Summer 2012 Coop Report

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1 Introduction

During the past summer I have had the privilege of working on the TRINAT (TRIumf Neutral Atom Trap) experiment at TRIUMF. The current goal of TRINAT is to measure the beta asymmetry, A_β, in Potassium 37 as a precision test of the parity violation of the weak force.

Beta decay is a three body decay wherein a nucleon, either a proton or neutron, emits an (anti-)electron and a neutrino and converts into the opposite nucleon. Formally:

$$n \rightarrow p + e^- + \overline{\nu}_e \tag{1}$$

or

$$p \rightarrow n + e^+ + \nu_e \tag{2}$$

where p and n are proton and neutron, e^- and e_+ are electron and positron, and ν_e and $\overline{\nu}_e$ are electron neutrino and anti-neutrino. Note that the proton only reacts because the binding energy of the daughter nucleus is larger than the parent nucleus; an isolated proton is stable. In this context electrons are known as beta minus, β^-, particles and positrons are known as beta plus, β^+, particles. When it is clear from the context it is common to omit the specification of minus or plus. For ^{37}K the beta particles are β^+ particles.

In beta decay the maximally parity violating nature of the weak force manifests itself as an asymmetry in the angular distribution of the decay product beta relative to the nuclear spin of the parent nucleus. This is because the direction of beta emission is correlated to the direction of the neutrino which itself is controlled by the orientation of the neutrino spin relative to the nuclear spin since as far as we know neutrinos are only left-handed. Left-handed means that the particle's intrinsic angular momentum is aligned opposite to its direction of travel.

In order to measure beta asymmetry accurately one needs a small cold cloud of atoms with their nuclear spins all aligned along one particular quantization axis, figure 1. The accuracy of the measurement depends on how many nuclei have their spins aligned in the same direction along the quantization axis since if the nuclear spins were arranged randomly there would be no observable asymmetry.

An atom is polarized when it is in the state where its angular momentum is aligned with the quantization axis. A simplified picture is shown in figure 2. To move an atom between states we shine a laser beam on the atoms and the atoms absorb photons. Photons have total angular momentum of either $J = 1$ or $J = -1$ in units of $\hbar$. If the laser beam is composed of only $J = 1$ photons then to conserve angular momentum this means that in figure 2 only atoms in the $4S, m_J = -1/2$ state will absorb photons and be excited to the $4P_{1/2}, m_J = 1/2$ state. Higher energy states can spontaneously decay to lower states. When this happens there is no preferred axis and so in figure 2 atoms in the $4P_{1/2}, m_J = 1/2$ state can decay to either of the $4S$ states. The atoms that decay to the $4S, m_J = -1/2$ state will be pumped back into the $4P_{1/2}, m_J = 1/2$ state as long as the laser is on. But the atoms in the $4S, m_J = 1/2$ cannot absorb $J = 1$ photons and so will remain in that state. This process of moving atoms into a particular state is known as optically pumping.

This assumes that all of the photons incident on the atom cloud are $J = 1$ photons but in practice this is impossible to acheive. When $J = -1$ photons interact with atoms in the $4S, m_J = 1/2$ state they will be excited to the $4P_{1/2}, m_J = -1/2$ state. The fraction of the atoms in the cloud that are polarized once the system reaches steady state is dependent on the ratio between each handedness of photon. Note that if the laser beam were composed solely of $J = -1$ photons then the atoms would be optically pumped into the $4S, m_J = -1/2$ state and any stray $J = 1$ photons in the laser beam would depolarize the cloud. In fact

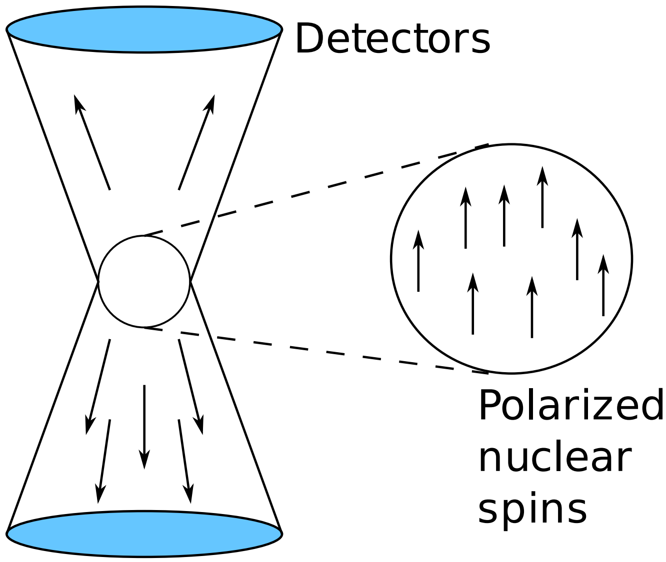

Figure 1: Diagram of beta asymmetry showing the asymmetry between the number of betas emitted upwards and the number emitted downwards. Also shown are the nuclear spins with perfect spin polarization. Note that A_β for ^{37}K is negative so the excess of beta particles will ocurr opposite to the nuclear spins.

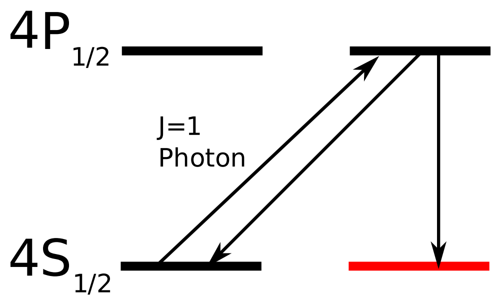

Figure 2: Simple level scheme of ^{37}K.

purposfully alternating pumping with $J = 1$ photons and $J = -1$ photons between runs is used to cancel systematic errors.

The previous explanation only considered the spin of the electron and did not include the nuclear spin. Figure 3 shows the same $4S$ and $4P_{1/2}$ levels as figure 2 but with the hyperfine splitting that results from including the ^{37}K nuclear spin. The process is similar with preferential exitation by $J = 1$ photons and isotropic decays. The result is a biased random walk towards the $4S, F = 2, m_F = 2$ state. Note that the absorbtions and decays only occur between the $4S$ and $4P_{1/2}$ levels. A decay from an $F = 2$ to an $F = 1$ level is not strictly forbidden but the rate at which this ocurrs is many orders of magnitude smaller than a decay from $4P_{1/2}$ to $4S$ and so on the microsecond time scales in optical pumping it is completely negligible. Thus once an atom reaches the $4S, F = 2, m_F = 2$ state it will remain there. The $4S, F = 2, m_F = 2$ state is the only hyperfine state with the nuclear spin parallel to the quantization axis. Again this assumes that only $J = 1$ photons are incident on the cloud. When $J = -1$ photons interact with the cloud they cause a biased random walk away from the polarized state.

Both previous explanations did not include discussion of the magnetic field. If there is indeed zero megnetic field throughout the cloud volume then the discussion above holds. If there is a small non-zero magnetic field only along the quantization axis then there will be Zeeman splitting of the hyperfine levels that will cause shifts in frequencies but as long as the splitting is not too large then the above discussion still holds. This is because any laser beam has a finite frequency width and the atoms are moving in the trap so there is dopplar broadening of their energy levels so photons will still be absorbed for all m_F. If

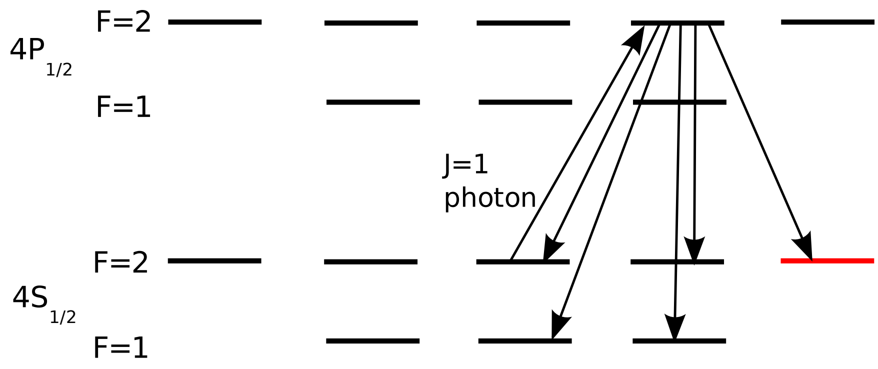

Figure 3: Level scheme of ^{37}K including hyperfine levels.

there is a non-zero field transverse to the quantization axis then the spins of the atom will precess around the total magnetic field vector which will rotate them away from the quantization axis. This is one of the major sources of depolarization of atoms in the cloud.

To quantify the polarization of the laser beam we use Stokes parameters. We are primarily concerned with the Stokes parameter S_3 which is defined as the degree of circular polarization of the light. To measure S_3 an analyzer linear polarizer is inserted into the laser beam and rotated through 360°. Recording the maximum, P_{max}, and minimum, P_{min}, power of the transmitted beam with a power meter allows us to define

$$S_{lin} = \frac{P_{max} - P_{min}}{P_{max} + P_{min}} \quad , \quad S_3 = \sqrt{1 - S_{lin}} \tag{3}$$

Using this method we can measure the composition of the laser beam. Theoretically the polarization of the atoms will be equal to the average of S_3 and 1 but we need to measure it explicitly. To measure the polarization of the cloud we can use the flourescence from the decay of the excited $4P_{1/2}$ state. When the opical pumping light is turned on and first begins to interact with the atom cloud a large number of atoms will be excited and decay. As the atoms are pumped into the $4S, F = 2, m_F = 2$ state there are less and less atoms capable of being excited and decaying. By measuring the flourescence from the decays we can estimate the fraction of atoms that are polarized.

2 Creating Optical Pumping Light

During my first coop semester here I spent a fair amount of time investigating how the optical pumping light would behave as it travelled from the laser to the center of the experimental chamber where the atom cloud is located. As shown in figure 4 the light from the laser is coupled into fibers that are mounted at angles above and below the chamber. The best location for the detectors that measure the beta particles are above and below the cloud along the quantization axis. Since the axis of the optical pumping laser light defines the axis of quantization and the detectors are opaque then the light must enter the chamber at an angle and be reflected off of mirrors in the vacuum. Both the mirrors and the viewports can affect the polarization of the laser beam and I spent a fair amount of time during my first four months here testing those elements.

The subject of this coop report is the construction of the apparatus that launches the optical pumping light from the fiber into the chamber and in the process circularly polarizes it. This is complicated by the requirement that the light used to trap the atoms must also enter through the same viewport. A schematic of the upper optical pumping apparatus is shown in figure 5. The fiber travels from the table containing the optical pumping laser and is connected to a fiber launcher with no built in lens. The light expands as it leaves the fiber and is collimated by an 80 mm lens in an adjustable lens tube. Both the fiber launcher and adjustable lens tube are screwed into a kinematic mirror mount which allows the angle of the laser light to be changed. The laser beam then passes through a high quality linear polarizer. The previous part of the assembly is mounted on an x-y stage which combined with the kinematic mirror mount allows fine tuning of the beam through the chamber.

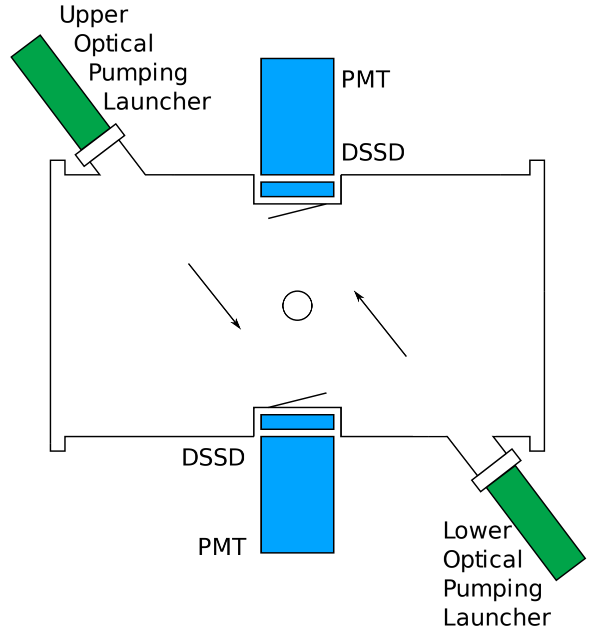

Figure 4: Schematic diagram of the experimental chamber. The optical pumping setups are shown in more detail in figure 5. Light from each launcher bounces off of a mirror and strikes the atom cloud. The Double Sided Strip Detectors (DSSD) and Photomultiplier Tubes (PMT) are the detectors used to measure the beta particles.

After the x-y stage comes a liquid crystal variable retarder (LCVR) which allows us to either pass the light without changing the axis of polarization or rotate the axis of polarization by 90°. Next is a Semrock filter that transmits the optical pumping light (769.9 nm) and reflects the trap light (766.5 nm). The angle of the filter relative to the optical pumping light and the trap light is critical for this to happen. The last element is the quarter wave plate which converts the linearly polarized optical pumping and trapping light into circularly polarized light.

2.1 Fiber Launcher and Power Density

The first section of the OP pumping apparatus collimates the light from the fiber and linearly polarizes it. The collimated beam should have uniform power density over the cloud. I measured the power density in the laser beam by inserting a calibrated aperture and measuring the power as the aperture was closed. The power density is simply the difference in power divided by the difference in area between two aperture sizes. The power density of the upper laser beam is shown in figure 6.

2.2 Configuring the Polarizer, LCVR, and Quarter Wave Plate

Once the beam is collimated the polarizer, LCVR, and quarter wave plate must be aligned so that they will produce well circularly polarized light of either handedness. By switching periodically between each handedness, ie. between $J = 1$ and $J = -1$ photons we, reduce the effects of systematic errors. The angle of the quarter wave plate is fixed so the LCVR determines the handedness by whether or not it rotates the light by 90°. The Semrock filter has different transmittances for s and p polarized light. To avoid this birefingence the two axes that the LCVR switches between should be aligned with the s and p axes of the Semrock filter. This determines the angles of the polarizer, LCVR, and quarter wave plate.

The LCVR is capable of continuously varying the retardance between two orthogonal axes called the fast and slow axes. The phase of the electric field vector parallel to the slow axis is retarded with respect to the fast axis. As such if the axis of polarization of incident light is exactly 45° from both the fast and slow axes the LCVR is capable of acting like a variable wave plate ie. 0λ, $\lambda/4$, $\lambda/2$, $3\lambda/4$, λ and everything inbetween.

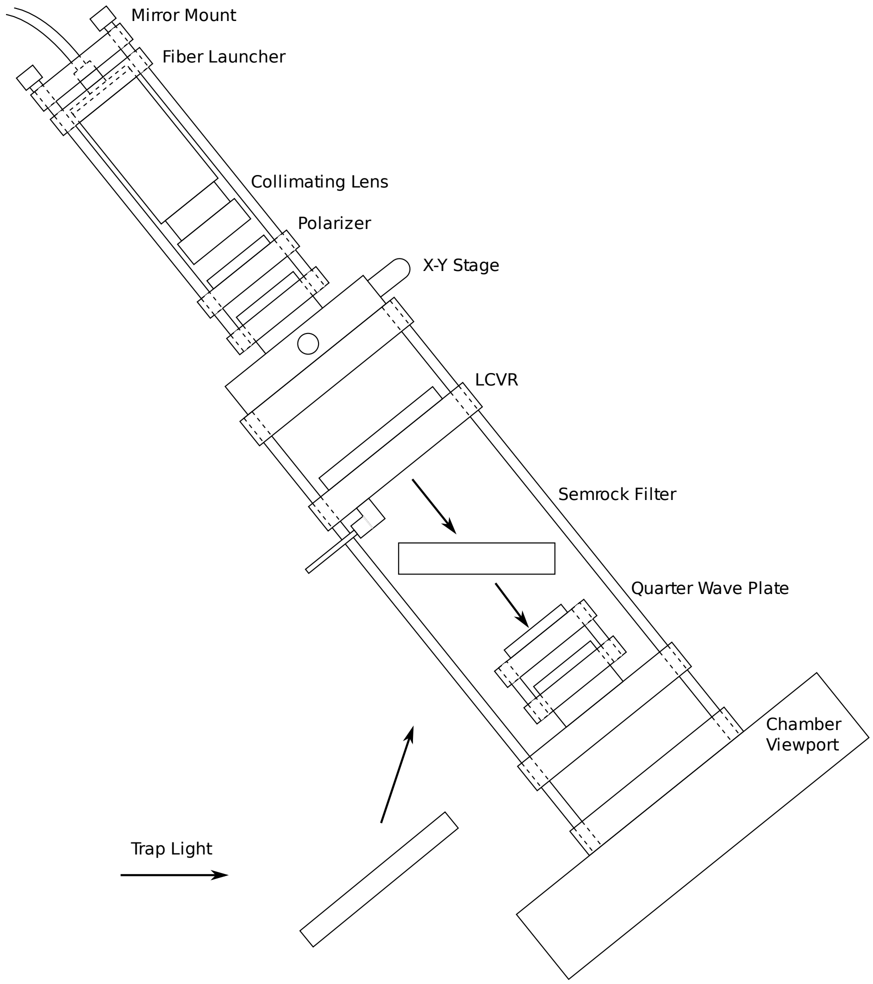

Figure 5: Diagram of upper optical pumping apparatus. The optical pumping light enters through the fiber at the top and the trap light enters from the side.

The magnitude of the retardance is controlled by the amplitude of the voltage of an applied square wave. Larger voltages result in less retardance. To switch between the different circular polarization handednesses the LCVR will be toggled between the two voltages for 0λ and $\lambda/2$ which will either not rotate or rotate the axis of polarization by $90°$.

The angle of the LCVR was set by aligning a groove in the glass substrate with $45°$. The metal case that contains the glass and polymer layers that constitute the actual LCVR had markings on it indicating the fast and slow axes but those markings were about $5°$ different than the groove in the glass. The angle of the polarizer was set by setting the LCVR to be a $\lambda/4$ and tuning both the polarizer angle and the LCVR voltage to acheive the best circular polarization as measured by S_3. This was repeated with the LCVR acting as a $3\lambda/4$. In principle the angle of the initial polarizer to give the best circularly polarized light should not change when the LCVR is switched between being a $\lambda/4$ and a $3\lambda/4$. In practice the angle changed by about $4°$. At this stage the angle of the initial polarizer was set to halfway between the angles for each handedness.

With the polarizer angle set and the LCVR angle set the quarter wave plate was inserted and the LCVR was set to retard by 0λ which preserves the linearly polarized light from the polarizer and so the quarter wave plate will create circularly polarized light when its fast and slow axes are $45°$ to the axis of polarization. The LCVR voltage and the angle of the quarter wave plate were tuned to give the best circular polarization. This was repeated for the LCVR acting as a $\lambda/2$. The difference in the angle of the quarter wave plate for the best circular polarization in each case was about $2°$. This implied that the LCVR was not rotating the axis of polarization by exactly $90°$ when switched between 0λ and $\lambda/2$. This was due to the polarizer not

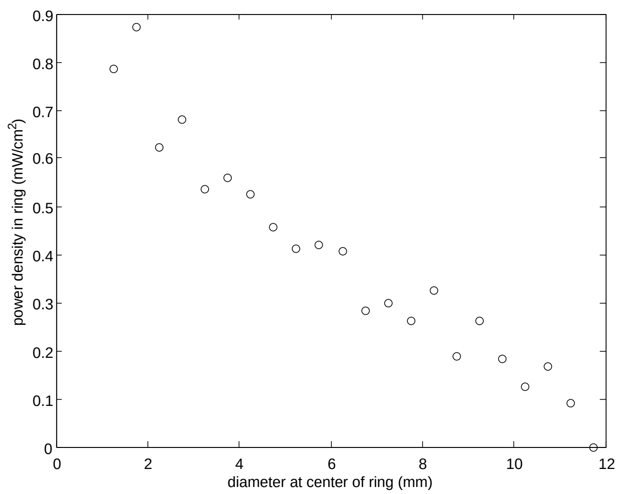

Figure 6: Plot of power density in a ring versus the diameter of that ring.

being set at the correct angle instead of an error in LCVR voltage. If the LCVR voltage is not set exactly to the 0λ or $\lambda/2$ values then the LCVR is changing the linearly polarized light into slightly elliptically polarized light which when passing through the quarter wave plate does not give as well circularly polarized light. There is no way to change the angle that linearly polarized light is rotated and still have linearly polarized light after by changing the LCVR voltage.

The polarizer angle was then moved and for each polarizer angle the LCVR and quarter wave plate were tuned to give the best circularly polarized light for both handednesses. The LCVR voltages stayed roughly the same while the quarter wave plate angles moved closer together until they were indistinguishable. This is important since the only thing that we can change to switch the polarization is the LCVR voltage. If the angles would not have coincided we would have had to set the quarter wave plate angle between the two best values and live with that. Our goal for this experiment is to measure A_β to be one part in one thousand. To do this we need the nuclear polarization of the cloud to be one part in one thousand. This implies that $1 - S_3$ should be 2×10^{-3}. Our chosen goal for $1 - S_3$ is 3×10^{-4} or $S_3 = 0.9997$. Note that better circular polarization implies larger values of S_3 and smaller values of $1 - S_3$.

Setting the angles of the polarizer, LCVR, and quarter wave plate as well as the LCVR voltage were all done away from the chamber. Figure 7 shows the final sweep of the LCVR voltage over the 0λ setting for the best angles of the polarizer and quarter wave plate on the lower setup. The best value of $1 - S_3$ was 4×10^{-6} at 5.625 V. A similar sweep over the $\lambda/2$ setting of the LCVR gave 3.1×10^{-5} at 2.038V. Mounting the upper and lower apparatuses onto the chamber required removing the quarter wave plate and remounting it which disturbed the angle by approximately 2-4°. Figure 8 shows the results of sweeping the angle of the quarter wave plate on the lower setup to find the best circular polarization again. Measuring the circular polarization on the chamber was difficult because of physical space restrictions and because the optical pumping light was being chopped on and off as it will be in the experiment. The error on the result is larger but values of 1.9×10^{-4} and 2.3×10^{-4} were measured for $1 - S_3$ for 0λ and $\lambda/2$ respectively. The results on the chamber of the upper setup are not as good. Currently the best values of $1 - S_3$ ocurr at different angles of the quarter wave plate which is consistent with the initial polarizer angle being incorrect. This has not been fixed yet due to other more pressing issues. At the current angle of the quarter wave plate which is approximately halfway between the two angles for best $1 - S_3$ the measured values of $1 - S_3$ are 1.5×10^{-3} and 2.3×10^{-3} for 0λ and $\lambda/2$.

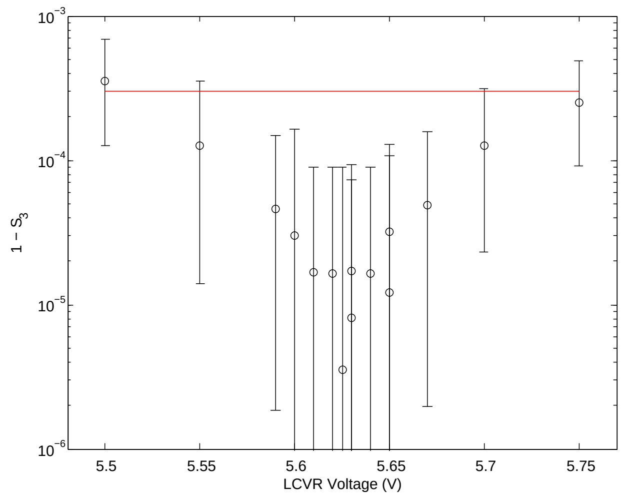

Figure 7: Final sweep of the LCVR voltage at the 0λ voltage after optimizing the polarizer and quarter wave plate angles. This plot is for the lower optical pumping assembly before mounting it on the chamber. The red line indicates our goal of $1 - S_3 = 3 \times 10^{-4}$. A smaller value of $1 - S_3$ is better.

2.3 Nuclear polarization

Measuring the circular polarization of the optical pumping light is important as a diagnostic but we need to know the nuclear polarization in order to measure A_β. To measure the decay fluorescence a photomultiplier was attached to the chamber. A sample fluorescence curve is shown in figure 9. The nuclear polarization, P, can be estimated from the relative strength of the peak to the tail of the curve as $P = 1 - \text{tail/peak}$. The latest results are that the nuclear polarization for the two handednesses are 0.989 ± 0.005 and 0.967 ± 0.01.

From the measurements of $1 - S_3$ above the nuclear polarization in theory should be at least 0.9992 and 0.9989 ie. $(S_3 + 1)/2$ using the values from the upper setup. One known factor that I worked to quantify in my first four months here is the impact of the viewports on the beam. Tightening the viewports to sufficiently to allow the creation of a 1×10^{-9} torr vacuum creates birefringence in the viewports. Based on those previous measurements this alone is not enough to cause the discrepancy. Another possible reason is that the power balance between the optical pumping beams, one coming upward, one coming down, is not very good right now. The power through one fiber might be twice as much as the other. This is due in part to steering induced by the Acoustic Optical Modulator (AOM) that is being used to chop the optical pumping beam on and off. A third reason for the low nuclear polarization might be that the magnetic field is too large during the optical pumping time.

3 Conclusion

We have acheived at least 0.967 ± 0.01 nuclear polarization of our atom cloud. This is approximately as good as the previous measurement several years ago. There are still a few things to tune and to check so we have hope that we will be able to do much better.

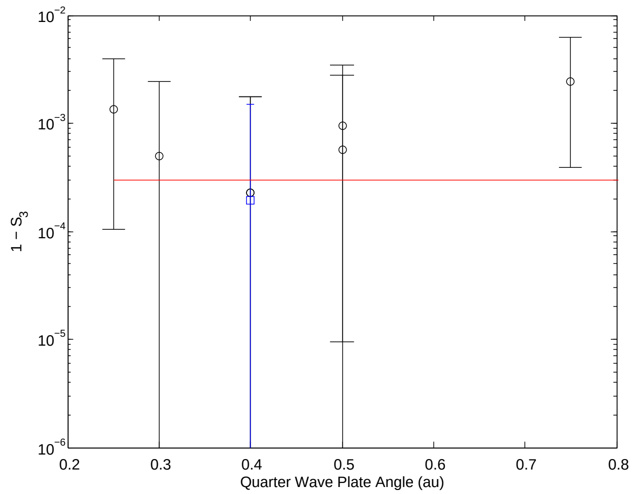

Figure 8: Sweep of the quarter wave plate after moving the lower assembly to the chamber. This is measured before the light enters the chamber. The LCVR and initial polarizer angles were not touched. The errors on this measurement are much greater than in figure 7. The red line indicates our goal of $1 - S_3 = 3 \times 10^{-4}$. A smaller value of $1 - S_3$ is better.

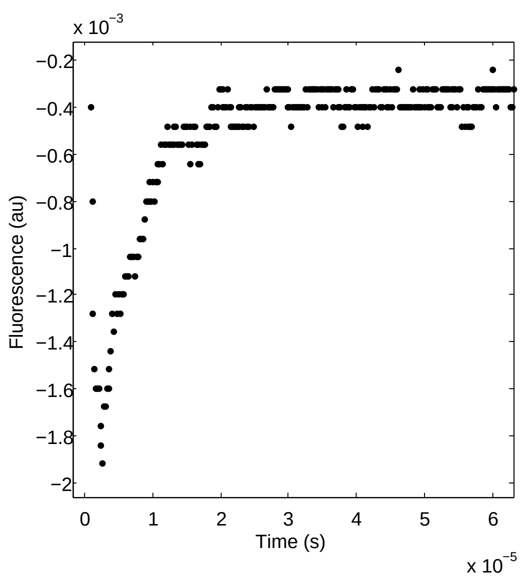

Figure 9: Sample fluorescence plot; more light means a more negative signal. The background, not shown, must be subtracted to calculate the nuclear polarization.