technische universität
dortmund

V01 - Lifetime of Cosmic Muons

Tabea Hacheney
tabea.hacheney@tu-dortmund.de

Steffen Kober
steffen.kober@tu-dortmund.de

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Technische Universität Dortmund - Fakultät Physik

1 Goals

In this experiment, the mean lifetime of cosmic muons arising in the atmosphere at an altitude of $\approx 10\,\mathrm{km}$ from particle showers is to be measured and evaluated. Further it is required to understand the detection method of muons. For this the interaction and function of each componant inside the detector has to be understood. This experiment should lead to an fundamental understanding of NIM-standard circuits.

2 Theoretical Introduction

2.1 Characteristics of Muons

Muons are leptons and belong, together with muon neutrinos, charm and strange quark as well as the corresponding antiparticles, to the second particle generation in the standard model. They have an energy of $m_\mu \approx 105.66\,\mathrm{MeV/c^2}$[4] at rest and therefore a higher mass as electrons with $m_\mathrm{e} \approx 510.99\,\mathrm{keV/c^2}$[4]. The lifetime of the muon has been experimentally established to be $\tau(\mu^\pm) = 2.1969 \times 10^{-6}\,\mathrm{s}$ [4].
Almost all ($\approx 100\,\%$) muons decay via the following decay channel [4]:

$$\mu^- \to \mathrm{e}^-\bar{\nu}_\mathrm{e}\nu_\mu \tag{2.1}$$

$$\text{resp. } \mu^+ \to \mathrm{e}^+\nu_\mathrm{e}\bar{\nu}_\mu. \tag{2.2}$$

At earth the biggest source of muons are cosmic high energy hadrons, which react with air particles when reaching the atmosphere and start particle showers. These particle showers consist of hadronic, electromagnetic and muonic components. The latter ones mostly come from the decay of charged pions, which have a very short mean lifetime of $\tau_{\pi^\pm} \approx 2.6 \times 10^{-8}\,\mathrm{s}$[4] and decay via

$$\pi^- \to \mu^-\bar{\nu}_\mu(\gamma) \tag{2.3}$$

$$\text{resp. } \pi^+ \to \mu^+\nu_\mu(\gamma) \tag{2.4}$$

to muons. Usually additional energy is emitted via photons γ. A schematic view of these particle showers is given in Figure 2.1.

Cosmic muons arise at altitudes of approximately 10 km[3]. Despite energies of a few GeV and a velocity similiar to the speed of light, cosmic muons decay after a few hundred meters. So muons would not be able to reach the earth from a classical point of view. Due to the extremely high velocity, relativistic effects (time delation) have to be taken into account. From a relativistic point of view, muons travel more than 10 km before decaying. This is enough to reach the earth's surface.

2.2 Mean Lifetime

In this experiment, the mean lifetime of cosmic muons is to be experimentally established. The mean lifetime is how much time usually passes, before a muon decays. It is the expected value of the lifetime distribution, which is derived in the following.

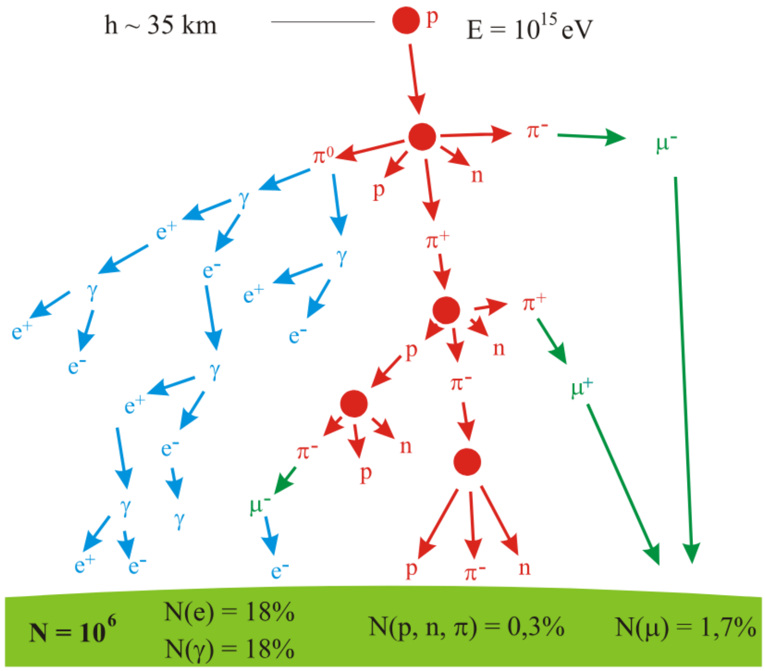


Figure 2.1: A schematic view of a classical particle shower including hadronic, electromagnetic and muonic components. [1]

In a short time intervall the amount of not decayed particles $N(t)$ falls via the law of radioactive decay:

$$\mathrm{d}N(t) = -\lambda N(t)\mathrm{d}t, \tag{2.5}$$

with λ being the decay constant, which is specific to the decay.
After solving the differential equation and integrating, yields an exponential dependency

$$N(t) = N_0 \exp\left(-\lambda t\right). \tag{2.6}$$

The expectation value of this distribution and therefore the mean lifetime is finally given by

$$\tau = \frac{1}{\lambda}. \tag{2.7}$$

2.3 Detection of cosmic Muons

The muons are detected via a scintillator detector. When a muon enters the scintillator, a light pulse is transmitted to two photomultipliers. Electrons are then released by means of the photoelectric effect, and are accelerated to an electrode via an electric field and release further electrons in the process. This step is repeated a few times until a strong pulse of voltage is created. The two pulses from the photomultipliers are sent into a coincidence via two discriminators and two variable delays. Since photomultipliers tend to spontaneously fire voltage pulses due to thermal radiation noise is generated, discriminators are used to supress this. The coincidence prevents incorrect spontaneous pulses from being registered as signals. Only those pulses are forwarded, which arrive

at both inputs at the same time. This way, only those pulses are accepted which were caused by an event in the scintillator. Since the pulses can have different delays until arriving at the coincidence due to differences in the photomultipliers and cables, variable delays can be used to adjust the delays.
Finally, three different channels leave from the coincidence. One channel first undergoes a delay of $\approx 30\,\mathrm{ns}$ and gets transmitted to a monoflip. This converts the pulsed signal into a continuous binary signal. The monoflop has a normal and an inverted output. A signal would mean TRUE and no signal FALSE. The inverted output of the monoflop is fed into an AND logic together with one of the other two channels of the coincidence to trigger a start of a timer. The normal output is fed together with the last output of the Coincidence into another AND logic, which is supposed to cause a stop of the timer. The entry of the muon should start the timer and a second impulse at the decay of the muon should stop it.
The delay before the monoflop is necessary so that the signals do not arrive at the AND logics at the same time. This way, a starting and stopping of the timer would not be possible.
The monoflop is used to set a search time after which an event is discarded. This is useful in the case that a muon's energy is too high to decay in the scintillator tank. The search time is chosen to be about 5 times the expected average lifetime. The amount of start and stop pulses are counted via counters.
The time between two pulses is converted into an amplitude via a time-amplitude-converter (TAC). These amplitudes are sorted into different channels by the multi channel analyser and a PC.
A schematic view of the detector and the electronics is shown in Figure 2.2.

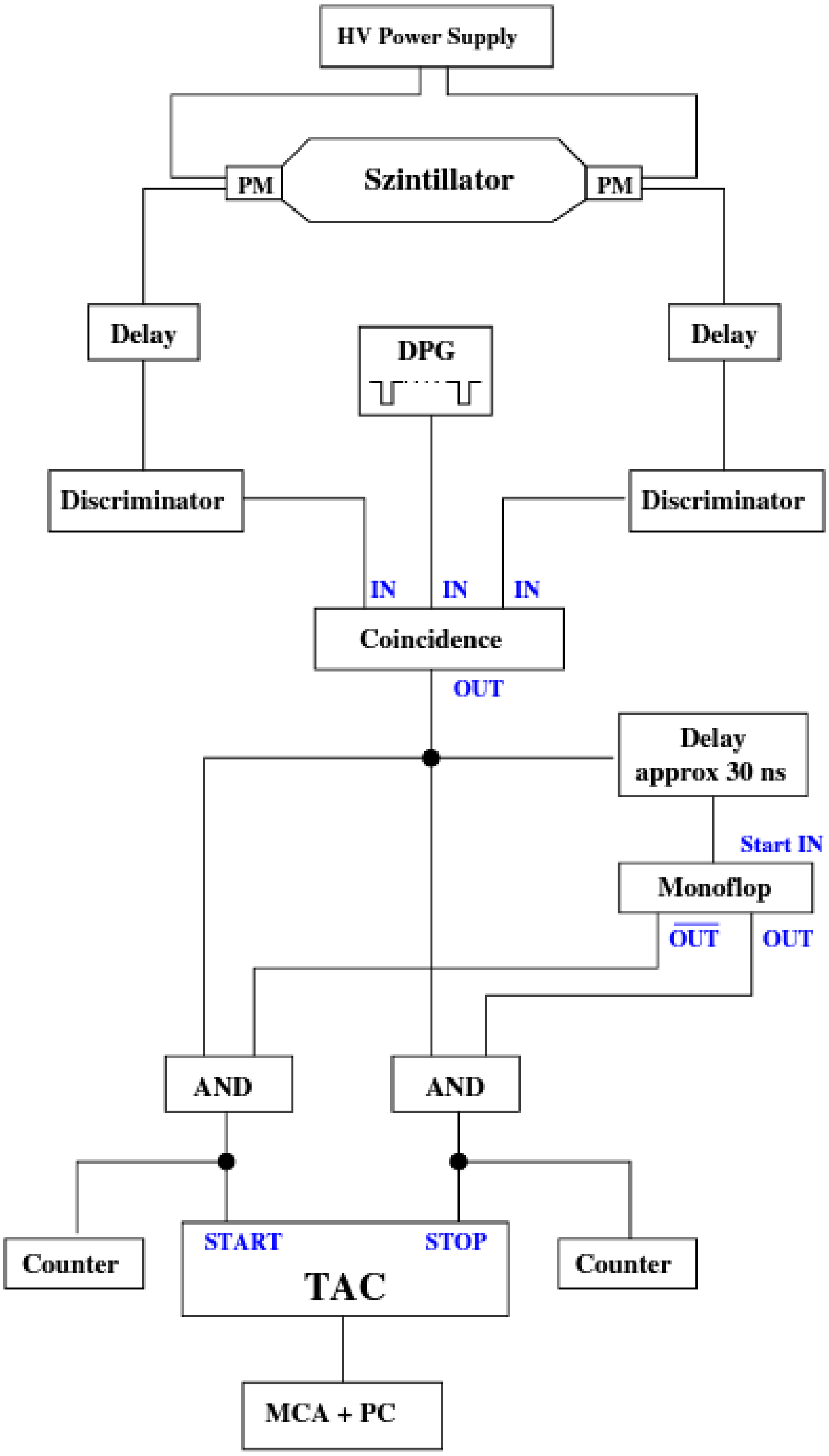


Figure 2.2: A schematic view of the experimental aparatus as well as the logic circuit. [5]

3 Experimental aparatus

By using a oscilloscope, the functionality of the photomultipliers is checked and the pulse duration is set to be approximately $\Delta t = 10\,\mathrm{ns}$. The threshold of the discriminators is adjusted, so that approximately 30 pulses per second are measured at both outputs. For this, a counter is used.
To adjust the variable delays, different delays are chosen and the countrate is measured. The distribution has a broad plateau, from which a value in the middle is chosen. The half-width of this distribution is to be determined. The event rate should be at $20\,\mathrm{s}^{-1}$ by now so that the measurement time of a few days is sufficiently high and noise is sufficiently suppressed.
The remaining electronics are connected as shown in Figure 2.2. A search time of $T_s = 10\,\mathrm{\mu s}$ is set at the monoflop and the measuring range of the TAC is adjusted, so that the measured time steps are small enough, but not too detailed.
A double pulse generator operating at $1\,\mathrm{kHz}$ is connected to the MCA, to check which time intervals correspond to which channels of the MCA.
After the calibration the measurement is started. The overall measuring time is approximately three days.

4 Data Analysis

The data was measured with the setup discussed in the chapters 2 and 3. The duration of the data collection was $T_{\text{Dur}} = 70.26\,\text{h}$. In this time $N_{\text{start}} = 3\,427\,476$ start signals and $N_{\text{stop}} = 1818$ stop signals were detected by the setup. The search time was set to $T_{\text{search}} = 10\,\mu\text{s}$.

4.1 Estimation of a Constant Background Detection

To estimate the background rate in this experiment the mean amount of muons has to be calculated. It is given by

$$\nu = \frac{N_{\text{start}}}{T_{\text{Dur}}} = 13.55\,\frac{1}{\text{s}}. \tag{4.1}$$

Since this is a counting experiment the counts should be possion distributed and the probability, that k muons hit the detector while it is measering is given by

$$P_{T_{\text{search}}\nu}(k) = \frac{(T_{\text{search}}\nu)^k}{k!}\mathrm{e}^{T_{\text{search}}\nu}. \tag{4.2}$$

The function 4.2 is proportional to the factorial of k, so every order above $k = 1$ is negligible. The propability of one additional muon entering the chamber in the search time is

$$P_{T_{\text{search}}\nu}(k = 1) = 0.013\,\%.$$

From this the estimation of the background rate U_0 is given by

$$U_0 = \frac{N_{\text{start}} P_{T_{\text{search}}\nu}(k = 1)}{N_{\text{channel}}} = 1.08\,\text{counts/channel}. \tag{4.3}$$

In this equation $N_{\text{channel}} = 430$ is the amount of channels.

4.2 Determination of the Resolution Time

To determine the resolution time of the setup a delay time T_{Delay} is introduced to the two different photomultipliers. This is necessary to phase the photomultipliers, since signals are only counted when both multipliers give a signal. As a counting experiment the data should comply with the possion distribution. Hence, the errors are given by $\sqrt{N}$. The measerd counts dependend on the delay time are shown in table 4.1. In this

Table 4.1: Measured Counts N dependend on the delay time T_D. T_N is the duration of the measurement. A negative delay time corresponds to one photomultiplier and a positive delay time to the second one.

T_D / ns	N	T_N / s
0	153	20
1	159	20
2	146	20
3	131	20
4	148	20
5	136	20
6	114	20
7	85	20
8	65	20
9	36	20
10	19	20
11	22	40
12	8	60
13	3	60
-1	148	20
-2	153	30
-3	104	20
-4	69	20
-5	55	20
-6	61	20
-7	40	20
-8	14	20
-9	16	40
-10	11	60
-11	3	60

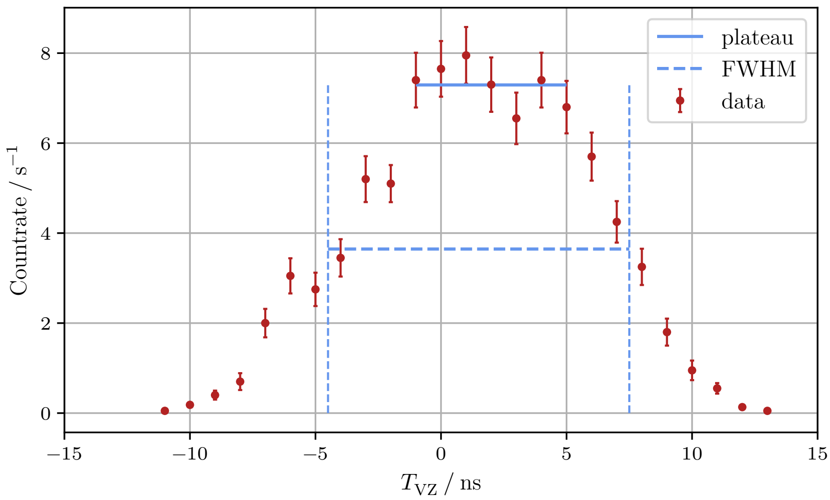


Figure 4.1: The dependece of the count rate to the delaytime. Negative delay corresponds to the delay of one cable and positive to the other cable. The dashed line shows the full width half at half maximum and the continuous blue line shows the plateau.

table a negative delay time corresponds to one photomultiplier and a positive delay time to the second one.

The data is also shown in figure 4.1. In this figure the course of the data shows a plateau from $-1\,\mathrm{ns}$ to $5\,\mathrm{ns}$ at around $7.2\,1/\mathrm{s}$. The resolution time corresponds to the full width at half maximum (FWHM) of the data. As shown in figure 4.1 the resolution time for this setup is $12\,\mathrm{ns}$.

4.3 Calibration of the Multichannel Analyser

As discussed earlier the TAC converts the temporal distance of the signals into an amplitude. The multichannel analyser (MCA) converts this amplitude into counts amoung different channels. The number of the categorized channel has a correlation to the measured lifetime of the muons. This correlation has to be determined before the measurement. The measured data of the time dependece of the MCA is given in table 4.2. For better visualization the data is plotted in figure 4.2.

Table 4.2: Channel number correspondend to the temporal pulse distance.

Kanal	t / µs
16	0.5
39	1.0
62	1.5
85	2.0
108	2.5
131	3.0
154	3.5
177	4.0
200	4.5
223	5.0
246	5.5
269	6.0
292	6.5
315	7.0
338	7.5
361	8.0
384	8.5
407	9.0
430	9.5

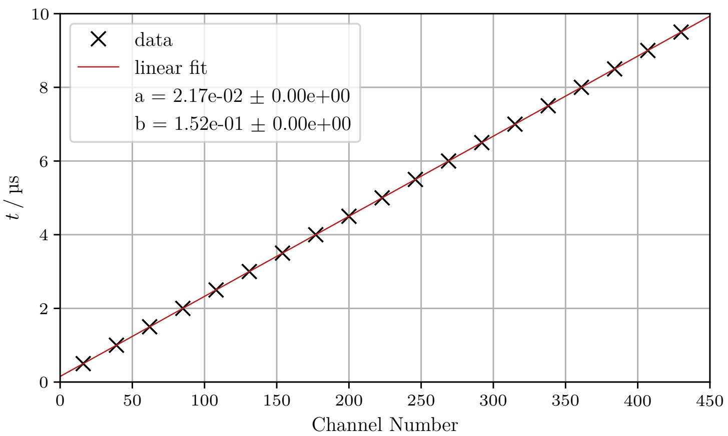


Figure 4.2: Linear regression[2] of the data to obtain a functional correlation between the channel number and the lifetime.

A linear regression of the data is used to calculate parameters, which determine the functional correlation 4.4 between the channel number K and the time t.

$$t[\mu\mathrm{s}] = 0.021739K + 0.15217 \tag{4.4}$$

4.4 Lifetime of Cosmic Muons

The program used for the counting yields a data file in which the counts of each channel are saved. With the conversion function 4.4 durations are calculated. The data is shown in figure 4.3.

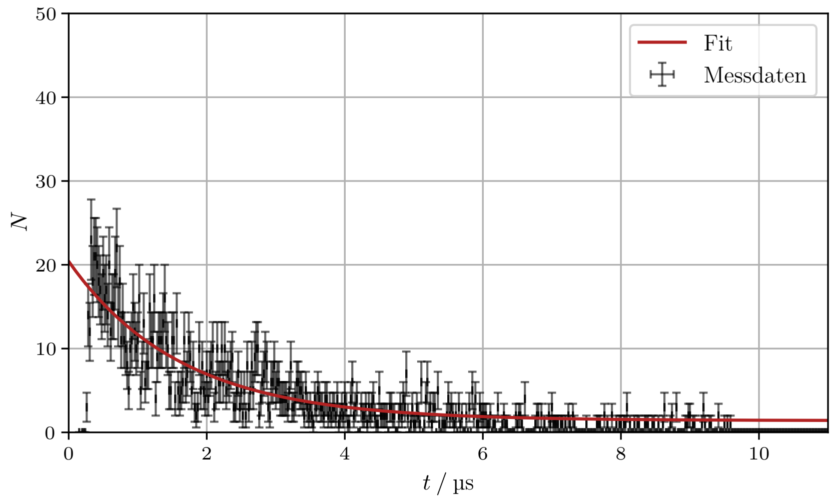


Figure 4.3: Data for the determination of the lifetime of cosmic muons. N are the counts of muons and t is time correspondend to the channel.

The counts of the muons should follow an exponential law.

$$N(t) = N_0 \mathrm{e}^{-t/\tau} + U_0 \tag{4.5}$$

In this equation N_0 is the basis amount of muons, τ is the lifetime and U_0 is the constant background. U_0 was estimated in section 4.1. Using non linear regression from *scipy* [2] the parameters of the exponential law are determined. This yields the values

$$N_0 = 18.9 \pm 0.7, \qquad \tau = (1.62 \pm 0.11)\,\mu\mathrm{s}, \qquad U_0 = 1.4 \pm 0.2$$

The regression is plotted in figure 4.3.

5 Discussion

This experiment yields a lifetime of muons $\tau = (1.62 \pm 0.11)\,\mu s$. The literature value is given by $\tau = (2.196\,981\,1 \pm 0.000\,002\,2)\,\mu s$ [4]. This experiment results in an deviation of $(26 \pm 5)\,\%$. This deviation is large and cannot be explained with statistical uncertainty. Small uncertainties could rise from minor side effects. But the deviation suggests an systematic error in the setup. The setup has many possible origins of systematic errors. The first problem could be the descriminator. If not adjusted equally and correctly the amount of data can be reduced drasticly and also a bias can be introduced, which could favor signals from longer or shorter lifetimes. Another problem could be an low event rate. It was given, that the event rate should lie around $20\,1/s$. But this event rate was not reached, so that the experiment was executed with an event rate of $\propto 15\,1/s$. This again reduces the data. Additionally to the already low amount of data the mesurement yielded one channel with extraordinary amount of counts. This channel is not included in the analysis due to an obvious error in the counting leading to a drastic reduction of the useable dataset. This again indicates a systematic error and also enhances statistical errors.

The same uncertainty can be seen in the difference of the predicted background ($U_0 = 1.08\,\text{counts/channel}$) and the background of the regression ($U_0 = 1.4 \pm 0.2$). All this indicates, that the regression is incorrect and the results are not trustworthy.

The resolution time for this setup yields $12\,ns$. A value approximately equal to the set pulse duration of $10\,ns$ is expected. This holds for the setup.

Nevertheless, besides an imperfect data collection, the goal of the experiment was also to achieve knowledge about the measurement concept and the NIM-standard. This goal is still achieved and therefore the experiment is partially successful.

Bibliography

[1] *Air shower (physics)*. Wikipedia. URL: https://www.wikiwand.com/en/Air_shower_(physics). (visited on 10/16/2023).

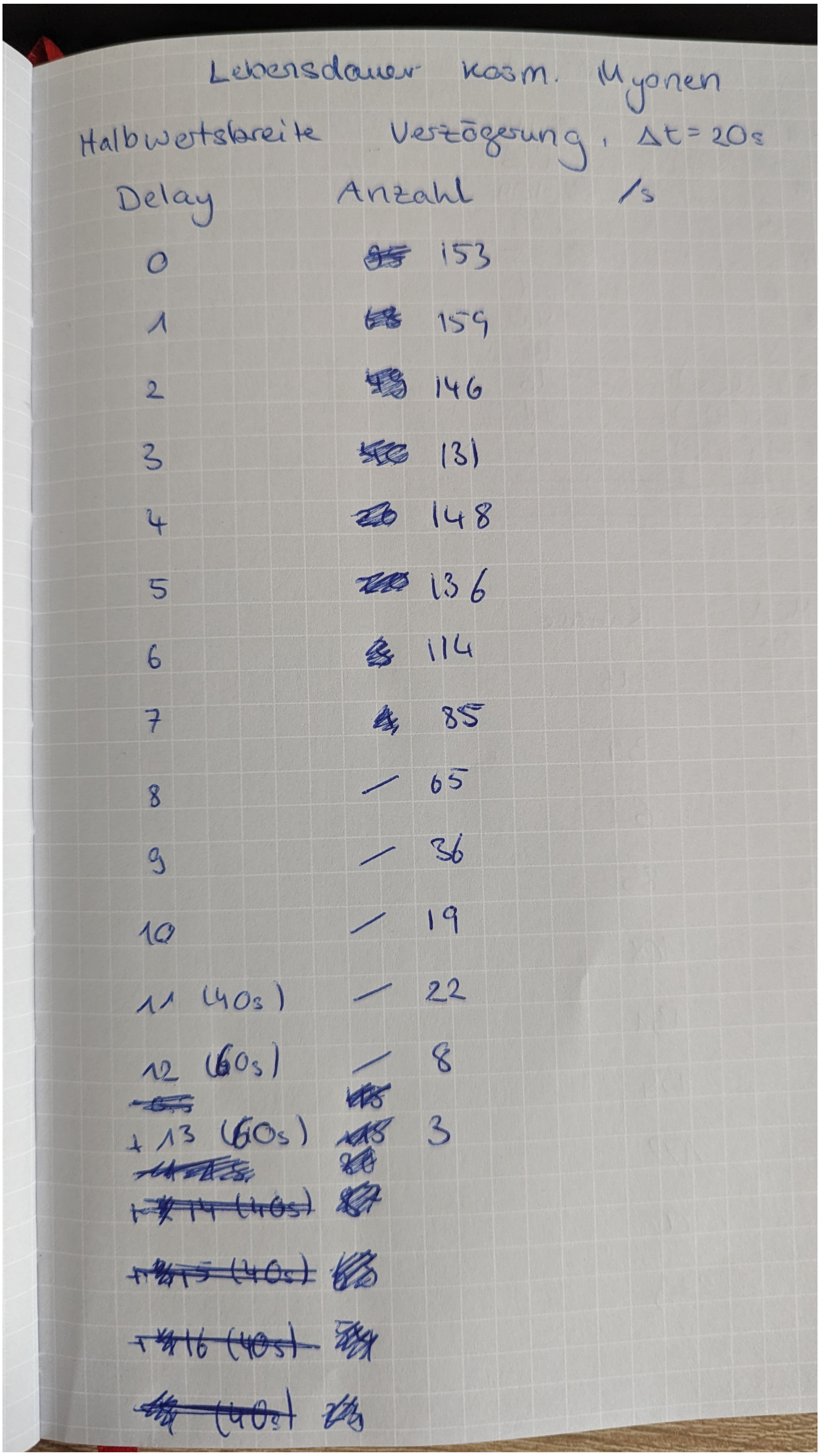
[2] Eric Jones, Travis E. Oliphant, Pearu Peterson, et al. *SciPy: Open source scientific tools for Python*. Version 0.16.0. URL: http://www.scipy.org/.

[3] *Kosmische Strahlung und ausgedehnte Luftschauer*. RWTH Aachen. URL: https://institut2a.physik.rwth-aachen.de/de/teaching/praktikum/Anleitungen/T20.pdf. (visited on 10/16/2023).

[4] *The Review of Particle Physics (2023)*. Particle Data Group. URL: https://pdg.lbl.gov/ (visited on 10/16/2023).

[5] *V01 - Lebensdauer kosmischer Myonen*. TU Dortmund. URL: https://moodle.tu-dortmund.de/mod/resource/view.php?id=1527850 (visited on 10/22/2023).

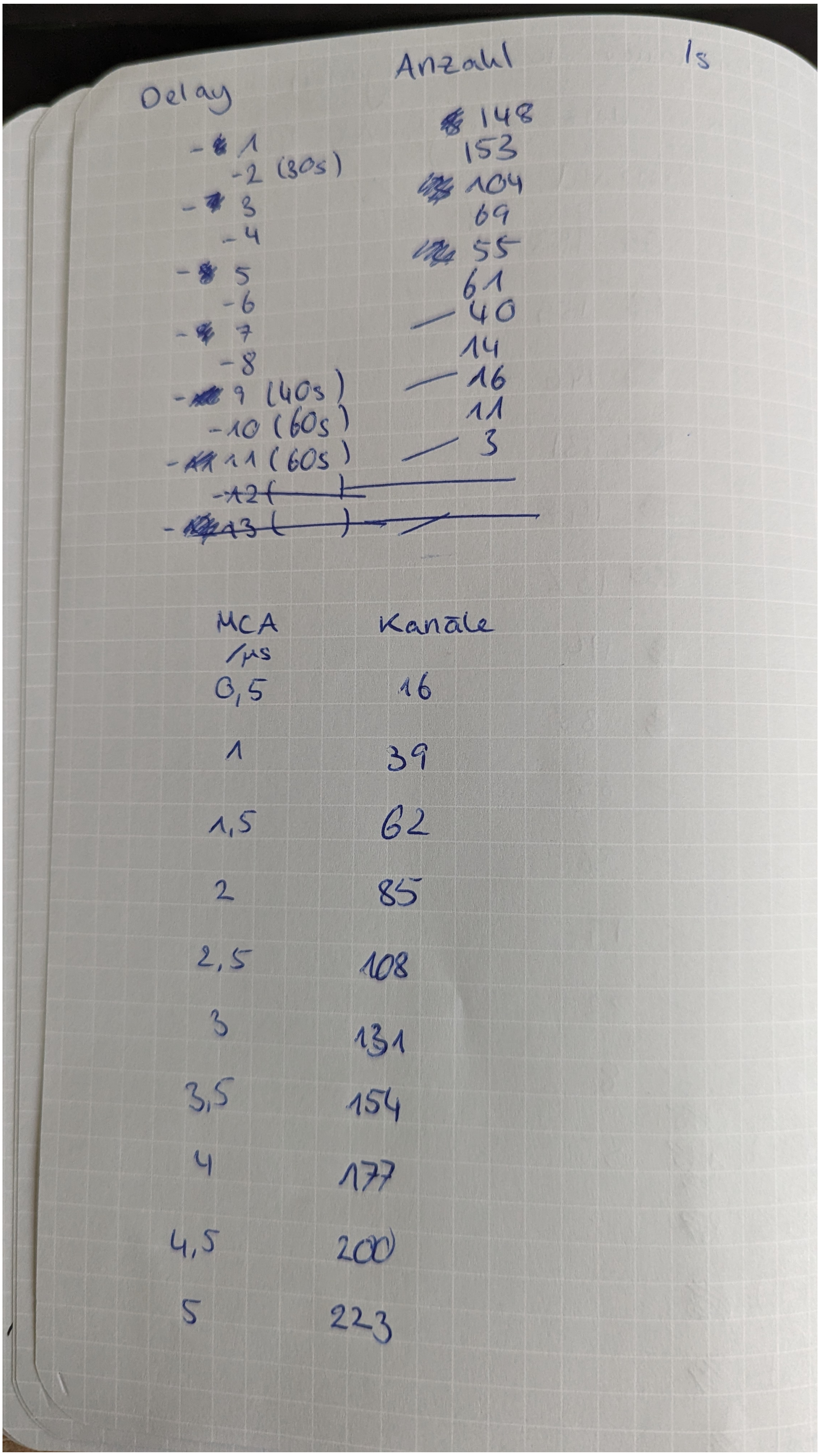
Appendix



Lebensdauer kosm. Myonen

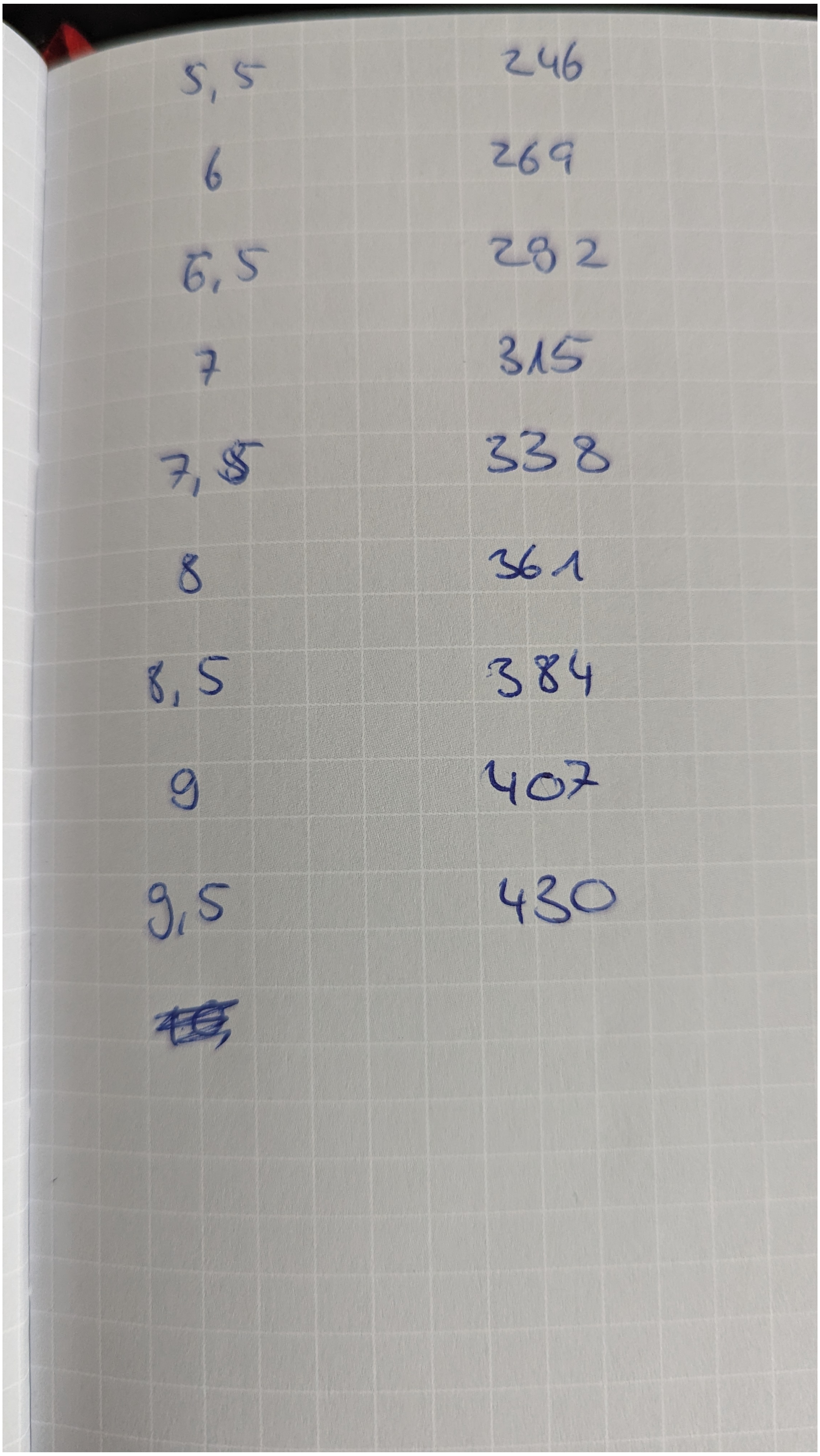
Halbwertsbreite Verzögerung, $\Delta t = 20s$

Delay	Anzahl /s
0	153
1	159
2	146
3	131
4	148
5	136
6	114
7	85
8	65
9	36
10	19
11 (40s)	22
12 (60s)	8
+ 13 (60s)	3
~~+ 14 (40s)~~	
~~+ 15 (40s)~~	
~~+ 16 (40s)~~	
~~(40s)~~	



Delay	Anzahl	1s
-1	148	
-2 (30s)	153	
-3	104	
-4	69	
-5	55	
-6	61	
-7	40	
-8	14	
-9 (40s)	16	
-10 (60s)	11	
-11 (60s)	3	
~~-12 ( )~~		
~~-13 ( )~~		

MCA /µs	Kanäle
0,5	16
1	39
1,5	62
2	85
2,5	108
3	131
3,5	154
4	177
4,5	200
5	223


5,5 246
6 269
6,5 282
7 315
7,5 338
8 361
8,5 384
9 407
9,5 430