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Muon Detector

Abstract

The aim of this experiment was to observe the exponential decay of muons by using a plastic scintillator for said particles to interact with, as well as to measure the muon mean lifetime and compare it to accepted values. The exponential decay was successfully studied, obtaining a mean life of $2.209 \pm 0.050\mu$s which is in excellent agreement with literature values of $2.197\,\mu$s. The evolution of the count rate over time was also analyzed observing a maximum at the solar zenith due to the warming up and expansion of Earth's atmosphere which causes a lower density supposing that the kaons and pions coming from cosmic rays decay into muon with more ease.

Contents

1 Introduction

When cosmic rays strike the atmosphere, mesons π and K[1] are generated, which can decay into muons μ with energies of a few GeV[2]. These, although they have a mean lifetime of just a few microsecond, they manage to reach the surface of Earth due to their relativistic speeds. When they do so, they interact with matter depositing their energy and therefore causing electron excitation.

The aim of this experiment was to observe the muon's exponential decay by using a plastic scintillator for said particles to interact with, as well as to measure the muon mean lifetime and compare it to the accepted values. The count rate of detected muons was also observed to study its evolution over time and examine what conditions and parameters affect its result.

This was done by connecting a photomultiplier tube to the scintillator sending the signals which would trigger 'START' and 'STOP' on the TAC (Time-to-Amplitude-Converter) indicating the time interval between the muon is stopped depositing all of its energy and it decays, therefore representing the muon lifetime for that event.

2 Theory

2.1 The lifetime of the muon

Primary cosmic rays reaching Earth, whether they are originated in galactic or extra-galactic sources are mainly composed of high-energy protons. These collide with nuclei in Earth's upper atmosphere, resulting mostly in the production of π and K mesons[1]. These light mesons later decay into muons and neutrino pairs as follows

$$\pi \rightarrow \mu + \nu_\mu$$

$$K \rightarrow \mu + \nu_\mu$$

causing a particle shower of relativistic muons which, due to time dilation, reach sea level heights despite their mean life of about $2.2\,\mu s$ [1, 3].

Once at the surface, the muons lose their energy mainly through ionisation, exciting atoms in matter in the process. These muons may even lose all of their energy reaching to a stop within the material before they reach the end of their lifetime and decay producing even more electron particles[3].

2.2 Muon detector with a scintillator

When a muon travels through a scintillator coming to rest, the energy lost in the process ionizes the plastic generating a pulse of light which is turned into an electrical signal via the photomultiplier tube. Only when the electric pulse is strong enough, the discriminator, which is connected to the PMT, will be triggered sending a fixed-width pulse 'START' signal to the TAC (Time-to-Amplitude-Converter). This same muon after being fully stopped at the scintillator losing all of its energy to excite the atoms in the plastic may later decay as described in section 2.1 with the neutrino leaving the scintillator without any further interactions and the electron leaving an ionization trail causing the discriminator to trigger again sending the 'STOP' signal as seen in Figure 1. The TAC then sends on a pulse the amplitude of which is linearly proportional to the time between both signals sent by the discriminator[3].

When a large amount of these pulses are recorded and displayed by a pulse height analyzer (PHA), an exponential curve described by

$$N = N_0 \cdot e^{-t/\tau} + C \tag{1}$$

is visible. This describes the probability of a muon surviving to a time t where N_0 is a normalisation constant representing the amount of muons in the first channel (i.e. the muons with minimal lifetime), τ is the muon mean lifetime, and C accounts for a small constant of background counts explained by accidental coincidences or electronic noise. Fitting this exponential form to the distribution of the time intervals amongst pulses allows the muon lifetime τ to be extracted experimentally[3].

Figure 1: Image captured in the discriminator representing the signal received through the PMT from a muon and the electron into which it decayed (in yellow) along with their corresponding pulses generated by the discriminator (in blue).

3 Methodology

3.1 Apparatus

The apparatus available used as part of this experiment were: a cylindrical plastic scintillator, a photomultiplier tube, an Ortec 456 high voltage power supply, a Quad Bipolar Amplifier, a LeCroy 623B discriminator and an Ortec 566 TAC. Other apparatus such as gate and delay generators, a CF discriminator or a 4-input logic were available to improve the accuracy of the experiment. However, these often introduced further delay and a lower resolution[4, 5]. For that reason, the use of these was discarded as an accurate result could be achieved without them.

The counts were recorded and displayed through the software KSpect the channels of which were converted to time intervals using the Teensy 4.0 Microcontroller programmed in Arduino/C and controlled from python[6]. In order to use this, LeCroy688AL Level Adapter was used for TTL to NIM conversion.

3.2 Experimental procedure

The first step was to connect all the necessary apparatus following Figure 2 with an amplifier between the PMT and the discriminator and a 2 m long cable from this one to the 'START' input in the TAC. Although this long cable will introduce a few nanoseconds of delay, this will not change the shape of the decay significantly still allowing an accurate measurement of the muon's mean lifetime.

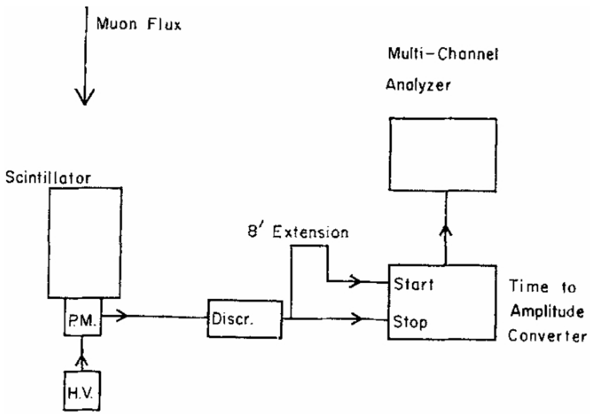

Figure 2: Diagram of the experimental setup[3].

Once this was done, the original signal was connected to an oscilloscope along with the signal output from the discriminator. The high voltage supply was set at 1.5 kV allowing one to observe a reasonable trigger rate with the lowest discriminator threshold value. By analyzing the signals in the oscilloscope, a discriminator threshold of about -0.4 V and a pulse width of 0.14 ns were selected. These values were chosen so that the discriminator would generate a single smooth pulse at reasonable signal strengths provided by the scintillator. Additionally, a range of $10\,\mu s$ was selected on the TAC so that all muons could be detected. This meant that if $10\,\mu s$ after a 'START' signal, o 'STOP' signal was received, then the next signal would be interpreted as the 'START' signal of the following detected muon rather than the 'STOP' signal of the previous one.

3.2.1 Calibration

Using the Teensy Double-Pulse Generator, the channels of the software were calibrated. A series of pulses ranging in time intervals from 0.2 to $10\,\mu s$ were generated. As some counts smeared to neighbouring channels, this calibration process was repeated 5 times in order to average the channel number and do the channel-to-time conversion by obtaining the parameters describing their relationship.

3.2.2 Muon detection

With everything set up, only the muon detection was left to do. 3 runs were performed. The first run lasted 150 hours, run 2 was 24 hours with a much higher discriminator threshold (i.e. more counts would be detected) and run 3 was again 150 hours with a threshold that was just slightly higher than the initial threshold of -0.4 V.

Once all the data was acquired, each run was analysed. A best-fit line was plotted on the final result following Equation (1). This allows one to obtain the muon's mean life τ as well as the background counts represented by C attached to their uncertainties. These were calculated by applying Poisson's errors on the counts per channel with a strong floor (the median of the Poisson errors of all channels before the first channel with 0 counts) so that later channels where low to none counts were detected wouldn't wrongfully weight the fit. On top of that, the counts per hour (and in the case of the 24 hour run, counts per 10 minutes) was obtained examining the evolution of counts over time explaining the dependence on the time of the day and helping a better calculation of the muon's life to be performed by helping identify and remove large intervals of running time where other sources might have been triggering the apparatus.

4 Results and discussion

The calibration line obtained and used throughout the experiment for the channel-to-time conversion can be seen in Figure 3. The slope obtained was of 400.27 ± 0.04 with an intercept of 1.15 ± 0.17. Although one would think that the intercept obtained should be of 0, this wasn't the case most probably because of the delay that the electronics implemented into the whole recording process.

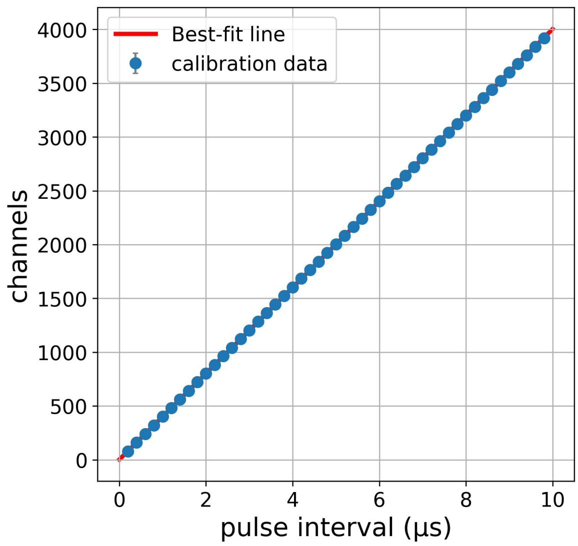

Figure 3: Calibration line used for channel to time interval conversion with slope

When the χ^2 test for goodness of fit was performed, a χ^2_ν value of 4.84 and a p-value ≈ 0 were obtained indicating that the fit was poor[7]. However, this is not because the fit doesn't represent accurately the relationship between the channels and the time intervals but instead because the errors were so small that they did not represent accurately the deviation of the data points from the best fit line. By rescaling the errors, the same slope and intercept were obtained (with slightly larger uncertainties) and a p-value of 0.47 was yielded proving the fit is excellent[7].

4.1 Run 1

The exponential decay obtained from the first run can be seen in Figure 4 with a mean life $\tau = 2.115 \pm 0.032\,\mu$s and a constant parameter $C = 0.687 \pm 0.136$.

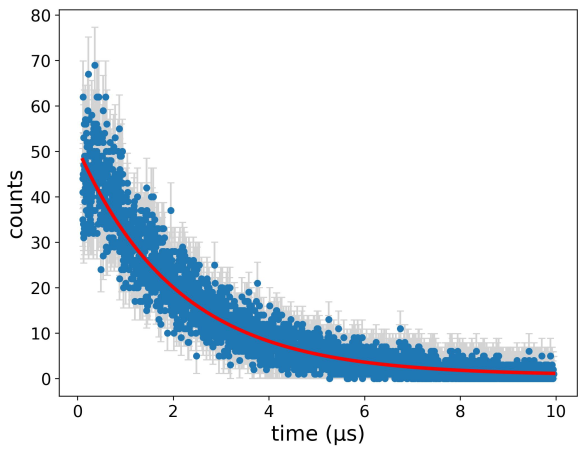

Figure 4: Exponential decay yielded from run 1 obtaining fitted parameters $N_0 = 49.94 \pm 0.45$, $\tau = 2.115 \pm 0.032$ and $C = 0.687 \pm 0.136$.

A chi-squared test for goodness of fit was performed obtaining a reduced chi-squared $\chi^2_\nu = 0.51$ and a p-value of 1 indicating the fit is too good. This was most probably indicating that the errors were too big although Poisson's errors were applied correctly. When a lower floor was used (e.g. 0.5 or 1 channels) to test the results, a muon mean life farther away form the accepted values was obtained yielding an exponential decay that was not representing the trend of the data accurately enough, resulting in a p-value $\leq 10^{-4}$ indicating a poor fit[7]. Therefore, for this and the following exponential decays, it was the original floor that was used along with Poisson's Error while being aware that the errors were overestimated.

Run 1 was investigated further in order to improve the results obtained. This was done by plotting the count rate (i.e. counts per hour) throughout time as seen in Figure 5.

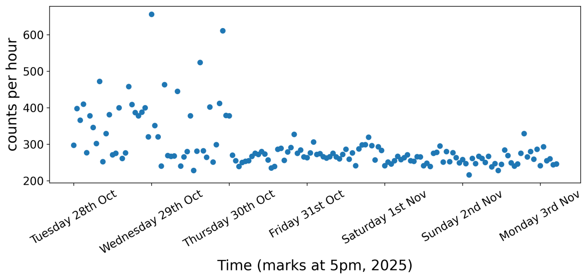

Figure 5: Count rate over time of the full data form Run 1. Time marks were set on the day marked at 5pm.

It can be observed how in the first 48 hours but specially in the first 24, a different source of radiation was causing the apparatus to trigger adding counts that did not corresponds to muons. Since undergraduate lab hours are Tuesdays, Wednesdays and Thursdays from 2 to 6 pm, a hypothesis was proposed defending that these counts could have been from some activity going on during the labs that wasn't shut off/sealed properly in-between sessions but only when the labs closed on Thursday at 6pm. This could have been, for example the radioactive calibration sources that are situated inside a metallic box really close by the scintillator.

Figure 6 represents this by showing how all three sections into which the day was divided (morning, lab hours/afternoon and night) but specially the 2 to 6 pm one, have a larger mean count rate and deviation from the mean in the first 48 hours. This indicates that indeed, whichever source was causing the extra background counts was more active specially, but not uniquely, during lab hours. The histogram at the bottom proves that the errors on the top left of the histogram are not due to there being a big difference in count rate between the first and second 24-hour period but that there were big fluctuations in count rate throughout all 48 hours. In addition, what had been mentioned earlier represented in Figure 5 regarding the fluctuations in the first 24 hours being the strongest can also be seen here in the histogram shown at the bottom.

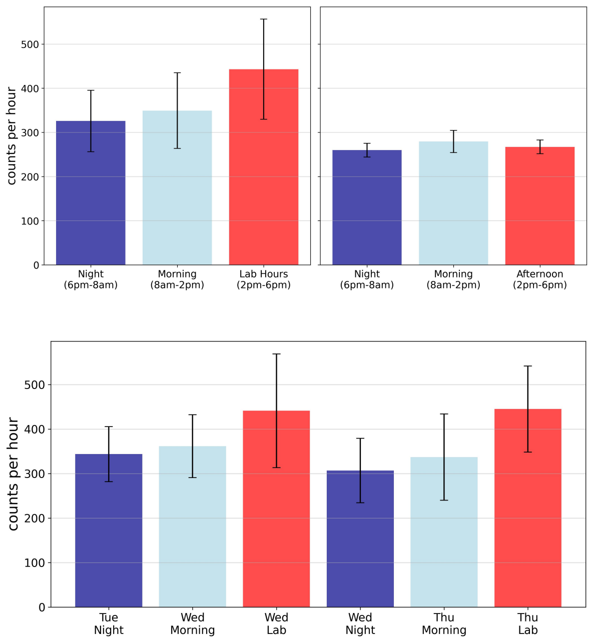

Figure 6: Histograms showing the trends in the count rates for run 1 with the night times (6pm to 8 am) in dark blue, the morning count rate (8am to 2 pm) in light blue and lab hours/Afternoon (2-6 pm) in red. *Top left:* average count rate per period of the day within the first 48 hours of the run. *Top right:* average count rate per period of the day within the following 102 hours. *Bottom:* detailed average count rate per period of the first 48 hours of the run.

The histogram on the top right corner of Figure 6 can be referred to as representing the 'uncontaminated' data. This shows how the counts throughout all three periods of the day where undergraduate labs were not opened, have similar counts per hour. Although the mean of the 8 am - 2 pm period is slightly higher in count rate than the one in the 2-6 pm slot which, at the same time, is slightly higher than the 6 pm to 8 am one. This might be because of the heating of the atmosphere by the sun, causing it to expand it and therefore decreasing the density of air slightly. Hence, making it harder for the pions and kaons to loose energy by interacting with the matter causing the rate of decaying into muons higher.

Both the change of the count rate throughout the hours of the day as well as the big fluctuations in count rate can also be seen in Figure 7, showing again how in the first 48 hours (in red, on the left), it was specially during the lab hours where the highest amount of counts were detected meanwhile in the rest of the hours (in green, on the right) it is at noon when the most amount of counts are detected since that is when the solar zenith occurs.

After it was mostly settled that the counts in the first 48 hours were just from another source in the labs and not muons, it was safe and correct to plot the exponential decay of the 'uncontaminated' data to obtain the muon's mean life instead of doing so from the full data. This resulted in Figure 8.

Although a p-value of 1 was obtained again for the same reason as for the full run 1 data, a mean life of $2.209 \pm 0.050\,\mu$s was obtained. This is closer, and in fact, is in excellent agreement to the literature values of 2.21 and 2.197 μs[3, 8]. In addition to that, a value for the background counts parameter of $C = 0.098 \pm 0.144$ was obtained. This is much lower than the one obtained with the data from the full run indicating that there was indeed additional external background counts during the first 48 hours causing the exponential decay fit to not be as accurate as possible.

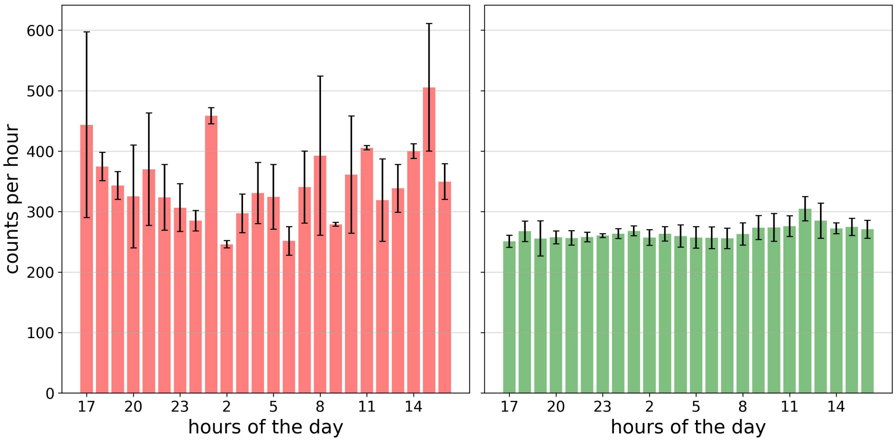

Figure 7: Histogram representing the count rate throughout the hours of the day. *Left:* the 'contaminated' data's (first 48 hours) count rate per hour of the day. *Right* the 'uncontaminated' data's (other 102 hours) count rate per hour of the day.

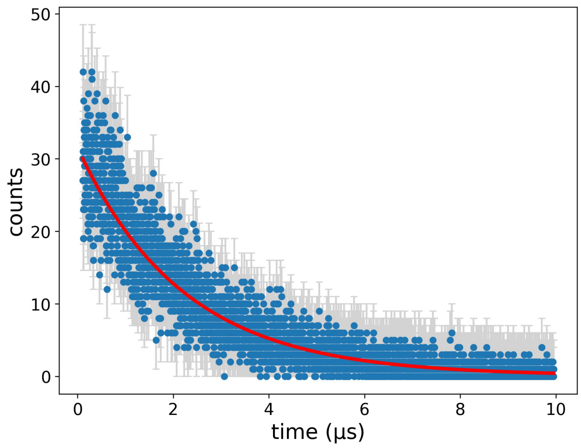

Figure 8: Exponential decay yielded from the 'uncontaminated' section of run 1 obtaining fitted parameters $N_0 = 31.43 \pm 0.36$, $\tau = 2.209 \pm 0.050$ and $C = 0.098 \pm 0.144$.

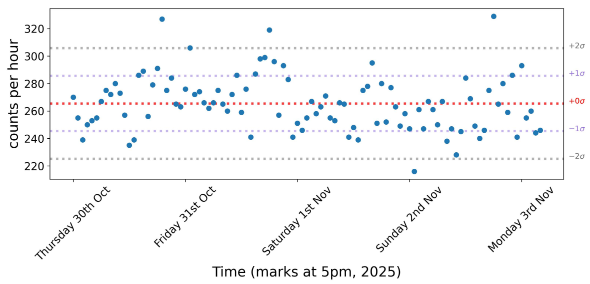

Figure 9: Count rate over time of the full data from Run 1 with 70% of the data points being within 1σ and 95% of them being within 2σ of the mean. Time marks were set on the day at 5pm.

Figure 9 shows how stable the count rate is, following the standard deviation models with 70% of the data points being within 1σ and 95% of them being within 2σ of the mean.

4.2 Run 2

Run 2, even if it was just a 24 hour run with a discriminator threshold that was significantly smaller than the one used in Run 1, backed up the hypothesis regarding the lab activity disturbing the detection of muons.

Although there did not seem to be any disturbance in between lab sessions, there did happen to be some disturbance during lab hours as seen in Figure 10. These plots can be compared to the ones in Figures 5, 6 proving what was just said in this section.

When not taking the lab hours into account for the measurement of the mean life, the value calculated slightly improved with respect to accepted values going from $2.752 \pm 0.127 \mu s$ to $2.698 \pm 0.145\, \mu s$. The improvement in this run is way smaller than the one in Run 1. This is due to the fact that, at this time, extra background counts didn't seem to affect outside-lab-hours recording. At the same time, the result obtained was 22.80% away from accepted values, implying that it was not possible to make an accurate measurement of the muon's lifetime with such a small discriminator threshold.

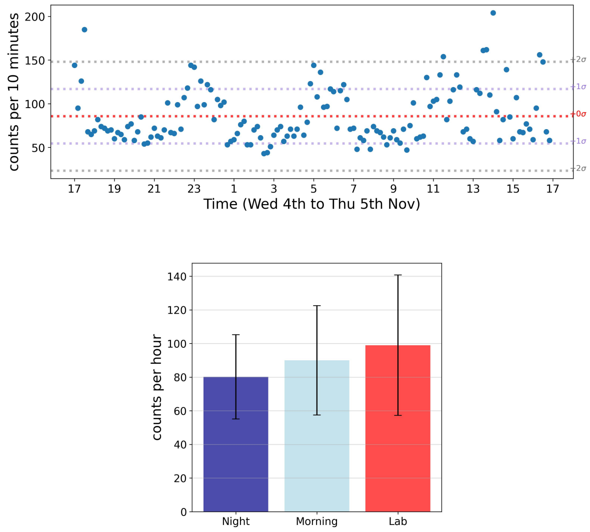

Figure 10: *Top:* scatter plot of the count rate of muons representing the extra counts happening at lab hours for run 2. *Bottom:* histogram grouping count rates per periods of the day showing a higher average count rate during labs than the rest of the time.

4.3 Run 3

Similar conclusions can be drawn from the results obtained from Run 3 with Figure 11 still showing some hours where extra counts were recorded, mainly around lab times.

Other than some hour at night where there might have been some additional counts from an unknown source, the night and morning periods stayed essentially at the same count rate having only the lab hours/afternoon period count rate go up when labs were back open. This once again supports the idea that some activity in the lab provides a high amount of counts that triggers the scintillator. This activity might have not been turned off in-between lab hours during the recording of Run 1, contrary to what might have happened during Run 3.

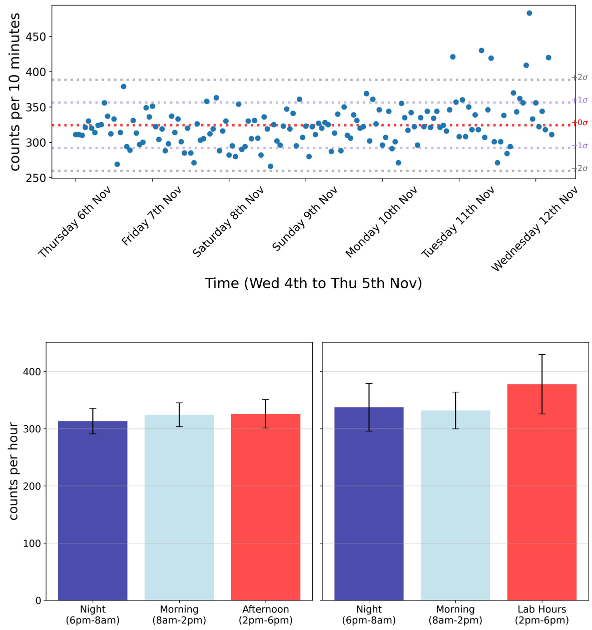

Figure 11: *Top:* Scatter plots of the count rate of muons representing the extra counts happening at certain hours mostly including during lab hours for run 3. *Bottom:* histogram grouping count rates per periods of the day both during non-lab days (Friday, Saturday, Sunday, Monday; on the left) and during lab-days (Tuesday, Wednesday; on the right) showing a higher average count rate than the rest.

Regarding to the exponential decay and the muon's calculated mean life, the parameters calculated initially were $\tau = 2.238 \pm 0.033\,\mu$s and $C = 0.583 \pm 0.146$ which, after leaving out the days containing lab hours (last 34 hours of the run) just like it was done for Run 1, reduced to $2.235 \pm 0.040\mu$s and 0.346 ± 0.143. Although the background counts did go down significantly, the muon's mean life did not. This is simply because of the small percentage that the hours with a higher background count make up on Run 3 (only reducing the calculated mean lifetime slightly) compared to that of Run 1.

And although a p-value of 1 was obtained implying that the errors on the data points were too large as before, the muon mean lifetime differed from the accepted value of $\tau = 2.197\,\mu$s by just 1.72% with this value falling within the error margins of the measured result.

However, this numerical result is still further away to accepted values than the one obtained from Run 1, indicating that the discriminator threshold selected back then was a more reasonable choice leading to a more accurate result.

5 Conclusion

With the data obtained from this experiment, the exponential decay was successfully studied, obtaining a mean life of $2.209 \pm 0.050\,\mu$s which is in excellent agreement with literature values of $2.197\,\mu$s[8]. The evolution of the count rate over time was studied observing a peak at the solar zenith due to the warming up and expansion of Earth's atmosphere which causes a lower density implying that the kaons and pions coming from cosmic rays will decay into muons with more ease. Apart form that, other factors that have an effect on the final result such as the discriminator threshold and the background radiation were studied in order to achieve the measurement of the muon's lifetime as accurately as possible.

Although uncertainties were provided and tests for goodness of fit were performed where applicable, some sources of uncertainty might not have been fully accounted for. Systematic errors could arise from the delay introduced by electronics; not only by the discriminator, TAC, etc. but also by the cabling. In addition, the choice of settings such as the high energy supply voltage, the discriminator threshold and the range of the TAC may introduce some error as they were not mathematically computed and could introduce a bias in the detected muon population. Background counts originating from both the laboratory and nearby activities are another major source of error. Although these can be partially addressed by removing 'contaminated' time periods, their presence cannot be entirely ruled out. Finally, statistical uncertainties might be underestimated in relation to calibration errors and overestimated in relation to the fitted exponential decays due to the use of Poisson errors with a chosen floor, potentially resulting in inflated goodness of fit values.

Further research could include the use of the 4-input Logic along with gate and delay generators to compare the accuracy difference between the setup used in this experiment and one that would include the use of those modules. Another example could be the study of the dependence on the zenith angle of the detecting rate of muons at sea level. This could be done with the aim to visualize the relationship described by $I\ \alpha\ cos^2\theta$ through the use of a muon detector telescope.

References

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Appendix

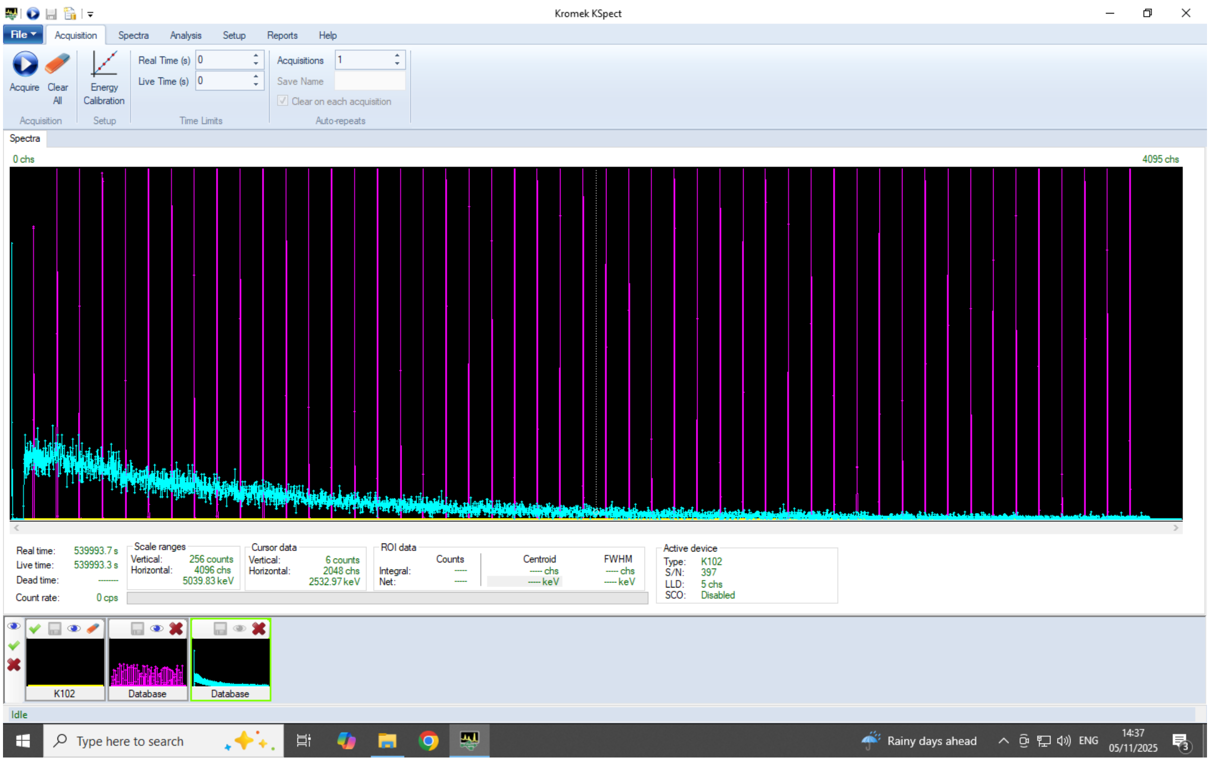

Figure 12: Calibration data superposed on top of Run 1 data

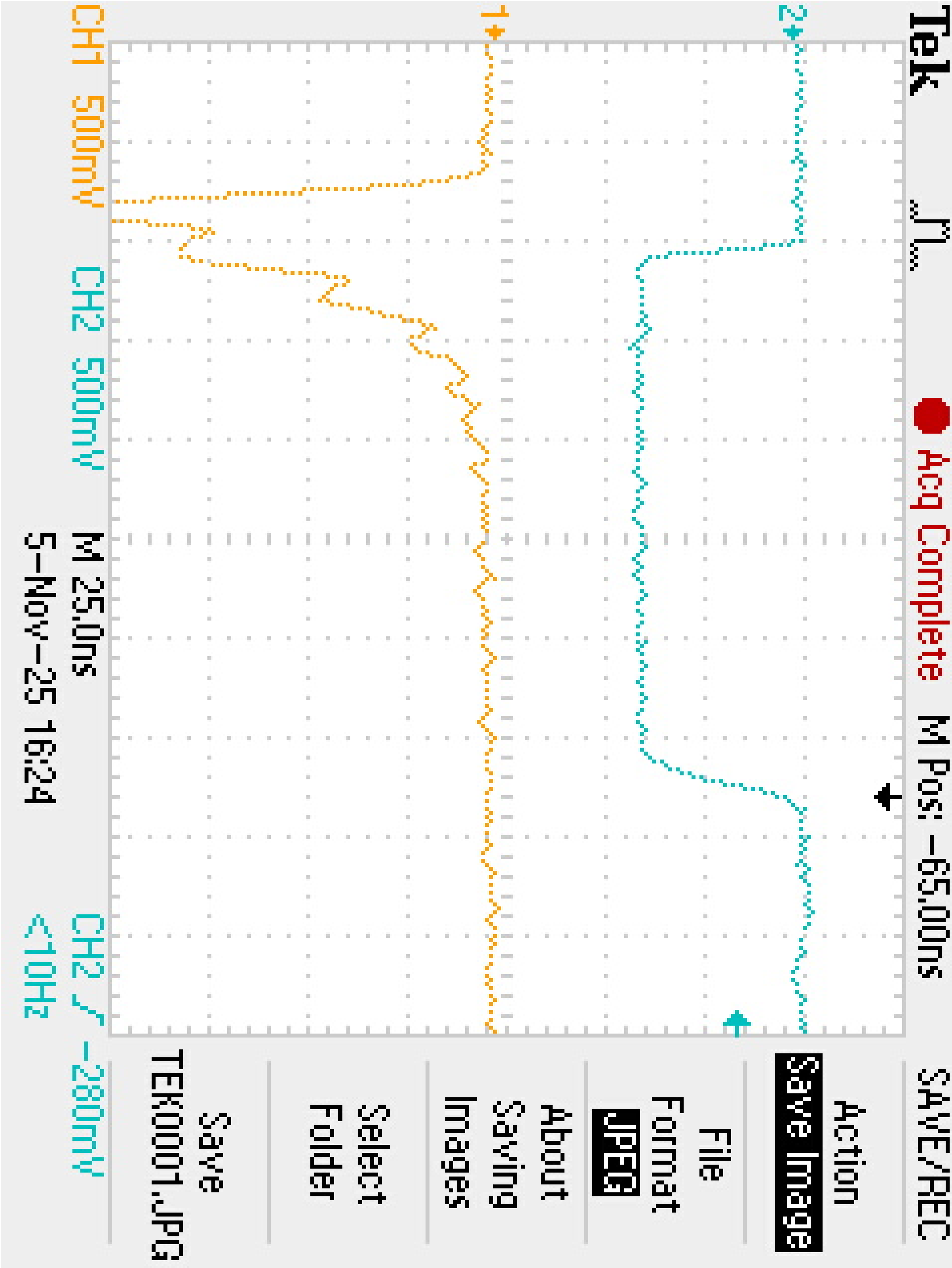

Figure 13: Oscilloscope screenshot showing the signal from the scintillator in yellow and the pulse from the discriminator in blue.