# Lifetime Measurements of the $5^2P_{1/2}$ state in K-39 at TRINAT

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**Abstract**

The lifetime of the $5^2P_{1/2}$ state in K-39 was measured at TRINAT using a photoionization technique on cooled potassium 39 atoms in a magneto-optical trap. Once the atoms were trapped a 405nm diode laser was used to excite the atoms to the $5^2P_{1/2}$ state, where they were then photoionized using the 767nm trap light. A chopping technique was applied to excite the atoms and then allow them to decay as they were being photoionized. The resulting photoions were detected using a microchannel plate. This yields a lifetime of 140.00(11)ns (GET THE REAL ERROR) for the $5^2P_{1/2}$ state of potassium.

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# 1 Introduction

The research group TRINAT conducts their experiments at TRIUMF located in Vancouver, BC. The Tri-University Meson Facility (TRIUMF) is Canada's National laboratory for nuclear and particle physics. They have a cyclotron which is used to produce the various radioactive isotopes required by the experimentalists at this facility. The TRIUMF Neutral Atom Trap (TRINAT) is headed by Dr. John Behr, and this group traps and studies neutral alkali atoms for use in beta decay experiments testing the Standard Model. They trap these atoms using a Magneto-Optical Trap (MOT), which consists of 6 counter-propagating laser beams and anti-helmholtz coils which cool and trap the atoms to temperatures on the order of a mK in a 1 mm sized cloud.

This work term the lifetime of the $5^2P_{1/2}$ state of $K^{39}$ was measured using a photoionization technique similar to time-correlated single photon counting. The basic idea is that the trapped atoms are excited into the $5^2P_{1/2}$ state using a 405nm laser. Once the atoms populated this excited state the MOT light would then photoionize them. We are detecting the photoions produced as oppose to the fluorescence in this experiment. Furthermore, we are using light at a wavelength short enough to photoionize only the $5^2P_{1/2}$ state and not lower lying states, thus allowing us to directly measure only this lifetime. As of yet we have not found any other lifetime measurments for this state, thus achieving one of similar accuarcy as the $5^2P_{3/2}$ state measured by W.Happer et al. to be 140.8(1.0)ns [1], would allow for comparison to theory. Finally, perfecting a way to measure lifetimes in this stable isotope of potassium with the existing setup, would allow for future extensions to the radioactive isotopes of Francium.

# 2 Theory

## 2.1 Magneto Optical Trap

The MOT is achieved using 6 counter propagating laser beams along orthogonal axes, which are all slightly detuned below resonance. These beams are made using a Coherent 899 Titanium Sapphire laser adjusted to output light with a wavelength slightly lower than the 766.7nm (767nm) resonant transitions. As a result, moving atoms would experience a Doppler shift. If the atoms were moving towards the beam they would be Doppler shifted towards resonance and if it were moving with the beam they would be shifted away from resonance, thus experiencing an overall force opposing its motion. This would act as a damping force slowing the atoms down, creating what is known as optical molasses.

A quadrupole magnetic is also used, created from anti-Hemholtz coils, which in turn causes Zeeman splittings in the atom. Circularly polorized light of opposite helicities propagate in opposite directions along each axis. Figure 1a) shows this situation for the z-dimension. As a result, for a laser tuned below the $B = 0$ resonance, an atom at $z > 0$ will absorb more $\sigma^-$ photons then $\sigma^+$ photons, observing an overall force towards the center. A similar situation occurs for atoms at $z < 0$, but the absorbtion preference is reversed again forcing the atoms towards the center.[5]

The laser beams and anti-Hemholtz coils work together to create velocity and position dependent forces respectively, producing a cool trap that remains in the same position.

## 2.2 Lifetime Measurments

Radiative lifetime measurements yield information concerning the atomic structure of an atom. They are most commonly used to check the *ab initio* calculations in atomic theory. The lifetime of a state k is related to the sum of the Einstien A coefficients for all the levels i lower in energy then k as shown by the formula below. [2]

$$\tau_k = \frac{1}{\Sigma A_{ki}} \tag{1}$$

Now the value of $A_{ki}$ is related to either the line strength of the transition, S, or the oscillator strength, $f_{ik}$, according to:

$$A_{ki} = \frac{16\pi^3}{3hg_k\lambda^3\epsilon_0}S = \frac{2e^2g_i\pi}{m_ec\lambda^2g_k\epsilon_0}f_{ik} \quad (2)$$

Here S is the line strength defined as:

$$S = <\psi_k|P|\psi_i>^2 \quad (3)$$

and $f_{ik}$ is the oscillator strength of the transition defined as:

$$f_{ik} = \frac{2}{3}\frac{\Delta E}{g_i}S \quad (4)$$

where $\psi_i$ and $\psi_k$ are the initial and final state wave functions and P is the appropriate multipole operator, or S is simply the square of the transition matrix element.[2]

It is clear from equation 2 that $A_{ki}$ is proportional to the line strength, so looking at the ratio of the linestrenths of the two states should allow us to say which state has the longer lifetime. If we consider the ratio of the n=4 states we obtain $\frac{4^2P_{3/2}}{4^2P_{1/2}} = (\frac{0.541}{0.333})^2 = 1.999$. [3] Since this is less than 2 it implies that the $P_{1/2}$ state has a longer lifetime then the $P_{3/2}$ state. This is indeed the case as the lifetimes are 26.69ns and 26.34ns for the $4^2P_{1/2}$ and $4^2P_{3/2}$ states respectively.[4] Applying this to the n=5 state yields $\frac{5^2P_{3/2}}{5^2P_{1/2}} = (\frac{0.406}{0.275})^2 = 2.180$. Unlike the n=4 situation the n=5 state have several decay paths including the $5^2P_{1/2} -> 3^2D_{3/2}$ transitions which are very poorly calculated. Thus, it is difficult to apply this procedure in order to determine the how the lifetime of the $5^2P_{1/2}$ state should compare with the $5^2P_{3/2}$ state.

There exist many ways to measure the lifetime of a state all of which can be classified into two categories, time domain and frequency domain. Each of these have there own systematic problems associated with them. [6]

Since the experiment presented here can be classified as a time domain measurement, the focus of this section will be on the advantages and systematics effects associated with using the technique. Like most other types of lifetime measurements the atoms were excited to the desired state and then the decay from this state was recorded. However, in this experiment photoionization was employed, as a result, the photoions were used to monitor

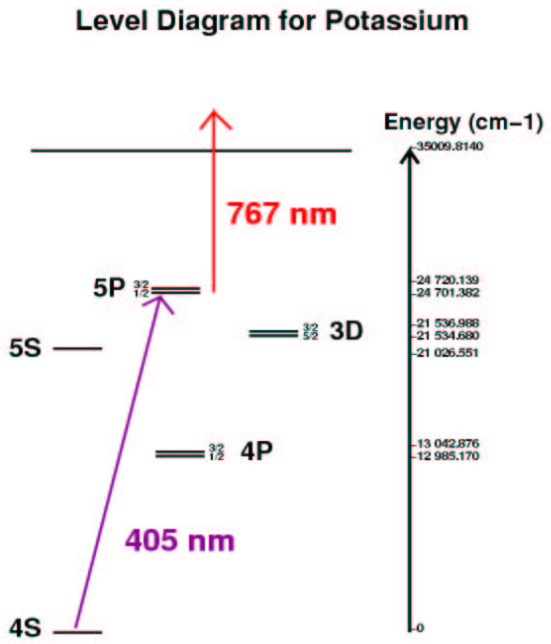


Figure 1: The level diagram of K-39 showing the photoion production.

the decay of the atoms from the $5^2P_{1/2}$ state. Since atoms in this excited state do not decay directly to the ground state but through three possible paths, observing the fluorescence produced to measure the lifetime would require knowledge of the branching ratio, which is only known to an accuracy of about 50%. [7] We measured the photoions from this state so no knowledge of the branching ratio or specific decay path taken is required allowing us to directly monitor and measure the lifetime. Figure 2 shows the level diagram of K-39 and how the photoions were produced.

There were two main systematic effects observed in this experiment, Radiation Trapping and Quantum Beats.

Radiation Trapping occurs when an excited atom releases a photon which is then reabsorbed by another atom before it is detected. As a result, the lifetime of the state would appear to increase. This effect becomes more dominant as the optical density of the trap increases.

Quantum Beats can occur if the energy separation between two sublevels is comparible to the bandwidth of the laser pulse. If such a situation exists then you may cause a coherent excitation of both states resulting in a sinusoidal modulation of the exponential decay. This occurs since short laser pulses in the time domain, once Fourier transformed, result in a broader function in the frequency domain. This is known as power broadening of the laser, and will increase the chance for coherent excitation. Such a situation can occur between the magnetic sublevels as well, and this phenomenon is known as Zeeman Quantum Beats.

The subsection on errors found in Observations and Analysis discusses how these systematics were treated in order to minimize their effects.

# 3 Experimental Setup

## 3.1 Light Profile

One of the first tasks completed was to measure the light profile of the 405nm and 770nm diode lasers. This was done mainly for the photoionization cross section experiment, but it was useful to know how large and uniform the 405nm light was over the trap for the lifetime measurement. I will only report the findings for the 405nm light. This light entered the MOT through one of the side viewports so that it was overlapped with the 770nm light for the photoionization experiment. A mirror was then placed in front of the viewport which brought the light over to a power meter. This power meter was stationed approximentally the same distace away from the beam as the MOT center, and was placed on an adjustable mount so that there was both horizontal and verticle freedom. This allowed us to locate the maximum of the beam and then scan it along the x and y axes. Figure 3 shows the data obtained from this procedure and shows both the gaussian fit and theortical gaussian produced by PHYSICA.

The full width at half maximum (FWHM) of the horizontal and verticle profiles for the 405nm light was found to be 3.35mm and 6.10mm respectively. Since the trap size is on the order of 1mm in size we were confident that the 405nm light well surronded the trap and was fairly uniform over its structure.

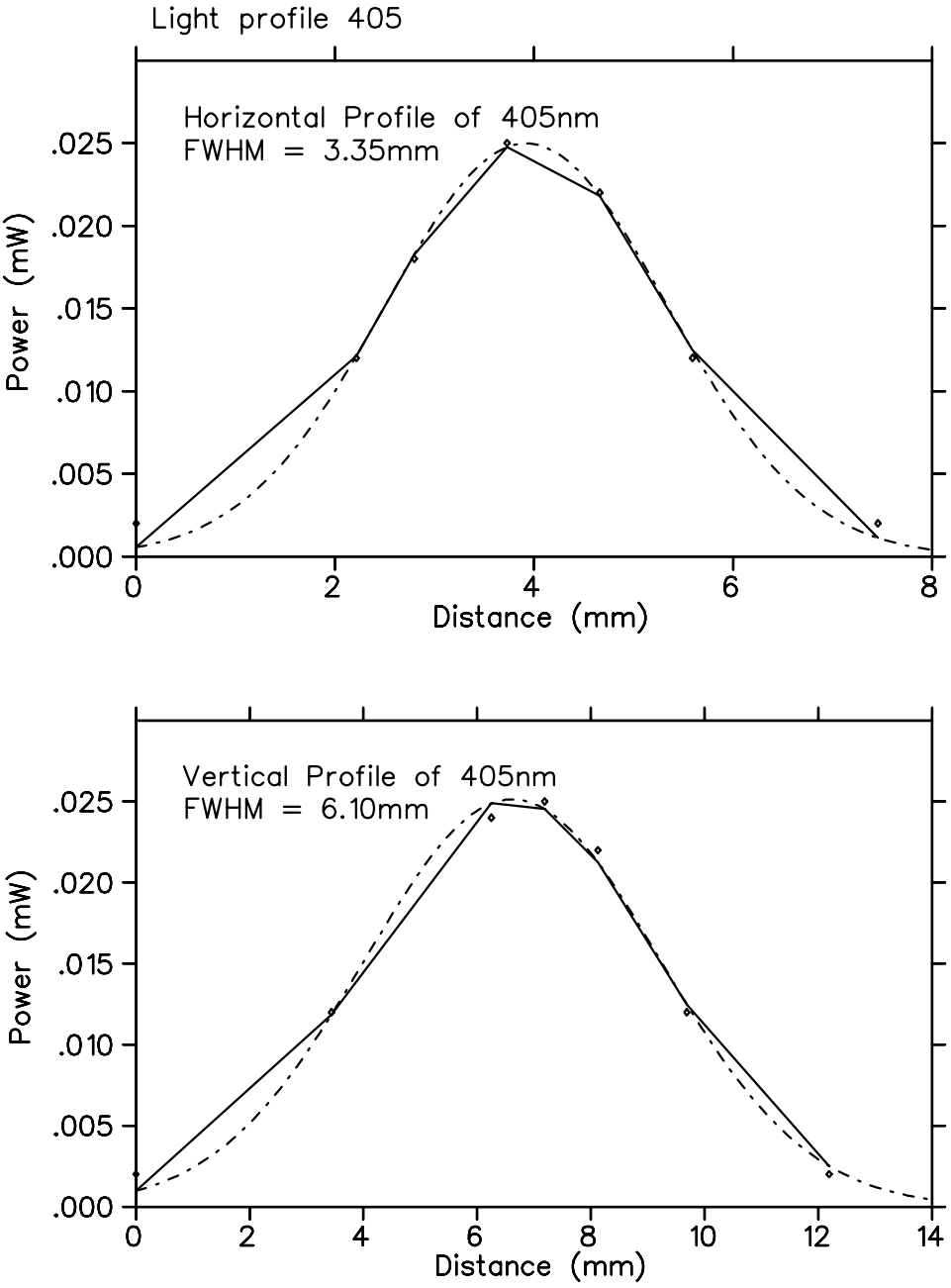


Figure 2: The horizontal and verticle profile of the 405nm laser.

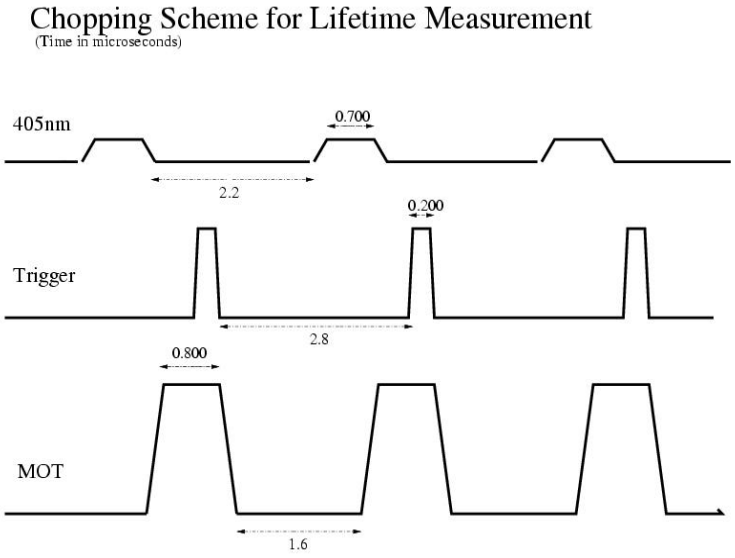


Figure 3: The chopping scheme used for the lifetime measurement of the $5^2P_{1/2}$ state in $K^{39}$

## 3.2 Methodology

The potassium 39 atoms were sent into the MOT via a dispenser, which allowed us to control the density of the atoms in the trap. Once the atoms were dispensed into the first MOT they were cooled and trapped. The atoms were then pushed into a second MOT in order to provide a lower background enviroment. The trapping lasers for the second MOT were closer to resonance, meaniing this trap had a smaller size and was more optically dense. After the initial transfer of atoms from the first to the second trap, more were periodically transfered to ensure a constant number of atoms trapped in the second MOT. These trapped atoms were then excited into the $5^2P_{1/2}$ state with a 405nm laser, locked to the F=1 to 2 resonance using saturation spectroscopy. [8] The 405nm light and the MOT light were chopped on and off opposite to each other via acousto-optic modulators (AOM), the duty cycle created is shown in Figure 4.

Crudely speaking an AOM is a device which applies a sound wave, provided by a RF driver, to an optically transparent crystal. This in turn creates

a phase grating which diffracts incident light, allowing frequency control and steering. By chopping the RF driver on and off we can allow and prevent light from transmitting through the crystal, thus creating our desired chopping cycle. This chopping was done to maximize the count rate on the microchannel plate (MCP) and allowed for photoionization and decay of the state to occur simutaneously. The 405nm and MOT light overlapped for approximentally 200ns as seen in the figure, and this is where the photoionization begins. The 405nm light excites the atoms, and just before it turns off the MOT light turns on and is allowed to reach full power. This can then photoionize the excited atoms into the continuum. As the 405nm light shuts off the $5^2P_{1/2}$ state begins to decay thus less photoions are produced and the lifetime is measured. The photoions created in this procedure are collected using a MCP and stored using the data acquisition system MIDAS.

In order to account for background in the MCP and the AOM fall time of the 405nm light several runs were taken. In the background run both the 405nm light and the MOT light were turned off and background was counted at a rate of 50Hz for approximentally 2 hours. Then the 405 nm light was sent into the trap off resonance with the MOT light at the normal duty cycle. This allowed us to measure the AOM fall time, but underestimated the background so this had to be taken into account during the analysis. This type of run was done at several differnet count rates in attempts to match the rates used during the lifetime measurement.

## 3.3 Data Sorting

The largest problem encountered was a consistent determination of the background in the MCP so that it could be included in the fit of the lifetime. To assist in minimizing the background effects and improve the signal to background ratio, the in house computer program NOVA was used which would make cuts to the incoming data from the MCP in real time. It also allowed for dead time corrections in the electronics. Figure 3 shows a typical run and the resulting MCP data.

It is clear that 'flares' occur causing a large amount of background that is not the true background or real counts for the decay of the state. These flares are believed to be caused since the trap itself blocks some of the retro reflected beam in the MOT thus making it weaker than its counterpart. This would cause the atoms to 'leak' out of the trap creating false MCP hits. There

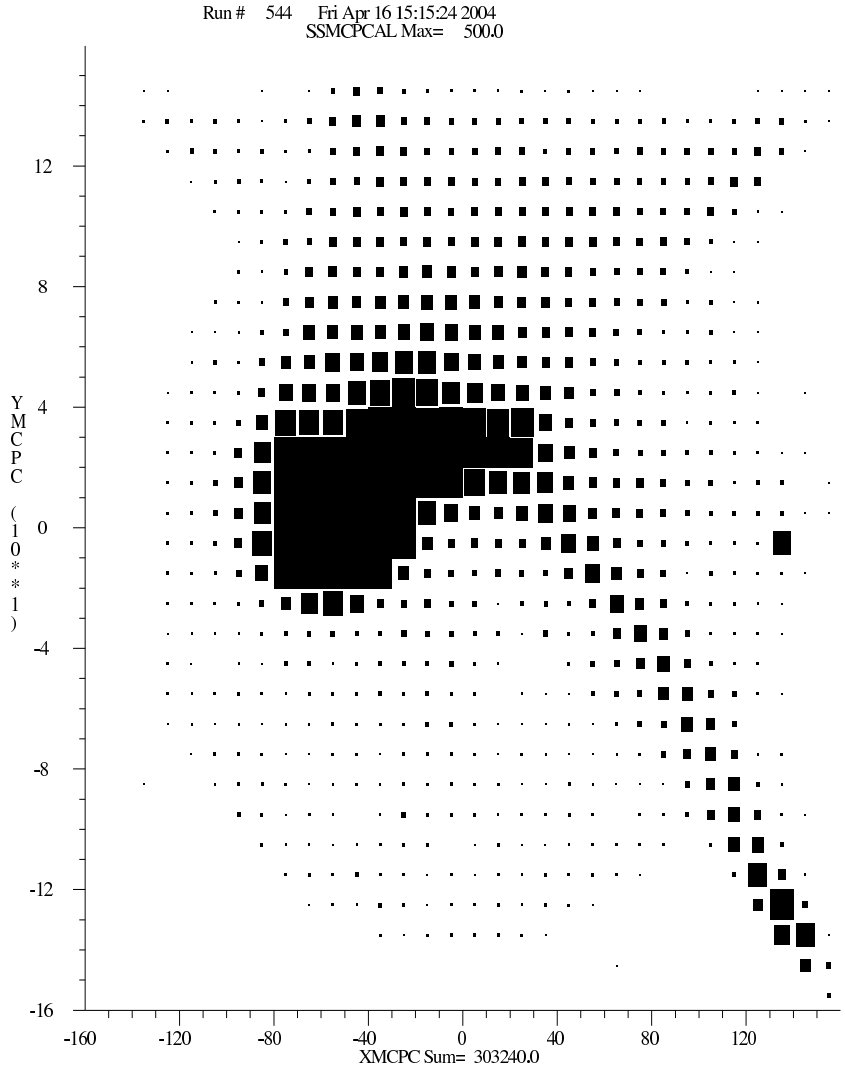


Figure 4: MCP position sensitive readout for run 544

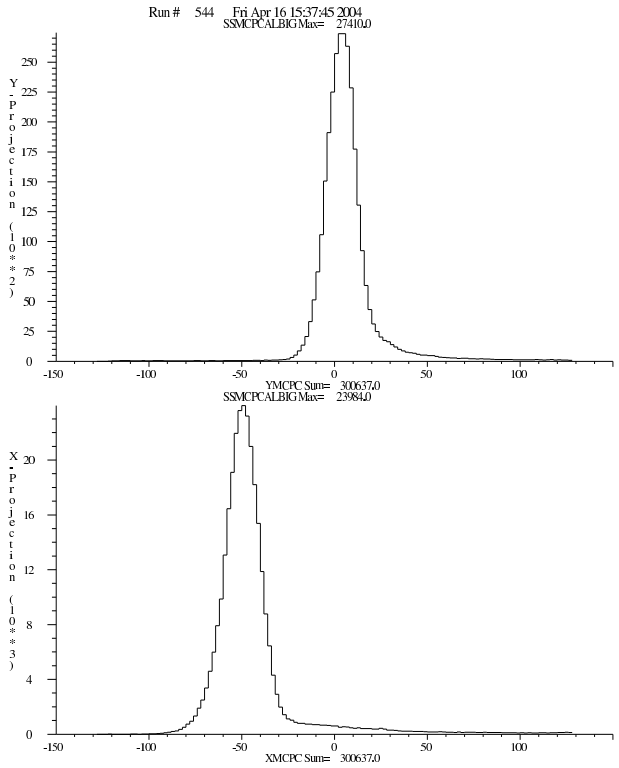


Figure 5: The x and y projections of the MCP position sensitive readout run 544

is also a dead spot on the MCP caused by an earlier experiment that must be avoided. So efforts were made to ensure that the trap did not cover this part of the MCP. Finally, the natural background, as well as, the flares could be reduced by making tight cuts to the MCP itself. Figure 5 shows the x and y projections of the MCP position sensitive readout.

The cuts were made at $-64 < x < -34$ and $-14 < y < 16$ in the x and y axes respectively. Although this did throw away approximentally 18% of the real events it was believed that this was required to improve the signal to background ratio by reducing the background. It simply meant we needed to count for longer to get similar statistics. Another cut on the MCP pulse height was made since it was seen that about 2/3 of the background could be elminated from this with almost no effect to the real pulse height. Figure 6 shows both the MCP pulse height from the signal and from the background,

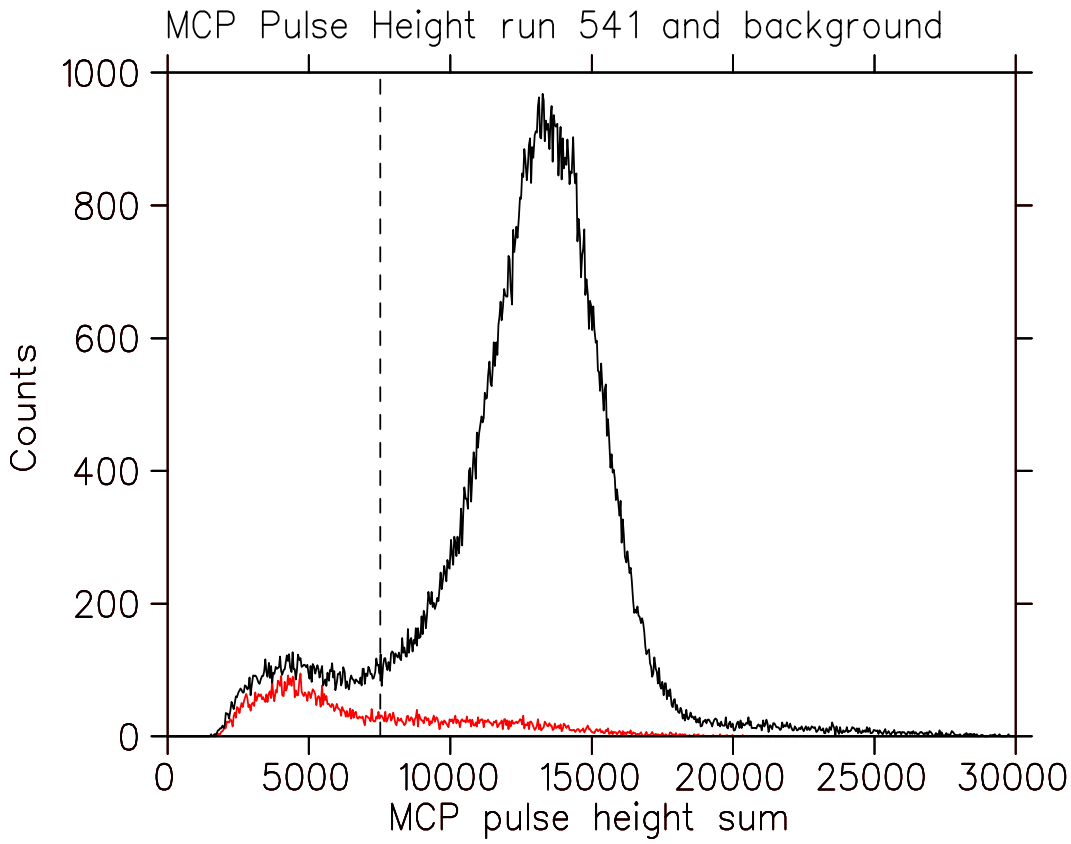


Figure 6: MCP pulse height for the signal and the background

as well as, the where the cut was made.

# 4 Observations and analysis

## 4.1 Fitting

The data accumulated from each run with the appropriate cuts applied was sorted to give a log plot of the number of counts in the MCP versus time. The data was then arranged into bins of four and the decay of the lifetime of the $5^2P_{1/2}$ state was modeled using an exponential of the form shown below.

$$ExponentialFit = A\exp(\frac{-(t-t_0)}{\tau}) + B \quad (5)$$

A is the height of the signal, B is the background calculated by normalizing to the background run, t is the time passed in nanoseconds, $t_0$ is the starting point of the fit, and $\tau$ is the lifetime of the state. In the fitting program the values of A and $\tau$ were allowed to vary while the rest remained fixed. Attmepts were made to allow B to vary as well, however the background obtained from the fitting program was not consitent with the background calculated from the data, so it was decided to leave the background fixed to the measured value.

The fitting program was then adapted to include the AOM fall time of the 405nm light once it was chopped off. The background obtained from the data for these runs underestimated the previous background measurement so this was adjusted accordingly and the final fit for the lifetime was changed to:

$$ExponentialFit = A\exp(\frac{-(t-t_0)}{\tau}) + falltime + AdjustedBkg \quad (6)$$

Again only A and $\tau$ were allowed to vary, whereas the other constants were kept fixed to experimentally measured values.

## 4.2 Runs

Each run was then analyzed and fit with either equation 1 or equation 2 if the data was available. The fit then generated a value for the lifetime of the $5^2P_{1/2}$ state for that run. Once the fit was completed the $Residual = \frac{Data}{Fit}$ was plotted to see how well the fit matched the data. It was important to ensure that each run contained the correct background and if the data allowed the AOM fall time. Figure 6 shows a sample run at a low count rate (low optical density). The first graph shows counts recorded by the MCP versus time, as well as, the AOM fall time normalized to that runs peak. The AOM 10%-90% fall time for the 405nm light was found to be 28ns. The second curve shows the data after the truncation to which the fit was applied and the fit itself. Finally the last graph shows the residual of the fit.

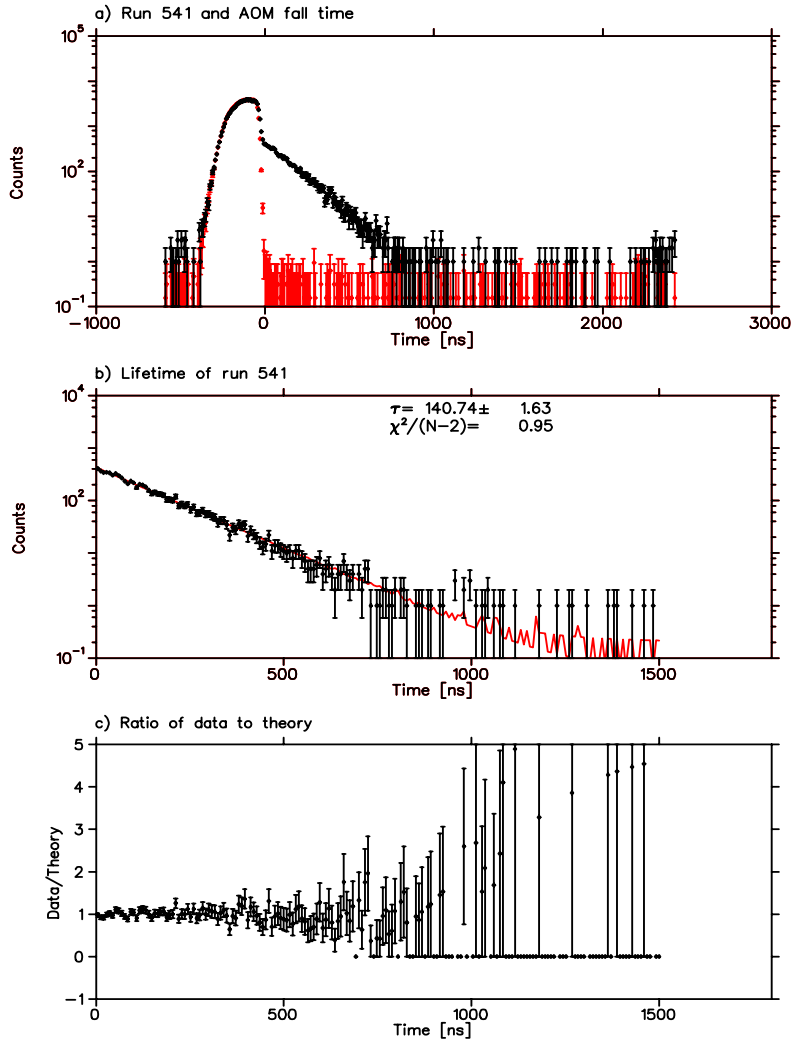


Figure 7: a) The data obtained from run 541 with the AOM falltime. b) The fit curve and the truncated data. c) The residual of the fit.

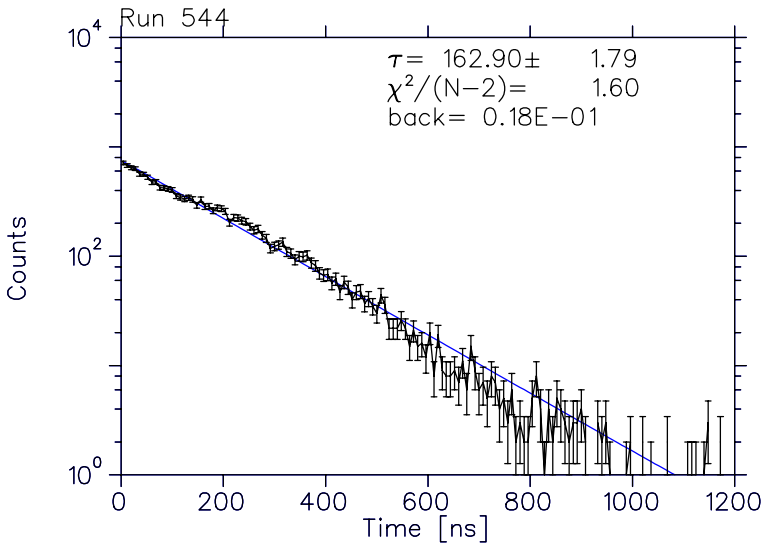


Figure 8: The fit of run 544 with a normalized countrate of 13.7

Every effort was made to ensure that the conditions from run to run remained constant, however the frequency lock of the laser did vary from day to day and may have varied from run to run.

An interesting effect was noticed at the higher count rate (optical density) runs as shown in figure 7. There seemed to be a bump which occured approximentally 150ns after the start of the fit. This may be due to deadtime effects in the electronics since we were running at high count rates.

This is quite plausible since deadtimes occur when more events come in then the electronics can process. For example while the electronics are busy handling one count another count may come in that goes undetected or not noticed by the electronics until later. Such an effect is the most likely explaination for the bump seen in this figure.

## 4.3 Radiation Trapping

We were concerned about radiation trapping in the system so in order to check for it the value of the dispensor setting was changed from run to run, while the rest of the settings remained constant. By increasing the dispenser setting we could trap more atoms, increasing the optical density of the trap.

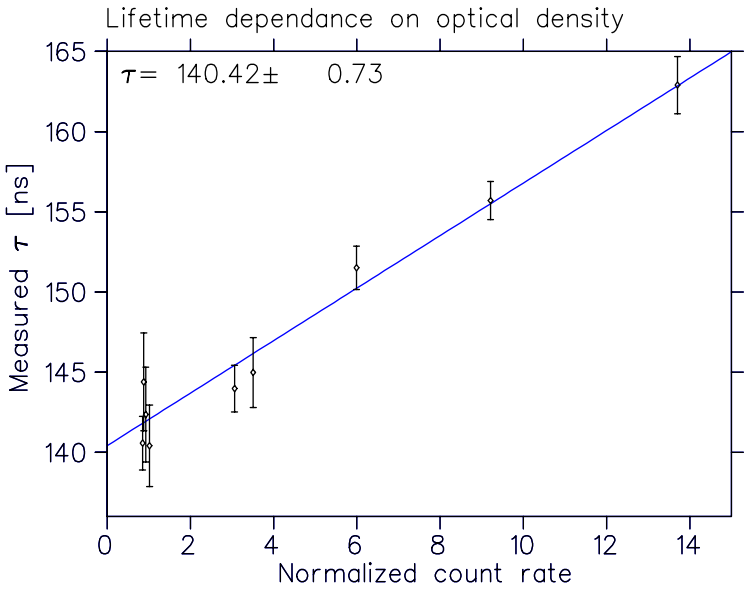


Figure 9: The lifetime dependance of the $5^2P_{1/2}$ state on optical density.

This would result in a longer lifetime measurement if radiation trapping was present. The runs were completed and the lifetime of the state increased with the optical density. To be able to account for this effect the lifetime calculated from each run was plotted against the countrate normalized to the background runs pulsers. These values are proportional to the optical density, and were fit with a straight line, as shown in figure 7. The radiation trapping was modeled and the first order approximation was taken, which varies linearly with the number of atoms in the trap. This was then extrapolated back to zero, or no optical density, where radition trapping would have no effect. This gave a value of 140.42(73)ns for the lifetime of the $5^2P_{1/2}$ state. So using this method we believe that we have accounted for radiation trapping as a systematic effect.

## 4.4 Truncation Error

It is clearly seen from figure 8 that we must chose an arbitrary location to start the fit (the value of $t_0$). If we vary $t_0$ it is observed that the lifetime changes by 2-3%. This effect is known as truncation error.[9] Although it

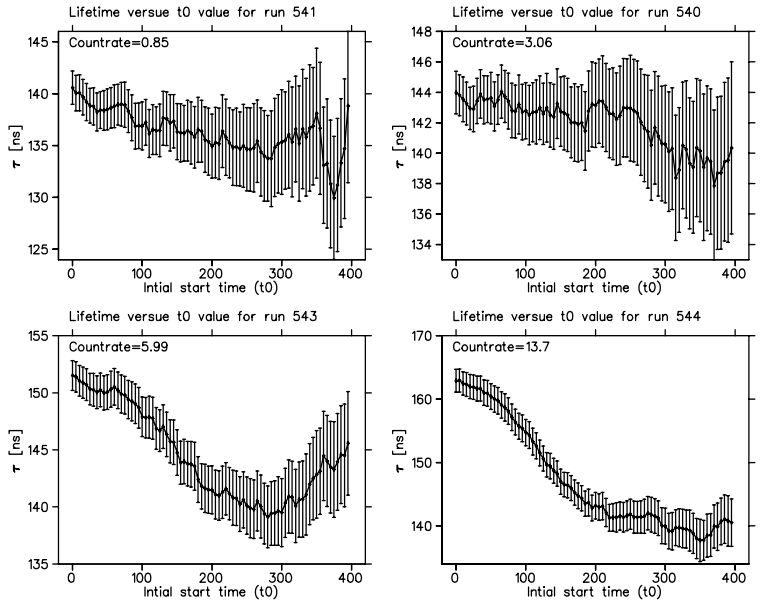


Figure 10: The effects of truncation error on the lifetime measurement for several different runs

does seem to change systematically it is very difficult to be sure, as the statistcal quality of the data drops as the cuts are made farther along the decay curve. However, in the high optical density runs this effect seems to be more dramatic, when compared with the low density runs, as seen in figure 8.

It is not clear as of yet why the higher count rate runs exhibit this behavior more dramatically then the lower count rate runs. Looking closely at two of the high countrate runs reveals a sinusodal modulation indicating a possible quantum beats effect. Since the lifetime we calculate is an extrapolation to zero optical density due to radiation trapping a similar plot was created to see if the effect was present on the extrapolated value, or if it would statistcal drop away. Figure 9 shows a plot of how the extrapolated lifetime varies with the initial time cut and indeed a sinusodal modulation is observed.

This figure presents a strong case that quantum beats are inherant in this system and that they must be taken into account. For now we deal with this effect by average the sine function, or simply fitting a constant through the result. Figure 10 shows the extrapolated lifetime fitted with a constant

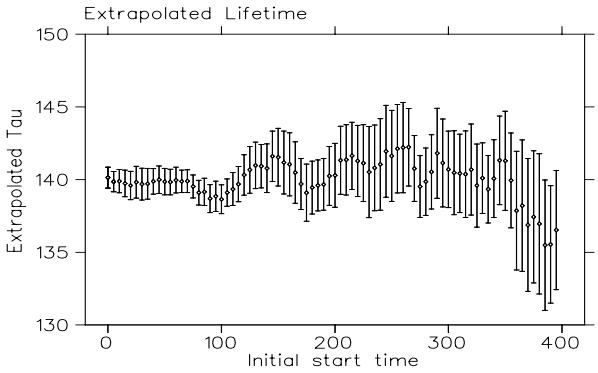


Figure 11: Effect of initial time cut on the extrapolated lifetime measurement

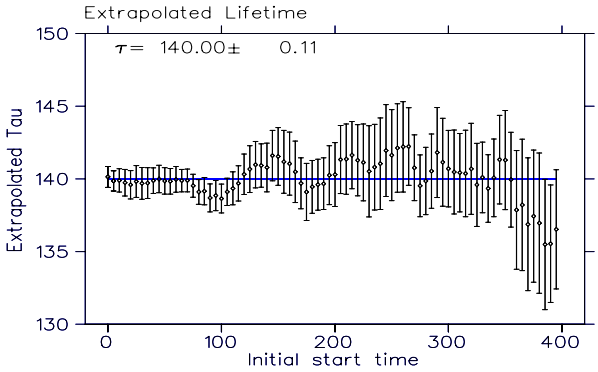


Figure 12: Fitting a constant value through the extrapolated lifetime measurements to account for quantum beats.

value this producing a lifetime of 140.00(11)ns. It is important to realize that the 0.11ns error seen here is only the statistical error and is not a true representation of the error on the lifetime measurement.

# 5 Conclusions and Recommendations

This approach to measuring the lifetimes proves to be a very powerful technique, as oppose to measuring flourescence, since it allows for a direct measurement with no consideration of the decay path or branching ratio of the state. As a result, we measured the lifetime of the $5^2P_{1/2}$ state of K-39 to be 140.00(11) (GET THE REAL ERROR).

The systematic errors associated with this technique are thought to be well understood except for the issue of quantum beats. To further improve on this measurement the error produced by quantum beats must either be elminated or more carefully included into the lifetime measurement.

Further improvements can be made to this experiment to both decrease the error and allow for better stastics without having to count for hours. Using the MBR laser to photoionize the $5^2P_{1/2}$ state would allow for more power, meaning better stastics without having to increase the number of atoms in the trap. Furthermore, it would allow us to check to see if there exists a polorization dependence on the lifetime. We are not absolutely convinced that the atoms in the trap have no polorization. By photoionizing them with different polorization from the MBR we could determine weather or not this was true. This cannot be accomplished with the present setup because the trap light does the photoionizing and its polorization cannot be changed without destroying the trap. The MBR would also allow us to photoionize the $3^2D_{3/2}$ state and measure its lifetime with a similar techinique to the one used in this experiment.

Another useful idea is to include the next order term in the radiation trapping expression into the fit of the lifetime, to see if this helps explain the strange effects observed at the high optical density runs. This may offer another explaination for the bump observed in this runs and may slightly improve the extrapolation.

Finally, being able to run at lower optical densities then achieved here would also help in the extrapolation technique used. The further we are from zero the more dangerous it is to extrapolate to it and believe the result. Again this would be easily accomplished using the MBR laser.

The lifetime measurement of this state has been seen to be a very difficult measurement to achieve to the accuracy required to be useful. Although we believe to have a 2% measurement it would be very nice to be able to decrease this to a 1% or even 0.5% number. Such a value is probably possible using

the MBR laser to photoionize the state.

# 6 Acknowledgments

I had an excellent term here at TRIUMF this winter and wish to express my deepest thanks to John Behr. John's passion and knowledge of physics really made this experience all the more enjoyable. I learned an incredible amount here by completing this experiment and gained a lot of coinfidence in the labratory through hands on experience. John encouraged my learning and further peaked my intrest in experimental physics. I hope to take this knowledge on to graduate work which may be here at TRIUMF.

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