Optical Pumping Beam Polarisation and its Effects on ^{41}K Fluorescence[1]

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Contents

1 Introduction

A significant portion of time this past semester was allocated to optimise the polarisation of potassium in order to achieve a higher degree of precision in future $\beta - \nu$ experiments at TRIUMF. This paper will focus on the improvements made to the polarisation of the D1 optical pumping beam since it plays a large role in polaristing atoms. The effects of D1 polarisation improvement cannot be fully determined because there are other factors which contribute to the polarisation of atoms that were also optimised during this time. For example, stray magnetic fields were better compensated for in the trap region. Still, significant improvement can be attributed to the better quality of D1 polarisation.

Another project that consumed a significant portion of time included learning to program in C and writing RS-232 protocols for data communication between the computer in the lab and a digital oscilloscope. Two final versions of the codes used are included in Appendix A with a brief explaination of their use.

2 A Mathematical Approach to Polarization

Many processes can be described by the mathematics of wave motion [8]. Light is not an exception. The wave nature of light can be explained both classically and quantum mechanically. A classical approach will be taken and will eventially lead to formal descriptions of the polarisation of light.

2.1 The Wave Equation

A wave can be thought of as a disturbance [8]. Picture a disturbance moving along in the z direction with speed v. Mathematically, this can be written in a general form:

$$\psi = f(z, t)$$

where f is a function of position and time and ψ is the disturbance.

The shape of this disturbance can be sketched simply by holding t constant. If this were to be done at two different but constant times, the disturbance will have moved a distance vt. If a new co-ordinate system were introduced, called S', that travels at speed v with the disturbance, then the disturbance can be characterised by a function of one variable:

$$\psi = f(z')$$

where $z' = z - vt$

If ψ is then rewritten in terms of the original, stationary co-ordinate system, S, then:

$$\psi(z, t) = f(z - vt)$$

Solutions can be determined if the differential wave equation is derived. If the second partial derivative is taken with respect to position and again with time, then combined, the relation:

$$\frac{d^2\psi}{dz^2} = \frac{1}{v^2}\frac{d^2\psi}{dt^2} \tag{1}$$

emerges.

Anything that varies position and time like Equation 1 is a wave. Possible solutions to Equation 1 are sine, and cosine functions.

2.2 Light as an Electromagnetic Wave

According to Maxwell, after his analysis of Faraday's Law, Ampere's Law, and Gauss' Laws, the equations that describe these laws can be manipulated into two concise vector expressions [8]:

$$\nabla^2 E = \epsilon_0 \mu_0 \frac{d^2 E}{dt^2}$$

and

$$\nabla^2 B = \epsilon_0 \mu_0 \frac{d^2 B}{dt^2}$$

When ϵ_0 and μ_0 were experimentally determined and evaluated in order to determine the speed of this electro-magnetic wave, the result was close to the result found by Fizeau, who measured the speed of light with a rotating toothed wheel. Maxwell concluded that light was an electro-magnetic wave and can thus be described by a solution to the wave equation [8].

One important characteristic to know about a light wave is its polarization. The polarization describes the coherence of a wave in the sense that if the orientation of the electric and magnetic fields form a pattern, the polarisation characterises it. Since the electric and magnetic fields are in phase with each other [8], the pattern the electric field displays is the convention commonly adopted to describe the polarization of light.

2.3 Polarisation

In the following descriptions of polarisation, the electric field of the light wave will be split into two components along the x and y axis (assuming that the z axis is the direction of propagation). Thus, the two equations are:

$$E_x(z,t) = \hat{\imath} E_{0x} \cos(kz - \omega t + \delta_x) \tag{2}$$

$$E_y(z,t) = \hat{\jmath} E_{0y} \cos(kz - \omega t + \delta_y) \tag{3}$$

They can be added to give the electric field vector $E(z,t) = E_x(z,t) + E_y(z,t)$ where the phase difference between the two components is $\delta = \delta_x - \delta_y$.

2.3.1 Linear Polarisation

When the phase difference between E_x and E_y is an integral multiple of π, the light is said to be linearly polarised. This means that the electric field components are in phase with each other or 180° out of phase. Linear light of this kind falls somewhere between the x and y axis as a line that goes through the origin. The slope of this line depends on the relative intensities of E_{0x} and E_{0y} [15]. For vertically polarised light $E_{0x} = 0$, and for horizontally polarised light $E_{0y} = 0$. In vertically and horizontally polarised light, the phase difference is irrelevant.

2.3.2 Circular Polarisation

When the phase difference between the two components is an odd integral multiple of $\pi/2$, and $E_{0x} = E_{0y}$, the light is said to be circularly polarised. This means that the electric field components are 90° out of phase. As one component gets larger, the other gets smaller. If $E(z,t)$ were sketched as time progesses, an observer would see the electric field rotate around the direction of propagation; $E(z,t)$ would trace out a circle. Light can either be left handed or right handed depending on the direction the light is rotating with respect to an observer who is looking at the oncoming wave. The definition usually adopted is left handed circular polarisation (σ^-) represents a counter-clockwise rotation and right handed (σ^+) represents a clockwise rotation [8, 15].

2.3.3 Elliptical Polarisation

When the phase of $E_x(z,t)$ and $E_y(z,t)$ are not an integral multiple of $\pi/2$, or when the light is circularly polarised but $E_{0x} \neq E_{0y}$, the light is said to be elliptically polarised. Elliptically polarised light is the same as circular light only $E(z,t)$ traces out an ellipse instead of a circle. The same rules apply as before when characterising elliptically polarised light as left or right handed.

2.3.4 Changing the Polarisation of Light

Many devices and materials have been found to change the polarisation of light. For instance, linear polarisers only pass linearly polarised light at the same angle as the transmission axis of the polariser. Another type is a wave retarder. With a wave retarder, there are two, orthogonal axes: the fast axis and the slow axis. The fast and the slow axis both get retarded but the slow axis is retarded more with respect to the fast axis. If the wave retarder is said to be a quarter wave retarder, then the phase of the slow axis is retarded by $\pi/2$. This changes linear light to circularly polarised light and circularly polarised light into linear light. If the wave retarder is a half wave retarder, the slow axis is retarded by π. This changes circularly polarised light into the opposite handedness of circularly polarised light and linear light to linear light oriented 90° from the original angle of the linear light. A full wave retarder retards the slow axis by one full period so there is no change. Wave retarders are also dependent on the freqency of the incident beam.

3 Stokes Parameters

3.1 Deriving Polarisation Parameters

To characterise these states of polarization mathematically, an examination of the electric field vector will show the previously mentioned patterns. Using Equations 2 and 3, the parametric ellipse can be formed. The parametric equation of the ellipse is used because it can characterise all three polarisations of light, including linear light. This is true if linear light is thought of as a beam composed of left and right circularly polarised waves with a phase difference of an integral multiple of π. The parametric equation for an ellipse for the electric field is:

$$\frac{E_x(t)^2}{E_{0x}^2} + \frac{E_y(t)^2}{E_{0y}^2} - \frac{2E_x(t)E_y(t)}{E_{0x}E_{0y}}\cos(\delta) = \sin^2(\delta) \tag{4}$$

In this, E_{0x}, E_{0y}, and δ are all constants while $E_x(t)$ and $E_y(t)$ vary over time. To represent the parametric ellipse for the electric field in terms of observables, the average electric field over an infinite period of time must be solved for the functions that vary with time [5]. When the average is taken and both sides of Equation 4 are multiplied by $4E_{0x}^2E_{0y}^2$, the result is:

$$4E_{0y}^2 < E_x(t)^2 > +4E_{0x}^2 < E_y(t)^2 > -8E_{0x}E_{0y} < E_x(t)E_y(t) > \cos(\delta) = (2E_{0x}E_{0y}\sin^2(\delta)) \tag{5}$$

From Equations 2 and 3, if this averaging formula is used [5]:

$$< E_i(t)E_j(t) >= T^{-1}\int_0^T E_i(t)E_j(t)dt$$

where i and j can be x or y, the averages are:

$$< E_x(t)^2 >= \frac{1}{2}E_{0x}^2 \tag{6}$$

$$< E_y(t)^2 >= \frac{1}{2}E_{0y}^2 \tag{7}$$

$$< E_x(t)E_y(t) >= \frac{1}{2}E_{0x}E_{0y}cos(\delta) \tag{8}$$

When Equations 6, 7, and 8 are substituted back into Equation 5, Equation 5 yields:

$$2E_{0x}^2E_{0y}^2 + 2E_{0x}^2E_{0y}^2 - 2E_{0x}E_{0y}\cos^2(\delta) = 2E_{0x}E_{0y}\sin^2(\delta) \tag{9}$$

Finaly, if $E_{0x}^4 + E_{0y}^4$ is added to and subtracted from the left side of Equation 9 and then factored, the final result is:

$$(E_{0x}^2 + E_{0y}^2)^2 - (E_{0x}^2 - E_{0y}^2)^2 - (2E_{0x}E_{0y}\cos(\delta))^2 = (2E_{0x}E_{0y}\sin(\delta))^2 \tag{10}$$

If the quantities inside the parenthesis are written as [5]:

$$S_0 = E_{0x}^2 + E_{0y}^2 \quad (11)$$

$$S_1 = E_{0x}^2 - E_{0y}^2 \quad (12)$$

$$S_2 = 2E_{0x}E_{0y}\cos(\delta) \quad (13)$$

$$S_3 = 2E_{0x}E_{0y}\sin(\delta) \quad (14)$$

then Equation 10 can be re-written as:

$$S_0^2 = S_1^2 + S_2^2 + S_3^2 \quad (15)$$

3.2 Expanding the Polarisation Parameters to be Measurable by Light Intensity

Equations 11, 12, 13, and 14 can be thought of as a vector based way to describe the polarisation of light. The four vector idea was developed by G. G. Stokes in 1852 [7]. Stokes parameters, as they are called, are a popular method and provide an extremely effective way to measure the polarisation of light using measurable quantities [2]. Light intensity is easier to measure than electric field strengths so it would be convinient to be able measure light intensities. Hecht defines the Stokes parametres using the intensity of the light and then proves that this definition does characterise the polarisation of light as previously defined [7].

Picture a set of four optical filters that, under normal illumination, would only allow half the incident light to pass. Suppose the first filter only did just that, block half the incident light. Suppose, the second filter is a horizontal polariser while the third filter is a polariser whose transmission axis is orientated at $+45°$ from the horizontal. Finaly, suppose the fourth filter is opaque to left handed circularly polarised light. Stokes parametres can be determined by placing each of these four filters in front of the beam in question seperately.

In this case, the intensity of the beam after each of the filters is what is measured. Let I_0, I_1, I_2, and I_3 be the intensities from each of the filters respectively. Thus, the definitions of the Stokes parametres in this context are:

$$S_0' = 2I_0 \quad (16)$$

$$S_1' = 2I_1 - 2I_0 \quad (17)$$

$$S_2' = 2I_2 - 2I_0 \quad (18)$$

$$S_3' = 2I_3 - 2I_0 \quad (19)$$

S_0' is simply the original intensity of the beam while S_1' characterises how horizontally vs vertically polatised the light is. S_2' is how polarised the light is along the $+45°$ axis vs $-45°$, and S_3' characterises how right circularly polarised vs left the light is. Here is how Equations 16, 17, 18, and 19 can be written in terms of electric field [7] and shown to be equal to Equations 11, 12, 13,and 14. The incident irradiance of a beam of light is:

$$I = \epsilon_0 c E^2(z,t)$$

or

$$I = \epsilon_0 c(< E_x^2(z,t) > + < E_y^2(z,t) >)$$

where the angled brackets represent time averages. One thing to note is that E_{0x}, E_{0y}, δ_x, and δ_y change quite slowly in comparison to $(kz - \omega t)$. Essentially, they may not very over millions of cycles but still change millions of times per second. For example, if the coherence time is 10^{-9} seconds and the mean frequency is 10^{15} Hz, the wave will undergo 10^6 cycles during that interval. Therefore, over a length of time that is relatively short compared to the coherence time, the amplitudes and phase angles would remain constant. The intensity of light over such a duration of time would be:

$$I_{ave}(t) = \frac{1}{2}\epsilon_0 c(E_{0x}^2(t) + E_{0y}^2(t))$$

where E_{0x} and E_{0y} have become fuctions with respect to time because there is no guarentee that the electric field will remain constant.

One thing to remember is the intensity will be measured by a detector. Since a detector will integrate over many periods, the intensity would be:

$$I = \frac{1}{2}\epsilon_0 c(< E_{0x}^2 > + < E_{0y}^2 >) \tag{20}$$

Equation 20 corresponds to S'_0 or equivalently $2I_0$.

The second Stokes Parametre, $S'_1 = 2I_1 - 2I_0$, can also be related to the light's electric field in the same manner. Remember, since I_1 is measured after the light has travelled through a horizontal filter, S'_1 is a measurement of the horizontal component of the electric field. Thus:

$$E_x = \hat{\imath} \cdot E(t)$$

Through the same averaging process as before:

$$I_1 = \frac{1}{2}\epsilon_0 c < E_{0x}^2 >$$

Therefore, in terms of electric field:

$$S'_1 = \frac{1}{2}\epsilon_0 c(< E_{0x}^2 > - < E_{0y}^2 >) \tag{21}$$

The third Stokes Parametre, $S'_2 = 2I_2 - 2I_0$, describes the amount of electric field that passes through a $+45°$ filter. It can be written as:

$$E_{45} = \frac{1}{\sqrt{2}}(\hat{\imath} + \hat{\jmath}) \cdot E(t)$$

Following the same logic in the averaging process as before

$$I_2 = \frac{1}{4}\epsilon_0 c(E_{0x}^2 + E_{0y}^2 + 2E_{0x}E_{0y}\cos(\delta))$$

Thus,

$$S_2' = \frac{1}{2}\epsilon_0 c(2E_{0x}E_{0y}cos(\delta)) \tag{22}$$

To write S_3' in terms of electric field, picture that the filter that will measure I_3 is made up of a quarter wave plate orientated so that the fast axis is along the y axis and the slow axis is along the x axis and the $+45°$ linear polarizer used to measure S_2'. This filter is opaque to left circularly polarized light because the quarter wave retarder orientates the beam so it is linearly polarised at $-45°$ from the horizontal. The $+45°$ linear polariser then blocks the light. Conversely, right handed circularly polarised light is linearly polarised at $+45°$ by the quarter wave retarder and fully transmitted. If only the $+45°$ linear polariser were present in this filter, S_3' would look exactly like S_2'. Since the retarder is present, the y axis will always lead the x axis by $90°$. That corresponds to a $-\pi/2$ addition to the phase difference. Thus the δ in S_2' becomes $(\delta - \pi/2)$ and S_3' can be written as:

$$S_3' = \frac{1}{2}\epsilon_0 c(2E_{0x}E_{0y}\sin(\delta)) \tag{23}$$

It has become common practice to drop the constants appearing in in Equations 20, 21, 22, 23, [7] so they are usualy written as:

$$S_0' = E_{0x}^2 + E_{0y}^2 \tag{24}$$
$$S_1' = E_{0x}^2 - E_{0y}^2 \tag{25}$$
$$S_2' = 2E_{0x}E_{0y}\cos(\delta) \tag{26}$$
$$S_3' = 2E_{0x}E_{0y}\sin(\delta) \tag{27}$$

Since Equations 24, 25, 26, and 27, are the same as Equations 11, 12, 13, and 14, the polarisation of light can be quantified by measuring the intensity of light. When the measured intensities are normalised to the incident irradience, then $S_0 = 1$, while S_1 and S_2 quantifies the linear polarisation of light and S_3 quantifies the circular polarisation.

3.3 Simplifying the Stokes Parameters

If it is not necessary to know the orientation of linear light, the Stokes parameters S_1 and S_2 can be generalised from two terms into one term which will be called S_{lin}. S_{lin} describes the amount of light that is linearly polarised. Thus:

$$S_{lin}^2 = S_1^2 + S_2^2$$

3.4 Malus' Law

Malus' Law describes the intensity of light transmitted through a set of two linear polarisers when there is an angle θ between their transmission axis. Only a component of the light through the first polariser will be transmitted through the second one [8]. This can be expressed as:

$$I = \frac{\epsilon_0 c}{2} E_0^2 \cos^2(\theta)$$

and rewritten using this trig identity

$$\cos^2(\theta) = \frac{1}{2} + \frac{1}{2}\cos(2\theta)$$

as

$$I = \frac{I_0}{2}(1 + \cos(2\theta))$$

where $I_0 = \frac{\epsilon_0 c}{2} E_0^2$

If the difference in angle between the transmission axis of the two polarisers is 90° then no light will pass the second polariser. If the angle is zero degrees, then all the light will pass the second polariser.

What if the first polariser were not a perfect linear polariser and allowed some circular light to pass? Circularly polarised light is not particular about the orientation of the transmission axis of a linear polariser and is transmitted equally through any angle. A degree of polarisation term needs to be added to Malus' Law in order to compensate for the quality of polarisation of the beam after the first linear polariser so that Malus' law accurately predicts the outcome. Walker [16] quantifies this term in his discussion of Malus' law by inserting the term:

$$P = \frac{I_{max} - I_{min}}{I_{max} + I_{min}}$$

into Malus' Law so it can be rewritten as:

$$I = \frac{I_0}{2}(1 + P\cos(2\theta))$$

This gives a percent of how linearly polarised the incident beam is. Since we already have a term that describes the linear polarisation of light, S_{lin}, then S_3 can be determined by:

$$S_3 = \sqrt{1 - S_{lin}^2}$$

where $S_{lin} = P$

4 TRINAT

The electro-magnetic interaction plays a central role in low-energy physics [4]. It not only provides information about the structure of atoms, but it also allows for the manipulation of an atom's various degrees of freedom. The two types usualy considered are the internal and external degrees of freedom. The internal degrees of freedom refer to the spin polarisation or electron configuration of the atom while the external degrees of freedom refer to the motion and position of the atom. The expanded knowledge in this field amassed over the past four decades has opened the way for new investigations in different areas of physics [4].

At TRIUMF, in TRINAT (TRIUMF Neutral Atom Trap) there is a group that uses these electro-magnetic interactions to trap atoms in a Magneto-Optical trap (MOT). Once trapped, the MOT is turned off and their spins are aligned using what is called a optical pumping beam. The purpose of this is to perform $\beta - \nu$ correlation experiments. The advantages TRINAT sees in using this setup are [3, 6]:

- The MOT can be loaded directly from a vapour cloud.
- The number of stable atoms trapped can be selected between 10^3 to in excess of 10^{10}.
- It allows for the low energy recoiling nuclei to escape easily.

The MOT provides a localised source of radioactive nuclei that can escape when undergoing β decay. Since the recoiling nuclei and resulting β particle is unimpeded, the time of flight to the detector can be measured. The neutrino momentum can be deduced from this information. If the atoms are optically pumped and polarised, then spin correlation experiments can be performed on the β decay to test how much parity symmetry is violated in the weak interaction. The tunable number of trapped atoms is also useful because trapping and optical pumping techniques can be tested using a large number of atoms to get large signals. Then the number of atoms can be scaled down to simulate performing actual tests on radiactive nuclei when the number of atoms is around 10^3.

4.1 Optical Pumping

Optical pumping is the process of using polarised light to change the angular momentum of a group of atoms so that they are polarised. At TRINAT, circular polarised light is most commonly used to polarise atoms and will only be considered in this report. Different polarisations of light carry their own internal angular momentum which is transferred to the atom when absorbed. Right handed circularly polarised light increases the internal angular momentum of the system projected along the light axis. Conversely, left handed circularly polarised light decreases the internal angular momentum of the atom.

4.2 Magneto-Optical Traps (MOT)

MOTs use many optical trapping techniques to slow or cool atoms. One principle it relies on, dubbed “optical molasses”, is the transfer of momentum from frequency tuned light [3]. Optical molasses is simply Doppler cooling [13]. Imagine a gas being irradiated with a retro-reflected beam of monochromatic light that has a frequency slightly lower then the gas’ atomic resonance frequency. If an atom moves in one direction, into one of the beams and away from the other, the atom will “see” more light from the oncoming beam due to a doppler shift in the light [13]. The light that the atom is moving into will increase in frequency closer to the atomic resonance of the atom while the light that the atom is moving away from will decrease in frequency. As a result, the atom will feel a net force that opposes its direction of motion. This can be characterised classically as damped harmonic motion [14]. If the atom is at rest, then the probability that it will see either beam is low so the atom will remain at rest.

Another principle MOTs employ to cool larger numbers of atoms to sub-doppler temperatures is the scattering force from the trapping laser. The initial concern was that the scattering force of the optical molasses is proportional to the intensity of the laser beams since the gradient of the scattering force is equal to zero [3]. This means that any region in empty space must have a net flux through it equal to zero. Thus, there can be no point where all scattering force field lines all point to a stable trapping location.

Pritchard, Carl Weiman, and their collegues noted that the scattering force is proportional to beam intensity need not be true and suggested using a spherical magnetic quadrupole field in conjunction with the trap [13]. This type of field would split the Zeeman sublevels in the atoms changing the probability of the atoms to absorb certain handedness of circularly polarised light. Figure 1 shows an example atom in a magnetic field with its sublevels split.

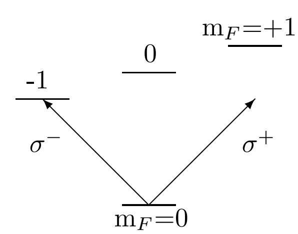

Figure 1: Example atom with its magnetic sublevels changed due to a magnetic field. Left Handed circularly polarised light is more likely to be absorbed in this case.

If the retro-reflected beam used in the optical molasses was circularly polarized (for instance the incident beam is right handed and the reflected is left handed) and since the symmetry of the energy levels is broken, the atom will be pushed to the region of the trap centre where the magnetic field is equal to zero. There the symmetry of the atomic sublevels will be re-established and the flux will return to zero[3].

5 Optimising the Polarisation in the D1 Laser

The necessity for pure circularly polarised light to pump the potassium atoms used here at TRINAT is one of the keys to limit systematic errors in the β decay experiments. In order to test the quality of the circularly polarised light, a series of polarisers were used to polarise and block the beam while power measurements where taken. The experimental setup to measure the polarisation of the D_1 is shown in Figure 2.

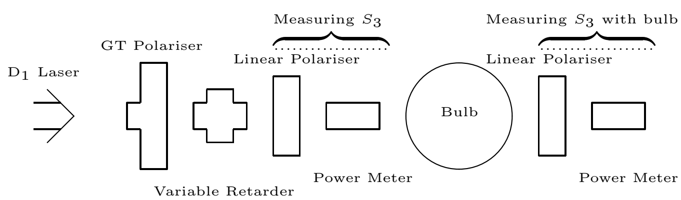

Figure 2: Diagram of Experimental Setup.

The normal trapping/pumping setup is similar. Only the linear polariser and power metre are removed.

The D1 beam was set to DC power and frequency locked. The beam goes through a Glen-Thompson polariser (a linear polariser), then the variable retarder and finaly through a linear polariser before coming to the power metre. The idea is to mimic the experimental setup for the β decay experiments but still use Malus' Law as a template to measure the polarisation. The linear polariser and power metre were changed between before and after the glass bulb that contains the potassium to see if there was any difference the bulb makes in the polarisation.

Using a plumb-bob suspended by a string, the GT polariser was set to as close to vertical as possible by aligning the transmission axis of the GT polariser, marked with a little white line, with the string. The assumption was that the retarder's transmission axis was at 45° from the vertical which is the angle the retarder needs to be from the linearly polarised light in order to create circularly polarised light.

To find the voltages the retarder would need to be set at to output circularly polarised light, the MOT was turned on and potassium was trapped. The logic signal that controls the MOT and pump beam was in a 20ms cycle where the MOT trap laser is on for 19ms and the pumping beam is on for the remaining 1ms. The MOT quadrupole field is turned off 1.25msec earlier than the MOT trapping lasers in order to ensure the trapping magnetic field is zero when the optical pumping begins. If the MOT magnetic field is on it reduces the quality of the polarisation of the atoms.

The pumping beam is actually two overlapped beams of slightly different frequencies so it excites different transitions. This pumping beam was set for transitions of F= 1 $\rightarrow$ 2 and F=2 $\rightarrow$ 2. During the 1ms pumping time, the circularly polarised pumping beam increases or decreases (depending on the handedness of the light) the anguler momentum of the potassium. During this time, the atoms are absorbing and emitting light. Once the valence electron of the potassium decays into an extremity of the F = 2 ground state, it is said to be in a "dark state" where the atom cannot absorb anymore light from the pumping beam because it cannot increase (or decrease) its angular momentum. Therefore, if the fluorescence of the potassium is zero, they are completely polarised.

The current way TRINAT measures this phenomenon is it uses a photomultiplier tube (PMT) aimed at the trap region while a digital storage oscilloscope (DSO) records the voltage. A high voltage on the DSO means that the potassium is absorbing and emitting many photons. A estimate of the polarisation of the atoms is done by taking the ratio of maximum to minimum fluorescence after the background is subtracted from the signal. The maximum fluorescence is seen at the beginning of the 1ms pumping time because the MOT beams depolarise the atoms while the minimum fluorescence is seen at the end. The waveforms collected from the DSO are transferred to the computer using the RS-232 protocols in Appendix A. The ratio is calculated as minimum to maximum because the program used to collect the data would crash if a number is divided by zero. There is a possibility that the minimum could be zero if the minimum background and signal measurements are the same.

The voltages of the wave retarder that will give circularly polarised light were found by using the above mentioned trap/pumping cycle while the voltage on the retarder was ramped. The minimum to maximum ratio of fluorescence was recorded. The minimums in the ratio correspond to the purest circularly polarised light because it corresponds to the greatest number of potassium that gets pumped into the dark state. The minimum ratios in flouresence was noted to be at 1.284V and 2.025V. Figure 3 is an example plot of this measurement. Note that the retardance is not linear with applied voltage for this device. At these two voltages, S_3 was measured before and after the blub using the scheme shown in Figure 2.

In an effort to make the polarisation better, it was decided that the transmission axis of the GT polariser would be rotated to see if it was 45° from the variable retarder's transmission axis. The retarder was set to 1.284V and the maximum and minimum intensities were again measured at different GT angles before and after the bulb to determine the best GT angle to produce circularly polarised light. The retarder was then set to 2.025V and the maximum and minimum intensities were again measured before and after the bulb.

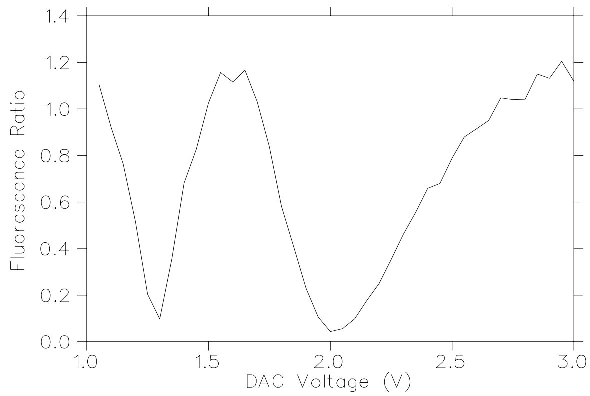

Figure 3: Ratio of Fluorescence vs. DAC Voltage on the Variable Retarder

6 Results

When the GT Polariser was set to vertical using the plumb-bob (329° on the GT mount), the S_3 polarisation at 1.284V across the retarder was found to be 0.998 before the bulb and 0.994 after the bulb. At 2.025V, before the bulb, S_3 was 0.997 and after the bulb S_3 was 0.994.

Table 1 shows the results of the GT polariser angle verses the S_3 polarisations for 1.284V and 2.025V.

	S_3 at retarder voltage	
GT Angle(°)	1.284V	2.025V
326	0.9997	N/A
326.5	0.9999	N/A
327	0.9999	0.9951
327.5	0.9993	N/A
328	0.9990	0.9984
328.5	N/A	N/A
329	0.9965	0.9993
329.5	0.9952	0.9999
330	0.9938	1.0000
330.5	0.9916	0.9996
331	0.9897	0.9989

Table 1: GT Polariser Angle with resulting S_3 measurement at given retarder voltage. N/A means that S_3 was not measured for that angle.

Figures 4, and 5 are example plots of the waveforms seen on the DSO from the PMT. They show the difference in fluorescence when S_3 is improved.

The fluorescence ratio for 1.284V at 329° is 49:1 while the ratio at 327° is

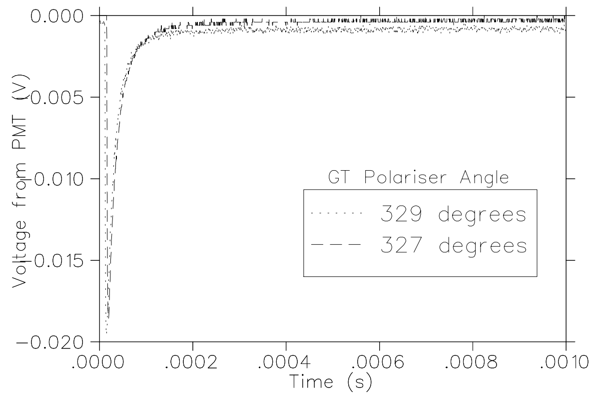

Figure 4: Wave retarder at 1.284V

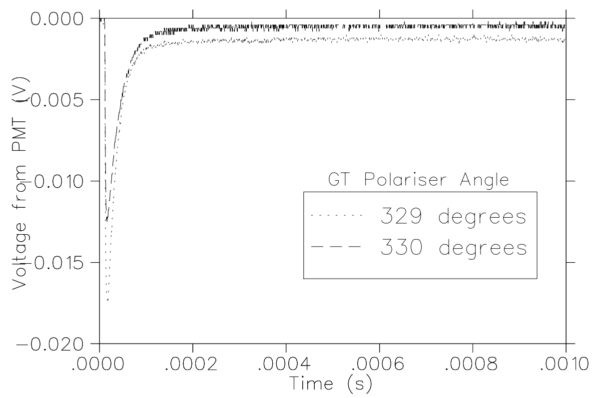

Figure 5: Wave retarder at 2.025V

88:1. The ratio for 2.025V at 329° is 14:1 while at 330° the ratio is 32:1. The more negative the PMT measures the voltage to be, the more optical activity the potassium in undergoing.

7 Discussion

It was found that the optimum angle for the GT polariser was 327° while the voltage across the retarder is 1.284V. There was a significant increase in the circular polarisation at 1.284V as seen in Table 1. It was expected that when the voltage was set to 2.025V, the other handedness of circular polarisation, similar results would be measured. Instead, the polarisation got worse. So, the optimum angle for the GT polariser was looked for while the retarder was set to 2.025V and was found at 330°.

A problem presents itself: Why are there two different optimum angles on the GT polariser for circular polarisation? The explaination given by Newport, the maker of the retarder, is the retarder absorbs some of the light along the common axis of the crystal like structure that makes up the retarder [11]. For there to be perfect circularly polarised light, both E_x and E_y must have the same amplitude or else the beam will be elliptically polarised (some linear light will pollute the circular light). If part of E_x or E_y gets absorbed then a slight angle (larger or smaller than 45 degrees) must be put between the transmission axis of the GT polariser and the variable retarder so that both components of the electric field are absorbed equally.

According to design specifications, as the voltage on the retarder increases, the amount of retardation on the slow axis decreases. The results hint that as the retardation decreases, so does the amount of light absorbed by the variable retarder but may not be the case. As a result, it is imagined that there is one other optimum angle for each voltage on the other side of the transmission axis difference of 45°. It was irrelevant that the GT polariser was set vertically because there is no guarantee that the variable retarder is at 45° from the vertical.

In light of this new idea of the retarder absorbing the light and giving two different distinct optimum angles for circular polarisation, it is not too illogical to think that the voltages on the variable retarder for circular polarisation could be inaccurate. They should be varied and retested to improve the circular polarisation. It is important that the voltage on the retarder is correctly set so the phase in $E_x(z,t)$ and $E_y(z,t)$ are properly tuned with the slight angle change from 45°. Since there is a deviation from 45°, both slow and fast axis get retarded at different rates.

Previous measurements performed earlier in the year of the polarisation suggest that the voltages currently used to produce circularly polarised light should be higher. Later, it was found that according to the design specifications, the retardance of the retarder decreases by 0.4% per °C [10]. The temperature of the room was not being monitored during any test. This leads to large discrepencies in the fluorescence ratios. For instance, when the optimum angles on the GT polariser were measured, the ratios for 1.284V and 2.025V were 88:1 and 32:1 respectively. Later, after the stray magnetic fields were further zeroed, the ratios for 1.284V and 2.025V were 39:1 and 212:1 respectively. Such a reversal in which handedness is favoured by the potassium could be attributed to a variation in temperature based reproducability issues on previous polarisation data measurements.

Furthermore, the fine adjustment knob on the GT polariser stand was not used in order to better characterise the angle on the GT polariser. Using this could give a more precise idea of the angle for which the GT polariser is aligned with the wave retarder.

A possible setup for an experiment to test both the voltage on the retarder and the angle on the GT polariser could use the same setup except a quarter-wave plate is inserted after the retarder, yet still between crossed linear polarisers. When the GT polariser is set to an angle the voltage on the retarder could be scanned over a limited range in order to see a maximum/minimum in power depending on how much the retarder changes the phase of the slow axis. The temperature should also be monitored throughout the process for consistency. For each angle, the maximum and minimum intensity of the beam without the quarter-wave plate would be measured so the quality of the circular polarisation can be found.

Also, since the bulb does affect the polarisation of the beam, the optimum S_3 that can be achieved before and after the bulb should be found. Then, the trap could be started and using both before and after the bulb polarisation settings it would become clear which window of the bulb corrupts the polarisation. If the optimum polarisation before the bulb gives a better fluorescence ratio, the second window is the problem. Vice versa, if the optimum polarisation for after the bulb gives the better ratio. the first window is the problem.

This study has significantly improved the polarisation of the atoms. Unfortunately, the polarisation of the D_1 laser is still the limiting factor. It is critical for the $\beta - \nu$ experiments that opposite nuclear polarisation is as precisely as possible achieved for both circular polarisations. So it would be useful is to be able to change the handedness of the light just by changing the voltage on the variable wave retarder without manually moving the transmission axis angle of the GT polariser. It would be ideal if this could be achieved for reproducability and simplicity without compromising the polarisation of the pumping beam.

A Created Communication Programs

The following codes were created for the purpose of communicating with the DSO. The DSO allowed for the storage of waveforms and it was necessary to transfer those waveforms to the computer for further analysis. SEAL was created to test the serial communications between the computer and the DSO. It is a terminal program that provides a user interactive interface that sends commands and displays replies from the serial device. Code fragments from SEAL were put into already existing data aquisition software used to control CCD cameras aimed at the trap region and display them on the screen. The purpose was to have the SEAL routines work in tandom with the CCD cameras so there are two different measurement methods when determining the fluorescence of the trapped potassium.

DUMP1 was created for the explicit purpose of transfering the waveforms from the DSO to the computer. It collects the ASCII characters, converts them to floating point numbers and saves them in a file. The time to download a complete waveform from the DSO is approximately two and a half minutes. The _bios_serialcom command is slow for it can only handle data transmission at speeds of 1200bps. Code fragments used to create these programs were taken from *Jamsa's C/C++ Programmer's Bible* [9] and the Microsoft support website [12].

A.1 SEAL

```
#include <stdio.h>
#include <bios.h>
#include <string.h>
#include <ctype.h>
#include <conio.h>
#include <stdlib.h>

void cmdsend(char[]);
void receive(char[]);
void copy(char[], char[]);
void convertfloat(char[], float[]);
void readnum(float []);
void readchar(char[]);

void main(void)
{
char cmd[15] = {"LANG?"};
char tmpsend[15]={'\0'}, tmprec[1000]={'\0'};
char  str[15] = {'\0'};
unsigned int com1_init;
unsigned com1_status;

com1_init = _bios_serialcom(_COM_INIT, 0, _COM_1200
| COM_CHR8 | _COM_STOP1 | _COM_NOPARITY);

printf("Init status: 0x%4.4X\n", com1_init);
com1_status = _bios_serialcom( _COM_STATUS, 0, 0 );
if ((com1_status & 0x80) == 0)
{
while (1)
{
printf("Input Command:");
gets(tmpsend);
if (tmpsend[0] == 'q')
{
printf("\n");
break;
}
if (strlen(tmpsend) == 0)
{
strcpy(str,cmd);
}
else
{
```

```
strcpy(str,tmpsend);
}
if (!(strnicmp(str, "curv", 4)))
{
printf("If you wish to save a waveform,use dump1.exe.\n");
}
else
{
strcpy(cmd,str);
sprintf(str, "%s\r", cmd);/
cmdsend(str);
printf("Sent: %s\n", str);
receive(tmprec);
readchar(tmprec);
}}}}

/*Sending String Command*/

void cmdsend(char str[])
{
unsigned com1_status;
int i = 0;
do
{
com1_status = _bios_serialcom( _COM_STATUS, 0, 0 );
} while ((com1_status & 0x90) == 0);
while (str[i])
{
_bios_serialcom(_COM_SEND, 0, str[i]);
i++;
}}

/*Receiving Response*/

void receive(char input[])
{
unsigned com1_status;
unsigned com1_rec;
int result1, mask, i = 0;
mask = 0x6100;
while (1)
{
do
{
com1_status = _bios_serialcom(_COM_STATUS, 0, 0);
com1_status = com1_status & 0xFF00;
```

```
} while( (mask & com1_status) == 0);/
com1_rec =  _bios_serialcom(_COM_RECEIVE, 0, 0);
result1 = com1_rec & 0x00FF;
if (!result1)
{
break;
}
input[i]=(char)result1;
++i;
}
input[i]='\0';
printf("\n");
}

/*Copy one string to another*/

void copy(char to[], char from[])
{
int i = 0;
while((to[i] = from [i]) != '\0')
{
++i;
}}

/*Converts ASCII characters to floating numbers*/

void convertfloat(char input[], float output[])
{
int i, j = 0, k = 0;
char acc[20]={'\0'};
for(i = 0; input[i] != '\0'; i++)
{
switch (input[i])
{
case 0x30: case 0x31: case 0x32: case 0x33: case 0x34: case 0x35:
case 0x36: case 0x37: case 0x38: case 0x39: case 0x2D: case 0x2E:
acc[k] = input[i];
++k;
break;
case 0x45:
if (isdigit(input[i-1]))
{
acc[k] = input[i];
++k;
}
else
```

```
{
printf("Unexpected Character.\n");
}
break;
default:
if (isdigit(input[i-1]))
{
acc[k] = '\0';
k = 0;
output[j] = atof(acc);
++j;
}
else
{
printf("Unexpected Character.\n");
}
break;
}}
output[j] = '\0';
}

/*Printing numbers to screen*/

void readnum(float input[])
{
int i;
for (i = 0; input[i] != '\0'; i++)
{
printf("%E\n", input[i]);
}}

/*Prints characters to screen*/

void readchar(char input[])
{
int i;
for (i = 0; input[i] != '\0'; i++
{
switch(input[i])
{
case 0x2C: case 0x0D: case 0x0A: case 0x3B:
printf("%c\n", input[i]);
break;
default:
printf("%c", input[i]);
break;
```

```
}}}
```

A.2 DUMP1

```
#include <stdio.h>
#include <bios.h>
#include <string.h>
#include <ctype.h>
#include <conio.h>
#include <stdlib.h>
#include <math.h>

void cmdsend(char[]);
void receive(void);

FILE *stream;
double ymu, yze, yof, curve, ti;
int k = 0, j = 0;

void main(void)
{
char cmd[15] = {"CURVE?"}, tmp[10]={'\0'}, str[15]={'\0'};
char tmplp[10]={'\0'}, tmprp[10]={'\0'};
unsigned int com1_init;
unsigned com1_status;

stream = fopen("wavepre.dat","a");

com1_init = _bios_serialcom(_COM_INIT, 0, _COM_1200 |
_COM_CHR8 | _COM_STOP1 | _COM_NOPARITY);
printf("Init status: 0x%4.4X\n", com1_init);
do
{
com1_status = _bios_serialcom( _COM_STATUS, 0, 0 );
} while ((com1_status & 0x80) != 0);
printf("What channel would you like to save?
(CH1, CH2, REFA, REFB, or MATH)\n");
gets(tmp);
printf("What location on DSO screen would you like
to start from?  (1 to 2500)\n");
printf("Default setting is 1.\n");
gets(tmplp);
if (strlen(tmplp) == 0)
{
strcpy(tmplp, "1");
}
```

```
printf("What location on DSO screen would you
like to stop at?  (%s to 2500)\n", tmplp);
printf("Default setting is 2500.\n");
gets(tmprp);
if (strlen(tmprp) == 0)
{
strcpy(tmprp, "2500");
}
printf("Setting up DSO.  Please wait.");
sprintf(str, "dat:star %s\r", tmplp);
cmdsend(str);
receive();
printf(".");
sprintf(str, "dat:stop %s\r", tmprp);
cmdsend(str);
receive();
printf(".");
sprintf(str, "dat:sou %s\r", tmp);
cmdsend(str);
receive();
printf(".\n");
strcpy(cmd, "wfmp:ymu?");
sprintf(str, "%s\r", cmd);
k = 1;
cmdsend(str);
receive();
printf("Y mult = %f\n", ymu);
strcpy(cmd, "wfmp:yof?");
sprintf(str, "%s\r", cmd);
k = 2;
cmdsend(str);
receive();
printf("Y off = %f\n", yof);
strcpy(cmd, "wfmp:yze?");
sprintf(str, "%s\r", cmd);
k = 3;
cmdsend(str);
receive();
printf("Y zero = %f\n", yze);
sprintf(str, "wfmp:%s:xin?\r", tmp);
k = 4;
cmdsend(str);
receive();
printf(".\n");
printf("Receiving DSO data.  (Approximately
2 minutes and 30 seconds.)");
```

```
strcpy(cmd, "curv?");
sprintf(str, "%s\r", cmd);
k = 0;
cmdsend(str);
receive();
}

/*Sending String Command*/

void cmdsend(char string[])
{
unsigned com1_status;
int i = 0;
com1_status = _bios_serialcom( _COM_STATUS, 0, 0 );
while ((com1_status & 0x90) == 0);
while (string[i])
{
_bios_serialcom(_COM_SEND, 0, string[i]);
i++;
}}

/*Receiving Response and changes ASCII numbers to numbers*/

void receive(void)
{
char rec[16] = {'\0'};
unsigned com1_status;
unsigned com1_rec;
int result1, mask;
int i = 0;
double num = 0;
mask = 0x6100;
while (1)
{
do
{
com1_status = _bios_serialcom(_COM_STATUS, 0, 0);
com1_status = com1_status & 0xFF00;
} while( (mask & com1_status) == 0);
com1_rec =  _bios_serialcom(_COM_RECEIVE, 0, 0);
result1 = com1_rec & 0x00FF;
{
switch (result1)
{
case 0x2C: case 0x0D: case 0x0A: case 0x3B: case 0x20:
switch (k)
```

```
{
case 1:
rec[i] = '\0';
ymu = atof(rec);
break;
case 2:
rec[i] = '\0';
yof = atof(rec);
break;
case 3:
rec[i] = '\0';
yze = atof(rec);
break;
case 4:
rec[i] = '\0';
ti = atof(rec);
break;
default:
rec[i] = '\0';
curve = ((atof(rec) - yof) * ymu) + yze;
fprintf(stream, "%6.9f\t\t%6.9f\n", num, curve);
num = num + ti;
}
i = 0;
break;
case 0x30: case 0x31: case 0x32: case 0x33: case 0x34: case 0x35:
case 0x36: case 0x37: case 0x38: case 0x39: case 0x2D: case 0x2E:
case 0x45:
rec[i] = (char)result1;
++i;
break;
}
if (!result1)
break;
}}
```

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