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Measurement of Muon Lifetime

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Abstract

Muons are elementary particles which are naturally produced in the upper atmosphere of the earth due to cosmic rays. This experiment aims to determine the average lifetime using a plastic szintillator and photomultipliers to detect them and a triggering system for the time meausurement.
HERE THE RESULTS OF THE ANALYSIS!

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Chapter 1

Introduction

This experiment aims to determine the lifetime of muons. Muons are produced by cosmic ray showers in the higher atmosphere. Incoming Protons react with the hadrons of the atmosphere and produce pions, which can decay into muons. Due to the high, relativistic velocities of the muons, they can reach the surface of the earth.

In this experimental setup the incoming muons are slowed down and stopped by layers of iron and then detected with a plastic scintillator. A trigger logic is used to determine the lifetime of the various incoming muons.

This report is structured as follows: in this chapter an introduction into the physical aspects of muons is given. chapter 2 describes the used components and the experimental setup. In chapter 3 the preliminary measurements for the calibration of the setup are described and their results are discussed. chapter 4 discusses the composition of the experiment and the process of data taking, while chapter 5 presents the the data analysis. chapter 6 concludes this report.

MAYBE MORE TEXT

1.1 General introduction to muons

The standard model of elementary particles differentiates between quarks, leptons and bosons. Quarks as well as leptons can be divided into three generations. The muons and the antimuon respectively are the second generation of leptons together with their each associated neutrinos. Like the electron, muons have a spin 1/2 and a negative elementary charge (a positive elementary charge for the antimuon). Although the similarities, both leptons differ in regard to their masses and their lifetimes.

While the electron is a stable particle, the muon has a finite lifetime, which this experiment is supposed to detect. The lifetime, given as an average result of past measurements, is $\tau = (2.196\,981\,1 \pm 0.000\,002\,2) \mu\text{s}$. Their mass is given as $m_\mu = (105.658\,374\,5 \pm 0.000\,002\,4) \text{ MeV}$, which is 206 times the mass of the electron [2].

1.2 Muons from cosmic ray showers

Muons are naturally produced in cosmic ray showers. When a particle strikes the hadrons in the upper atmosphere, they interact and produce a hadronic shower. These particles originate in various galactic and intergalactic sources like the sun, the Milky Way and other galaxies. The cosmic rays are mostly protons, but also electrons and atomic nuclei. The protons hadronize mostly into π mesons, because they are the lightest mesons, but also into K mesons and other hadrons. The primary cosmic rays are completely hadronized at altitudes of 20 km. Because π mesons and K mesons are not stable with lifetimes in the order of magnitude of 10^{-8} s they decay very fast. For the decay into muons, the π mesons have a branching ratio of $\Gamma = (99.98770 \pm 0.00004)\%$, while the K mesons have a branching ratio of $\Gamma = (63.56 \pm 0.11)\%$ [2]. It should be noted that these decays into muons only occur with charged π and K mesons. Neutral Mesons are also produced in these showers, but they do not decay into charged muons. The decay of the π mesons takes place via the weak interaction

$$\begin{aligned}\pi^+ &\rightarrow \mu^+ + \nu_\mu \\ \pi^- &\rightarrow \mu^- + \bar{\nu}_\mu.\end{aligned}$$

This process is analogous for K mesons. The muons also only decay via the weak interaction as follows

$$\begin{aligned}\mu^- &\rightarrow e^- + \bar{\nu}_e \\ \mu^+ &\rightarrow e^+ + \nu_e.\end{aligned}$$

Because the muons have a longer lifetime, they can reach the surface of the earth and can be detected through their decay. A schematic with typical processes, which lead among other things to the production of muon, can be seen in Figure 1.1.

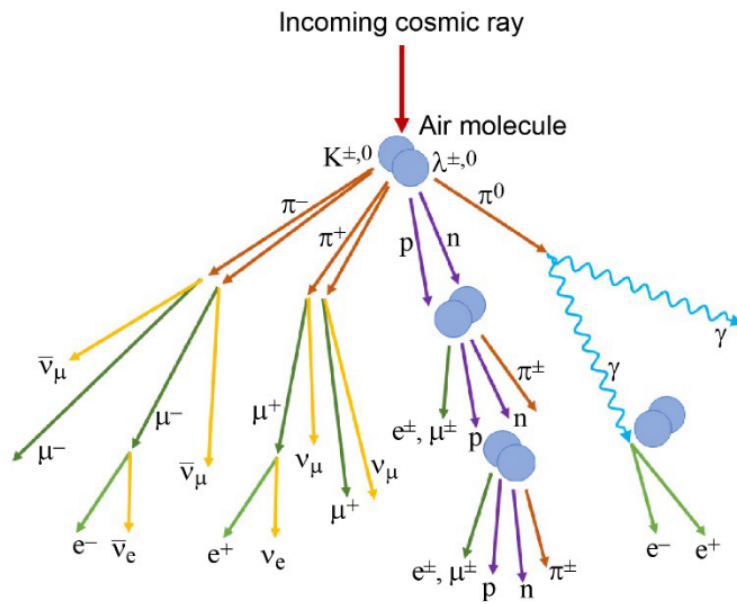


Figure 1.1: Typical shower processes after an incoming cosmic ray. The primary rays induce secondary particles by scattering with the molecules of the atmosphere. These secondary can decay or scatter again with the atmosphere and producing more particles in the process. This is called a decay chain or a cosmic ray shower[1].

Chapter 2

Experimental Setup

Chapter 3

Preliminary Measurements

3.1 Working Voltage for the Photomultipliers

In a first step, the optimal working voltages for the photomultipliers (PMTs) has to be found. Two PMTs were chosen for this measurement as a sample from the whole detector, R10B and R20A. It is important to choose PMTs from different planes to make sure the measured signal is due to a particle crossing the detector. A scematic for the measuring circuit is shown in Figure 3.1.

Only signals measured with both PMTs are taken into account. To determine these coincidences logic

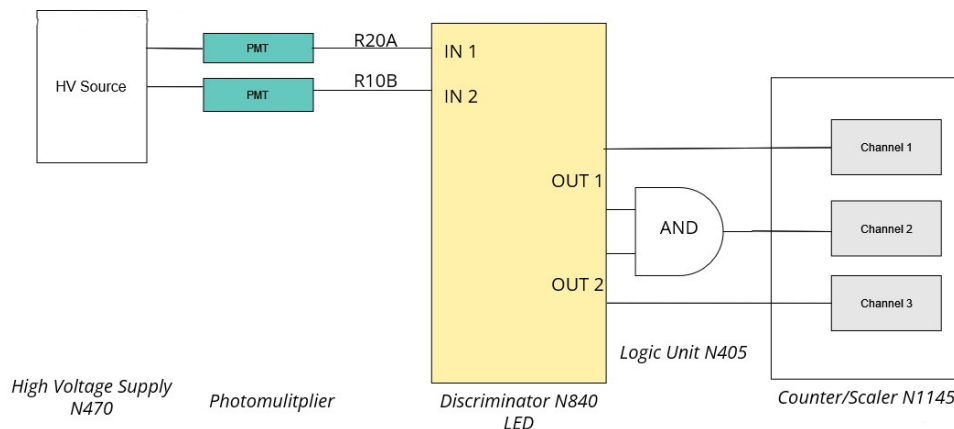


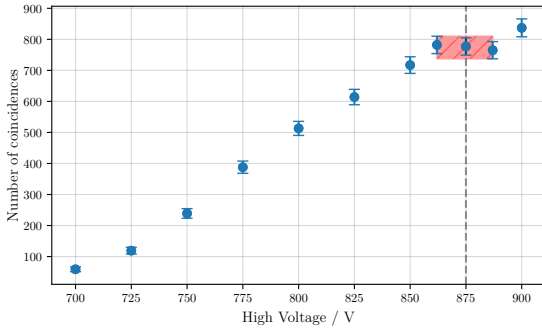
Figure 3.1: Schematic representation of the coincidence counting circuit for varying high voltage for the PMTs. The signal propagation is from left to right starting with the PMTs and their high voltage supply and ending with the scaler.

signals are needed. For that discriminators with a threshold of 40 mV are used. They convert the analogous signals of the PMTs into NIM standard signals. Using a logic unit module, the coincidences can be defined as the logic AND of both PMT signals. The NIM signals last for 40 ns each so the signals do not have to arrive at the exact same time but within 40 ns of each other. This is important, because the muons arrive in the different planes at different times and not necessarily at the same distance from

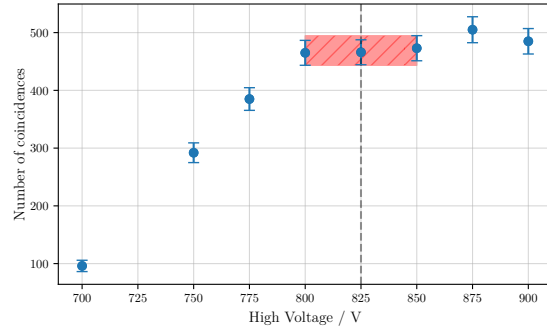
the PMTs. Furthermore, the PMTs may have different delay times as well.

For the measurement the R10B PMT works on a fixed high voltage of 775 V while the high voltage of R20A is varied from 700 V to 900 V. Each measurement lasts 200 s. The taken data is shown in Figure 3.2. A plateau can be found with 875 V corresponding to the middle value of it. This value is used as fixed value for the R20A PMT when the threshold of the R10B PMT is varied in the same range of high voltages. The measurements for this PMT were each taken in 100 s due to time limitations. The central value of the plateau for this PMT is 825 V. Both measurements were also stopped when the PMTs are operating in the discharge region due to the high voltage to avoid damaging the PMTs.

The results are shown in Figure 3.2a and Figure 3.2b. All uncertainties are obtained assuming a Poissonian distribution, meaning $\sigma \propto \sqrt{N}$, where N is the number of coincidences. Because the output of the high voltage sources can fluctuate, the central values of the plateaus, 875 V for the R20A PMT and 825 V for the R10B PMT, can be used as the optimal working voltages to ensure a voltage output in the region of the plateau. Both results are slightly higher than the voltages actually used in the experiment, because there are always three PMTs powered with the same voltage. For the R20 PMTs a voltage of 830 V is used which is a deviation of 5.4% and for the R10 PMTs a voltage of 780 V is used which corresponds to a deviation of 5.8%. Because of that, both measurements can be seen as successful measurements.



(a) Data of the R20A PMT. The central value of the plateau is 875 V.



(b) Data of the R10B PMT. The central value of the plateau is 825 V.

Figure 3.2: Measured number of coincidences in regard to varying high voltages of the R10B PMT and the R20A PMT. The dashed line indicates the central values of each plateau. The striped red areas mark the found plateaus.

3.2 Threshold measurements

After obtaining the optimal working voltages was found, the determination of the optimal threshold voltage of the chosen PMTs started. A good determination of the threshold is necessary to suppress electronic noise on the one hand, but also to make sure that real signals are not filtered as well on the other hand. So the threshold can neither be too low nor too high.

It should be noted that it is not possible to use only one PMT, but always the sum of the three PMTs of each halfplane. Similar to the step before, a counting experiment of coincidences in regard to the

threshold voltages is conducted. This time the circuit arrangement shown in Figure 3.3 is used. The PMTs are powered using the working voltages given in the laboratory as an average optimal working voltage for three PMTs.

In principle, the threshold of the discriminator of one plane is kept fixed at 15 mV, while the threshold of

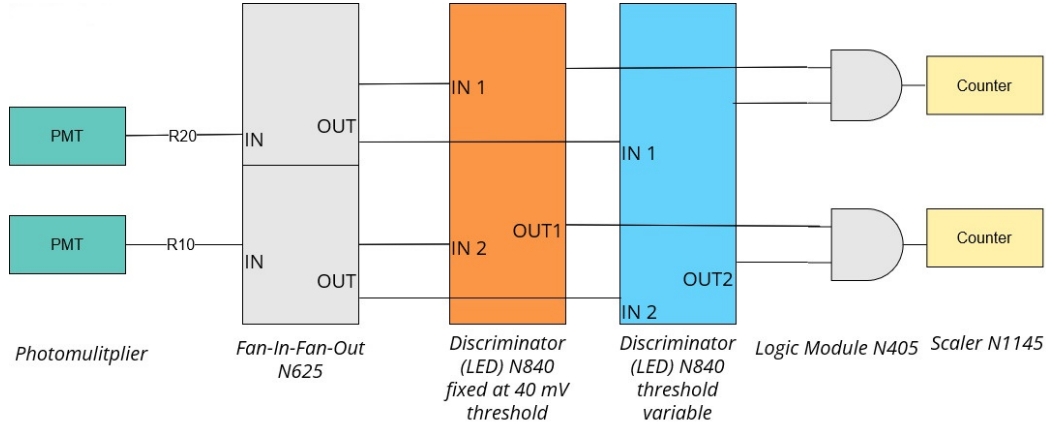


Figure 3.3: Schematic representation of the electronic circuit used to find the optimal threshold voltage. The signal flows from left to right, starting with the PMTs and Ending with the scaler.

the other discriminator is being varied from 5 mV to 250 mV in irregular steps. Using a discriminator and a Fan-in-Fan-out system as shown in Figure 3.3, it is possible to vary the threshold of the discriminators of both PMT planes at the same time and therefore cutting the measurement time in half. Each counting measurement was conducted in 60 s.

The results for the R10 and R20 planes can be seen in Figure 3.4. Results from other planes have to be taken from Appendix A, figures Figure A.1 to Figure A.6.

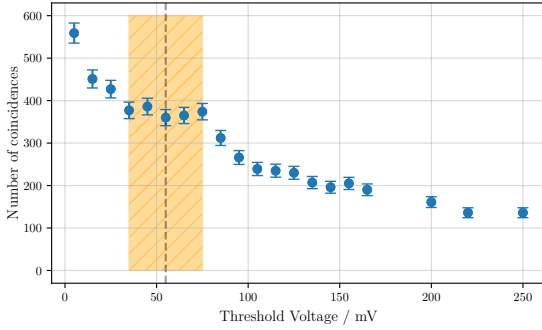
The data shows a higher number of coincidences at low threshold voltages, which declines with rising

Table 3.1: Overview of optimal threshold voltages for each plane.

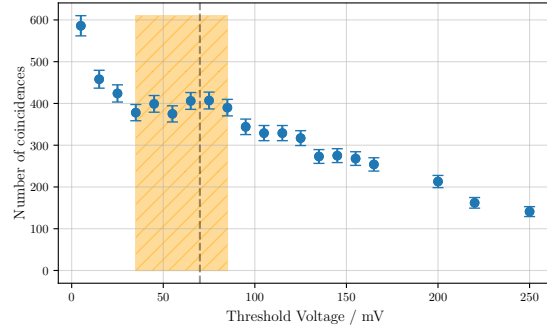
Plane	Voltage / mV	Plane	Voltage / mV	Plane	Voltage / mV
R00	50	R20	55	L01	55
R10	70	R21	55	L11	75
R10	45	L00	30	L20	50
R01	55	L10	35	L21	50
R11	60	L10	60		

voltages. This behavior is the same for all PMTs although not all curves show it that clearly. Also, a plateau of optimal threshold voltages can be seen. From the middle of this plateau a threshold voltage has to be chosen as the optimal threshold value. As before the uncertainties will be taken into consideration using the Poissonian error. The optimal threshold voltages of all PMTs are shown in Table 3.1. Note that for the L10 PMTs and the R10 PMTs two measurements were taken. Thus, in these cases only the value from the curve where it is easier to detect where the plateau is will be taken into consideration.

The other values are marked italic in the tabular.



(a) Data of the R20 PMTs. The central value of the plateau is 55 mV.



(b) Data of the R10 PMTs. The central value of the plateau is 70 mV.

Figure 3.4: Measured number of coincidences in regard to varying threshold voltages of the R10 PMTs and the R20 PMTs. The dashed line indicates the central values of each plateau. The striped orange areas mark the found plateaus.

3.3 TDC callibration

Chapter 4

Trigger Logic and Data Taking

Chapter 5

Data Analysis

Chapter 6

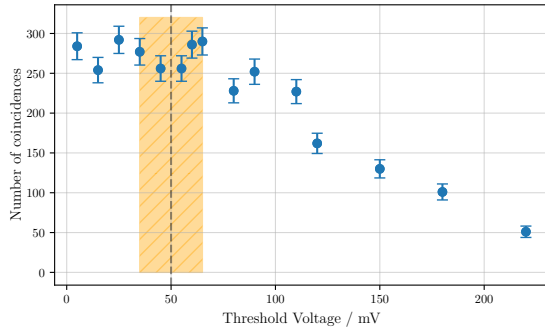
Final Results and Conclusions

Bibliography

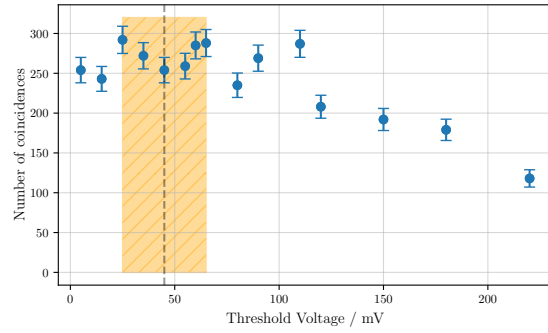
- [1] J.D. Wrbanek and S.Y. Wrbanek. “Space Radiation and Impact on Instrumentation Technologies”. In: (2020).
- [2] P.A. Zyla et al. “Review of Particle Physics”. In: *PTEP* 2020.8 (2020). and 2021 update. DOI: 10.1093/ptep/ptaa104.

Appendix A

Appendix

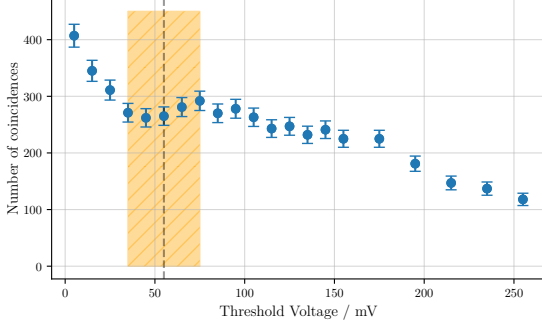


(a) Data of the R00 PMTs. The central value of the plateau is 50 mV.

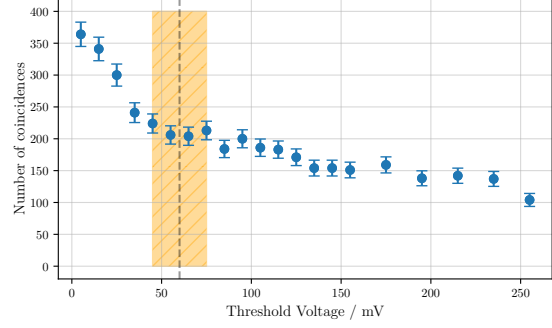


(b) Data of the second measurement of the R10 PMTs. The central value of the plateau is 45 mV.

Figure A.1: Measured number of coincidences in regard to varying threshold voltages of the R00 and R10 PMTs. The dashed line indicates the central values of each plateau. The striped orange areas mark the found plateaus.

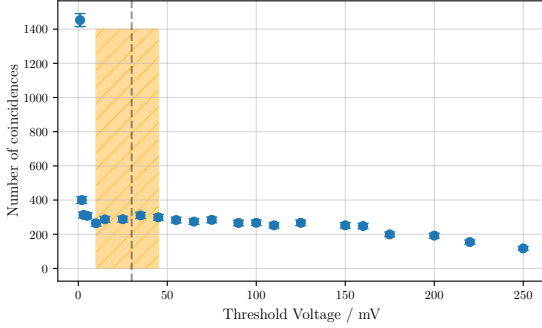


(a) Data of the R01 PMTs. The central value of the plateau is 55 mV.

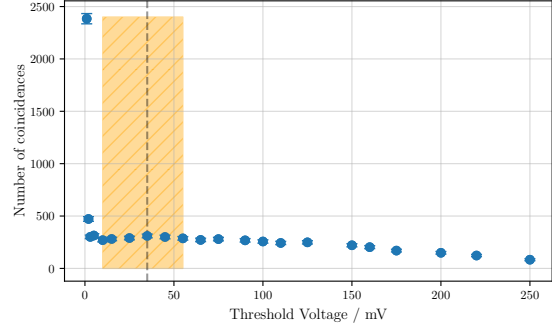


(b) Data of the R11 PMTs. The central value of the plateau is 60 mV.

Figure A.2: Measured number of coincidences in regard to varying threshold voltages of the R01 and R11 PMTs. The dashed line indicates the central values of each plateau. The striped orange areas mark the found plateaus.

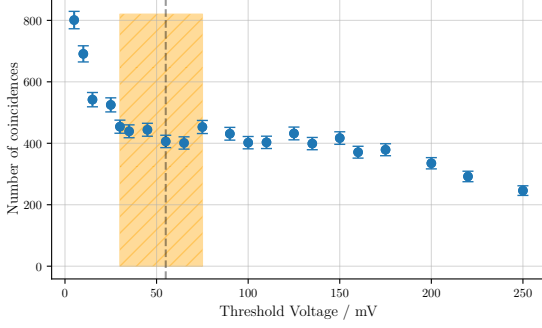


(a) Data of the L00 PMTs. The central value of the plateau is 30 mV.

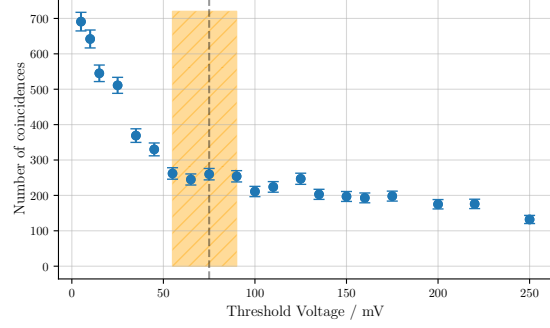


(b) Data of the L10 PMTs. The central value of the plateau is 35 mV.

Figure A.3: Measured number of coincidences in regard to varying threshold voltages of the L00 and L10 PMTs. The dashed line indicates the central values of each plateau. The striped orange areas mark the found plateaus.

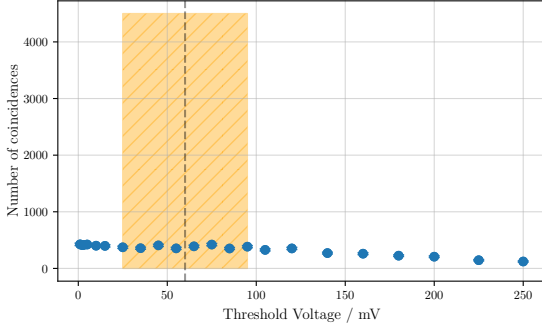


(a) Data of the L01 PMTs. The central value of the plateau is 55 mV.

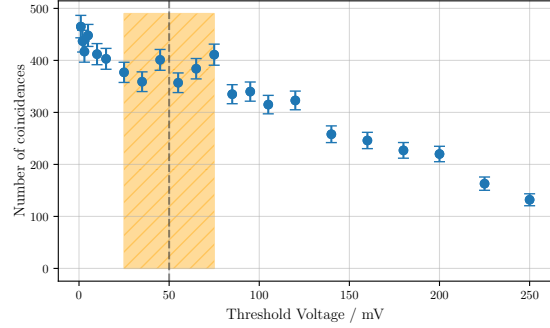


(b) Data of the L11 PMTs. The central value of the plateau is 75 mV.

Figure A.4: Measured number of coincidences in regard to varying threshold voltages of the L01 and L11 PMTs. The dashed line indicates the central values of each plateau. The striped orange areas mark the found plateaus.

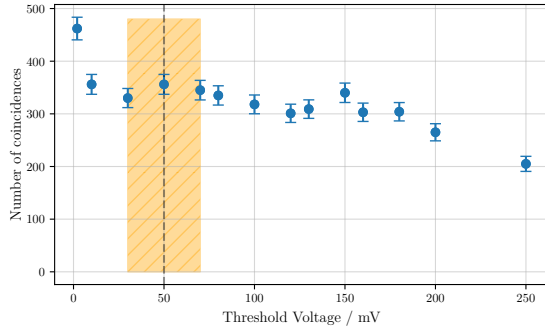


(a) Data of the second measurement of the L10 PMTs. The central value of the plateau is 60 mV.

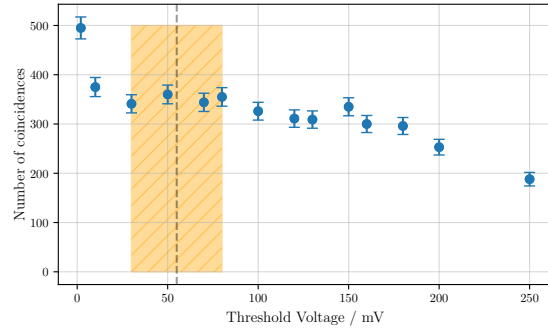


(b) Data of the L20 PMTs. The central value of the plateau is 50 mV.

Figure A.5: Measured number of coincidences in regard to varying threshold voltages of the L10 and L20 PMTs. The dashed line indicates the central values of each plateau. The striped orange areas mark the found plateaus.



(a) Data of the L21 PMTs. The central value of the plateau is 50 mV.



(b) Data of the R21 PMTs. The central value of the plateau is 55 V.

Figure A.6: Measured number of coincidences in regard to varying threshold voltages of the L21 and R21 PMTs. The dashed line indicates the central values of each plateau. The striped orange areas mark the found plateaus.