the coupling is still controlled by HWP2. The G-T prism allows the probe and coupling to be completely overlapped in the vapor cell and then split the two beams. This allows us to detect the probe beam without misaligning the two beams.

3.3.2.1 Purity of Optics Equipment

The polarizing beam-splitter (PBS) used in fig. 3.7 and fig. 3.9 has a purity of 99.5% for horizontal and 99.7% for the vertical. These purities were found using
the method in described below. According to the specification given by Thorlabs the extinction ratio is 1,000/1 for the PBS. Using the same method the purity was tested for the Glan-Thompson Polarizer, which has a separated extinction ration of 10,000/1. This purity is 100X better than the Thorlabs PBS which is beyond our detection ability. However, this significant improvement in polarization purity is directly verified by the extreme suppression of spurious sub-natural feature see in fig.3.8. This suppression is illustrated in fig.3.11 after we suppress stray magnetic fields.

3.3.2 Stray Magnetic Fields

Polarization impurity is not the only culprit that can cause the feature in fig.3.8. Stray magnetic fields also play a significant role. The Helmholtz coil is zeroed in all direction with in the abilities of the hall probe that was used. This method is acceptable to get the Helmholtz coil close to zero; however the Hall probe precision is not good enough to detect extremely low stray magnetic fields. Once again the spurious signal in fig. 3.8 is observed to fine tune the magnetic field, to suppress this feature. Fig.3.11 shows the same feature reproduced from fig.3.8 in orange. The blue curve shows the reduced size of the feature after stray magnetic fields were suppressed in fig.3.11 by fine-tuning the currents in the Helmholtz Coils. We measure a reduction in size of the spurious feature by a factor of 3.6X from orange to blue curve.

Figure (3.11): $^{85}\text{Rb}$, (Fg =2→ Fε= 1,2,3), Signal from Fig 3.8 overlapped with impurity with Glan-Thompson Polarizer (intensity of 529.1 $\frac{W}{cm^2}$)
3.3.3 Caution: Spurious Sign Reversal Signals

It was inherent to us that the signal of the spurious feature flipped, mimicking the sign reversal of EIT effects we seek to explore. This exposed us to the possibility that spurious signal may generate spurious sign reversal signals, as shown in fig.3.12.

Fig.3.12 shows the effect of a single sigma beam as the magnetic field is slightly changed in the $x$-direction. Voltage was measured from the power supply for the coils in the $x$-direction as the changes were made. The aim is to make the feature as small as possible. The reasoning behind this thought is the smaller the feature would imply a small amount of stray magnetic fields. This means the small middle dispersion feature shown in red would fit this goal. When the $y$-direction is varied the signal becomes taller and broader, so there is no reversal like the $x$-direction.

![Varied Magnetic Field](image)

Figure (3.12): Single sigma beam and the effect of changing the magnetic field of the Helmholtz coil in the $x$-direction.
Chapter 4
Data and Discussion

In this chapter I will discuss the data that we received for collected both with and without residual polarization impurities and stray magnetic fields. All the data collected is for two beams, a coupling beam and a probe beam derived from the same laser, with orthogonal linear polarization, co-propagating through the vapor. The probe beam is always horizontally polarized and the coupling beam vertically polarized. The probe transmission spectrum is displayed as a function of scanning longitudinal $B$-field. The Zeeman detuning conversion is 0.47 MHz/Gauss for $F_g=2 \rightarrow F_e=2$ transition of $^{85}\text{Rb}$, and 0.7 MHz/Gauss for $F_g=1 \rightarrow F_e=2$ transition of $^{87}\text{Rb}$. [23,24]

4.1 Sign Reversal in Rb with orthogonally linearly polarized coupling and probe beams, with and without suppression of polarization impurity and stray $B$-fields

4.1.1 $^{85}\text{Rb}$

EIT is obtained by bringing the laser into resonance with the lower ground state of $F_g = 2 \rightarrow F_e=1,2,3$ ($^{85}\text{Rb}$). The probe intensity is fixed and the probe transmission measured as a function of scanning longitudinal $B$, for different coupling beam intensities including a measurement at zero coupling intensity (i.e., the coupling beam is blocked).

Initial measurements of sign reversal were performed using the setup shown in Fig. 3.7, and are shown in Fig. 4.1. The coupling laser intensity was varied by rotating half-waveplate HWP1. Final measurements of sign reversal were performed using the improved setup in Fig. 3.11, and are shown in Fig. 4.2.

EIT is observed in both Figs. 4.1 and 4.2. However, it is seen that as a result of suppression of polarization impurity and stray magnetic fields in the improved setup, we achieve a far narrower EIT linewidth at zero coupling intensity in Fig. 4.2 (81 kHz) than in Fig. 4.1 (140 kHz) despite the fact that the probe intensity in Fig. 4.1 is actually set higher by almost a factor 2X than that in Fig. 4.2. Generally, the EIT linewidth increases with increasing probe intensity (see Ref. 17) – this just shows that there is unambiguous EIT linewidth narrowing after suppression of polarization impurities and stray $B$-fields. The sign-reversed signal is narrower too for the improved setup in Fig. 3.11 – the linewidth goes down from 369 kHz at a coupling intensity of 0.55 mW/cm$^2$. 

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to 172 kHz despite the use of more than an order of magnitude higher coupling intensities (~7 mW/cm²).

4.2.2 \(^{87}\text{Rb}\)

The laser is now brought into resonance with the \(F_g = 1 \rightarrow F_e = 0, 1, 2\) transitions in \(^{87}\text{Rb}\). Initial measurements of sign reversal without suppression of polarization impurity and with residual \(B\)-fields present were performed using the setup shown in Fig. 3.7, and are shown in Fig. 4.3. Final measurements of sign reversal with suppression of polarization impurity and of stray \(B\)-fields using the setup in Fig. 3.11, are shown in Fig. 4.4. In this case we observe that the EIT linewidth measured at zero coupling intensity after suppression of polarization impurity and stray \(B\)-fields is 131 kHz which is the same as the linewidth measured before the previously used setup in Fig. 3.7 (126 kHz), again despite the fact that the probe intensity used in the improved setup is 2X higher than that in Fig. 4.3. Further, linewidth narrowing is actually observed in the sign-reversed signal in the improved setup relative to the previous setup – the linewidth goes down from 354 kHz at a coupling intensity of 6.4 mW/cm² to 239 kHz at 14.4 mW/cm².

![Figure 4.1: \(^{85}\text{Rb, } (F_g =2 \rightarrow F_e = 1, 2, 3), \pi \perp \pi, \text{ Probe intensity: of } 214 \frac{\mu W}{cm^2}, \text{ Coupling intensity: zero } \frac{\mu W}{cm^2}\)](image)

FWHM of 140 kHz, 191.77 \(\frac{\mu W}{cm^2}\), 224.46 \(\frac{\mu W}{cm^2}\), 552.68 \(\frac{\mu W}{cm^2}\) FWHM of 369 kHz
Figure (4.2): $^{85}$Rb, ($F_g = 2 \rightarrow F_e = 1, 2, 3$), $\pi \perp \pi$, Probe intensity: $398 \frac{\mu W}{cm^2}$, Coupling intensity: zero (FWHM of 81kHz), 355 $\frac{\mu W}{cm^2}$, 1088 $\frac{\mu W}{cm^2}$, 3274 $\frac{\mu W}{cm^2}$, 6762 $\frac{\mu W}{cm^2}$ (FWHM of 172kHz)

Figure (4.3): $^{87}$Rb, ($F_g = 1 \rightarrow F_e = 0, 1, 2$), $\pi \perp \pi$, Probe intensity: $221 \frac{\mu W}{cm^2}$, Coupling intensity: zero (FWHM is 126 kHz), 273 $\frac{\mu W}{cm^2}$, 659 $\frac{\mu W}{cm^2}$, 6369 $\frac{\mu W}{cm^2}$, FWHM is 354 kHz
Figure (4.4): $^{87}\text{Rb}$, (Fg =1 → F_e = 0,1,2), $\pi \perp \pi$, Probe power: 448 $\mu W/cm^2$, Coupling intensity: zero (FWHM of 131kHz), 298 $\mu W/cm^2$, 1061 $\mu W/cm^2$, 2997 $\mu W/cm^2$, 14430 $\mu W/cm^2$ (FWHM of 239kHz)
Chapter 5

Conclusion and Future Outlook

5.1 Conclusion

We discovered there were significant polarization impurities and stray residual magnetic fields in our EIT experiment. These imperfections led to spurious sub-natural line width spectral features in the transmission spectrum of a single circularly polarized beam passing through the atomic vapor, where EIT or EIA effects could not have possibly existed. By identifying the sources of polarization impurity (several mirrors) and introducing Glan-Thompson polarizers and a Glan-Thompson prism in the setup, and carefully canceling stray B-fields we were able to reduce the size of the spurious feature down by a factor of almost four. This is an important achievement for our future investigations in EIT and EIA. We carried out a preliminary investigation of EIT in $^{85}$Rb and $^{87}$Rb and achieved our narrowest line widths to date, comparable to narrow line widths measured by other workers and reported in the literature.

5.2 Future Outlook

We would like to evolve a better theoretical understanding of EIT and EIA in order to arrive at a quantitative explanation for sign reversal. Furthermore, we would like to investigate EIT with circularly polarized probe and coupling beams, as this may considerably simplify the calculations.

Dahl, et al [13] were the first to showed sign reversal experimentally with $\sigma^-$ and $\sigma^+$ laser polarizations. Zigdon et al created models for $\sigma^+$ and $\sigma^-$ polarizations based on the atomic structure of cesium shown in fig.5.1. [15] Here, the strong $\sigma^+$ (coupling) beam optically pumps the population into ground levels with higher quantum numbers (on the right in Fig. 5.1), and $\sigma^-$ moves the population to the ground levels on the left. Zigdon showed that in the presence of an applied weak probe $\sigma^-$ beam, an EIA signal is observed in the transmission spectrum of the strong $\sigma^+$ beam. The reason we see EIA is due to the superposition between excited states $m_e = 3$ and $5$ in Fig. 5.1 which creates the necessary requirements to obtain a V-system. When this V-system is in place, it is more probable for a photon to emit down from $m_e=3$ to $m_g=4$ because $\sigma^+$ is stronger. Therefore, we observe EIA when detecting $\sigma^+$. However if the $\sigma^-$ beam was to become stronger than the $\sigma^+$ beam the signal would reverse its sign to an EIT feature. The reason for the EIT feature is due to
the population shift from the right side of these states to the left side creating a superposition between the excited states \(m_e = -5\) and \(-3\). In this case it is more likely for a photon be absorbed from \(m_g = -4\) to \(m_g = -5\) and to emit down \(m_e = -3\) to \(m_g = -4\). This will cause a peak in transmission of the \(\sigma^+\) beam, thus yielding an EIT feature.

![Diagram of atomic configuration of cesium](image)

Figure (5.1): Reproduced from [15]; atomic configuration of cesium, \(\sigma^+\) (coupling) in red and \(\sigma^-\) (probe) in green polarizations.

In the long-term we plan to intriguing new phenomena such as “slow light”, made possible by the fact that the quantum interference effect responsible for EIT is often accompanied by a million-fold increase in refractive index of the atomic vapor [20] This is a fascinating area of research, since optical signals may be slowed and information is used in optical communications and photonics to create controllable delay lines. [21]
Appendix A

Helmholtz Coils

The following is the experimental data of the Helmholtz coils was taken by Iris Zhang [22] shown in fig.A1. A-C. According the data there is uniformity of the coils range that spans up to 12mm in the $\hat{x}$ and $\hat{y}$ direction at the center of the coils. It is uniform across the $\hat{z}$ direction. The vapor cells used is 12.4mm in diameter and 71.8mm in length.

A)

B)
Figures (A1): A) Magnetic field in the $\hat{x}$ direction, B) Magnetic field in the $\hat{y}$ direction, C) Magnetic field in the $\hat{z}$ direction

Graphs shown in fig.A2 were created by Jason Barkeloo [17]. They are theoretical plots of the uniformity of the Helmholtz coil. The right graph of fig.A2 shows the magnetic field in the Helmholtz coil in the $\hat{z}$-direction along the vapor cell and the fractional difference of the magnetic field as a function of the distance from the center of the Helmholtz coil.

Figures (A2): The graph on the magnetic field vs. distance from the center (cm), graph on the fraction of the maximum field vs. distance from the center (cm) [17]
Appendix B

Checking Polarization Purity and Creating a Pure $\sigma$- Polarized Beam

Polarization purity is a check that is performed to see how well the laser’s polarization is maintained as the laser flows through the system. Linear horizontal or vertical polarization is checked by using a configuration shown in fig.B1 A. The laser passes through the polarizer (P) and is detected on the other side. To find the percentage of purity a maximum and minimum power is detected by rotating the polarizer. The following equation eq.1 is used to find purity after the maximum ($P_{\text{max}}$) and minimum ($P_{\text{min}}$) is established. This check should be completed after every piece of optics. Create circular polarization one can use a quarter wave-plate. To set the quarter wave-plate to the correct degree the configuration shown in fig.3.B1 B is used. The laser first passes through a polarizer (the polarizer is set to vertical or horizontal depending on what polarization one is working with) and then through a quarter wave-plate (QWP). The altered laser is then reflected off the mirror and passes back through the QWP and P. On the front side of the polarizer the laser is detected. The QWP is rotated until a minimum power is established by the detector. Then eq1 is used to check the purity. $P_{\text{max}}$ is detected before the laser passes through the QWP and $P_{\text{min}}$ is identified after the laser passes back through the QWP and P. These methods work to a certain extent. You are limited by the ability of the detector and polarizer that is used.

$$\frac{P_{\text{max}} - P_{\text{min}}}{P_{\text{max}} + P_{\text{min}}} \quad \text{equation (1)}$$

A)

![Diagram A](image1)

B)

![Diagram B](image2)

Figure (B1): (A) Check linear polarization; Polarizer (P), red arrows represents the laser, and the blue stars represents the detector, (B) Create circular polarization; Mirror (M), Quarter wave-plate (QWP)
Bibliography


[18] Irina Novikova, College of William & Mary, personal contact

[19] David Philps, Harvard-Smithsonian Center for Astrophysics, personal contact


