

A simple setup for cosmic muon lifetime measurements

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Abstract

Elementary particle physics is a fascinating field of modern physics investigating the basic constituents of matter and their interactions. In the experiments large accelerators and very sophisticated detector systems are usually used. However, it is desirable to have simple experiments for undergraduate and even secondary school courses which can demonstrate complex investigations in this field. We have constructed a simple setup for the measurement of the lifetime of cosmic muons based on a single scintillation detector. Expensive and complicated professional particle physics equipment for the signal processing, which has mainly prevented the realization of this experiment by non-experts, is replaced by simple, inexpensive and commercially available electronic components. With our setup we register time stamps of the events detected in the scintillation detector and from this data we determine the muon lifetime. Also, a Python software package has been developed for data analysis and presentation of the results.

Keywords: cosmic muons, scintillation detector, muon lifetime

(Some figures may appear in colour only in the online journal)

1. Introduction

Elementary particle physics investigates properties of the basic building blocks of matter and their interactions. According to the current knowledge described by the standard model of particle physics, the basic constituents of matter are fermions—quarks and leptons—and the interactions between them are mediated by bosons, so-called gauge bosons, see e.g. [1].

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Typical experiments in elementary particle physics include investigations of the products of particle collisions or decays of unstable particles. Usually, big accelerator facilities, the Large Hadron Collider at CERN being an extreme example [2], and very complex detector systems are used.

However, it is desirable to have adequate laboratory experiments for undergraduate and even advanced secondary school courses in order to demonstrate experimental techniques in this exciting field. The measurement of cosmic muons' lifetime has for a long time been considered as one such experiment, see e.g. [3]. In this experiment, cosmic rays provide a free and ubiquitous source of muons. The muon is one of the unstable leptons and its lifetime, one of the basic particle properties, is measured. There have been various realizations of this experiment, based mostly on scintillation detectors [4–8]. However, all these setups use expensive and pretty demanding ‘professional’ particle physics electronics for signal processing and storage which requires special expertise, and also comes with correspondingly high costs. The foregoing has prevented the realization of this measurement by non-experts and much broader employment of this experiment, even in secondary schools. Nevertheless, some compact setups, based on low-cost electronics, have also started to appear [9].

Exploiting the advances in electronics, we have constructed a simple setup for the measurement of the lifetime of cosmic muons. It consists of a single scintillation detector for the detection of both muons and electrons (or positrons) from the decays of the muons which stop in the scintillator. The scintillation detector is coupled to the electronics that register time stamps of signals in the detector above a certain threshold. The time resolution is 12.5 ns and these data are stored either on a memory card or on a computer hard disk. The time differences between the two subsequently registered events in the detector can be determined from these time stamps. Suitable cuts can be applied on these time differences in order to extract the time distribution of events that corresponds to muon decays, and subsequently the mean lifetime of muons, loosely also called muon lifetime, can be determined.

Using Python software we have also developed a graphical user interface (GUI) for the presentation of data, data analysis and presentation of the results. Depending on the level of students, they can either develop their own analysis software or use the existing analysis tools.

There are various educational topics that can be discussed in connection with this experiment, such as relativistic time dilation, muon lifetime in matter, Fermi weak interaction coupling, parity violation in weak interactions and the existence of two different types of neutrino [8]. Since our setup registers time stamps of the events detected in the scintillation detector, it is also possible to study the statistics of random events, and this topic will be treated in a separate article.

In the second section we briefly review the properties of muons and cosmic muons. In the third section we describe the principles of our measurement of the muon lifetime. In the fourth section a description of the experimental setup and measurements is given, and in the fifth section data analysis and results are presented.

2. Muons and cosmic rays muons

A muon is an unstable lepton, approximately 206 times heavier than the more familiar electron, with a half integer spin $1/2$. Its charge can be either positive or negative. A negative muon decays, by the weak interaction, almost exclusively into an electron (or positron in the case of positive muon) and two corresponding neutrinos/antineutrinos [10]:

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

Muons were discovered as new particles in cosmic rays in the 1930s [11], and their properties have been subsequently investigated in cosmic rays and accelerator experiments. Although the muon has been known for almost eighty years, the precise measurement of its lifetime is still a topic of scientific research; see, e.g. [12]. In our measurement of muon lifetime we will use muons from cosmic rays. Cosmic rays were introduced by Victor Hess in 1912 as an explanation of the observed increase of environmental radiation with altitude [13]. By that time, the existence of radioactive elements in the Earth had been established, and they were considered as a source of natural background radiation. However, that could not explain the observed increase of radiation with altitude, and V. Hess proposed a cosmic origin. Subsequent investigations revealed the nature of this cosmic radiation and led to the discovery of many new particles, such as the positron, the first discovered antiparticle, the muon, pion, strange particles (hadrons with strange quarks) and hypernuclei (nuclei which alongside ordinary nucleons contain also baryons with strange quarks). Nowadays, the nature of cosmic rays is pretty well known, although there are still some open questions: for example, the nature of their high-energy part is still being strongly investigated; see, e.g. [14]. Cosmic rays consist of high-energy particles that impinge on the Earth's atmosphere from outer space, the so-called primary cosmic rays. The charged primary cosmic rays consist mainly of protons (86%), helium nuclei (11%), nuclei of heavier elements up to uranium (1%) and electrons (2%), with a small component of antiparticles which is produced through the interaction of the primary cosmic rays with the interstellar matter; see, e.g. [15].

In the reactions with the nuclei in the atmosphere they generate secondary particles, such as pions. In the decays of charged pions, muons and neutrinos are produced:

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

The production of muons occurs at approximately 10 km above the Earth's surface. Taking into account the speed limit given by the speed of light, and knowing the muon lifetime, it is clear that without the effect of time dilation it would not be possible for muons to reach the Earth's surface.

The average muon flux on the Earth's surface is approximately 200 muons/m²s and their average energy is about 2 GeV. There is a very small fraction of muons with an energy below approximately 30 MeV that can be stopped in our scintillator, and which subsequently decay in it.

3. The mean lifetime of the muon and the principle of our measurement

Decays of unstable nuclei and particles, including muons, are characterized by the decay probability in a unit of time, λ . The mean lifetime of the particle, τ , is defined as $\tau = \frac{1}{\lambda}$. Decays follow the exponential radioactive decay law:

$$N(t) = N_0 e^{-\frac{t}{\tau}} \quad (1)$$

where N_0 is the number of unstable particles at the beginning, $t = 0$, and $N(t)$ is the number of particles that survive until time t . We know that the mean lifetime of the muon is $\tau = 2.1969811 \pm 0.0000022 \mu\text{s}$ [10].

In the case of radioactive nuclei, if $e^{-\frac{t}{\tau}}$ changes significantly in a reasonable time, one can prepare a sample of a certain number of nuclei and measure the activity, $A(t)$, which is the

number of decays in a unit of time. The activity follows the same exponential time dependence as the number of nuclei:

$$A(t) = \frac{dN(t)}{dt} = A_0 e^{-\frac{t}{\tau}}, \quad (2)$$

where A_0 is activity at time $t = 0$. From the obtained time dependence of the measured activity, by fitting an exponential function one can determine the lifetime.

In our case of the lifetime measurement of cosmic muons, we cannot enclose cosmic muons in a box and prepare a sample of a certain initial number of muons. Instead, we register muons that come randomly into our scintillator. Most of the muons pass through the scintillator, but some of them stop and decay in it. Since $e^{-\frac{t}{\tau}}$ in the case of muons changes significantly over time, we will use a quantity that corresponds to the activity for the determination of the muon lifetime. In our case, the entrance of a muon into the scintillator represents the time $t = 0$. It is a consequence of the fact that the exponential radioactive decay law, which governs the decay of muons, is independent of the measurement starting time. Registering the time differences between the entrance of muons and their decay, that is, the appearance of the signals from the corresponding electrons (positrons) in the scintillator, we can determine the distribution of muons decaying at time t , $I(t)$. This corresponds to the activity, $A(t)$, in the case of decay of radioactive nuclei, and $I(t)$ follows the same exponential time dependence:

$$I(t) = I_0 e^{-\frac{t}{\tau}}, \quad (3)$$

where τ is the muon lifetime and I_0 is the decay rate at $t = 0$. By fitting an exponential function to the measured distribution one can obtain the muon lifetime.

Neutrinos and antineutrinos, which are also produced in the decay of a muon, leave the detector unobserved, because they interact with the weak force with the matter.

4. Experimental setup and measurement

4.1. Scintillation detector

For the detection of cosmic muons, in our setup we used a type UPS-89 plastic scintillator (Amcrys, Ltd, Kharkov, Ukraine). It is cylindrically shaped with a base diameter of 10 cm and a height of 30 cm. All scintillator surfaces, except one cylinder base, were wrapped in aluminum foil. The uncovered base was coupled to a 3-inch and 9-stage photomultiplier tube (PMT) using optical grease (we have used an older PMT, a Philips XP5312/SN, but any with similar properties can be used). The scintillator and the PMT were mounted within an aluminum tube, which protected them from the room ambient light.

The PMT's high-voltage (HV) supply was custom built, and provided a fixed high voltage of -950 V. For it we designed a printed circuit board (PCB) which uses a CCFL inverter as a primary voltage boost device. After the CCFL inverter, a two-stage Cockcroft–Walton multiplier is used. At the end of the chain are zenner diodes in order to limit and keep the high voltage well defined and stable. As the input the HV supply requires 5 V, which is supplied by a USB cable either from our electronics, by a computer, or directly from the grid using an appropriate adapter. The high-voltage supply is placed in a box that is mounted beneath the aluminum tube with the scintillator and the PMT.

We monitored the negative signals from the scintillation detector, which were mainly produced by cosmic muons, using a digital oscilloscope (Tektronix TDS 2024B). The signals are shown in figure 1 (left), with the oscilloscope working in persistence mode. With a threshold of -48 mV, which eliminates the noise, the observed rate was several Hz, as

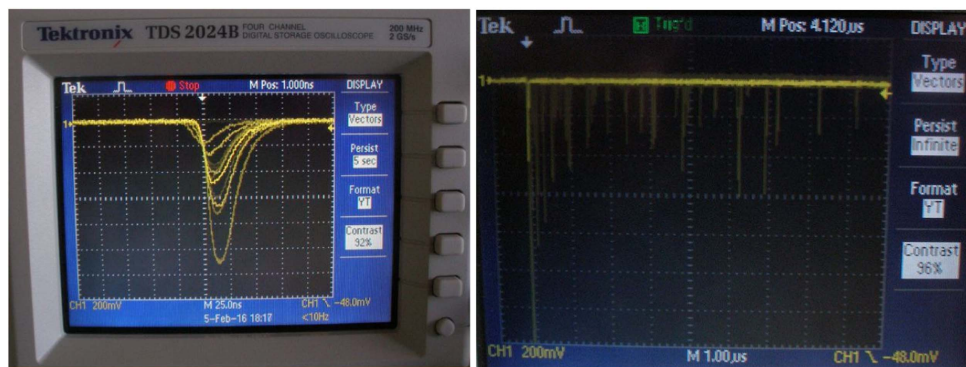


Figure 1. Muon signals from the scintillation detector observed on the oscilloscope with a threshold of 48 mV (left). The time distribution of the electrons from decays of muons (right). The trigger is given by an incoming muon and the second signal is produced by the electron (or positron) from the decay of a stopped muon.

expected from the muon flux on the ground level and the dimensions of the scintillator. These signals are produced mainly by cosmic muons, but among these events are signals also produced by electrons (or positrons; in the following discussions we will use the word ‘electron’ for both particles) from the decays of muons that are stopped in the scintillator as well as by background events. Using the time scale of the oscilloscope in the microsecond region, a decay of the stopped muon can be observed as the second signal on the oscilloscope caused by the electron from the decay in the scintillator. Using this time scale and persistence mode, one can directly observe the time distribution of the electrons from the decays of muons on the oscilloscope screen (figure 1 (right)).

In principle the simplest, though impractical, way to determine the muon lifetime is to use this observed time distribution [16]. A much more convenient way is to record this time distribution in a file for further analysis.

4.2. Readout electronics

The majority of previous setups have used conventional nuclear physics electronics, usually nuclear instrument module (NIM) discriminators, to process signals from a scintillation detector, and all have used some kind of time-to-digital converter (TDC). In the TDC an incoming muon gives a start signal and the electron from the decay gives a stop signal. We have followed a different path and have used low-cost electronics to record the time stamps of the events that are registered in the scintillation detector. The muon lifetime can then be determined in the subsequent analysis of the recorded events.

In order to register the time of a signal appearance, the signals from the scintillation detector are fed to a fast comparator. For that purpose we designed a comparator PCB module. We used an AD8561 fast TTL comparator with a variable threshold in the range of 0 to -500 mV, and after it the signal shape was modified by a 74121 chip, which gives a constant width of the output pulse regardless of the input pulse width. The output of the comparator module is a positive logical signal for each input signal above the set threshold. For pedagogical reasons, signals from the comparator module can also be monitored on the oscilloscope. We set the threshold to -50 mV in order to discriminate the noise from the PMT and acquire as much as possible of the physical signals.

Signals from the comparator module are led to the custom-designed timer PCB module, which contains a 32-bit PIC32 processor [17]. This module can record time stamps of the

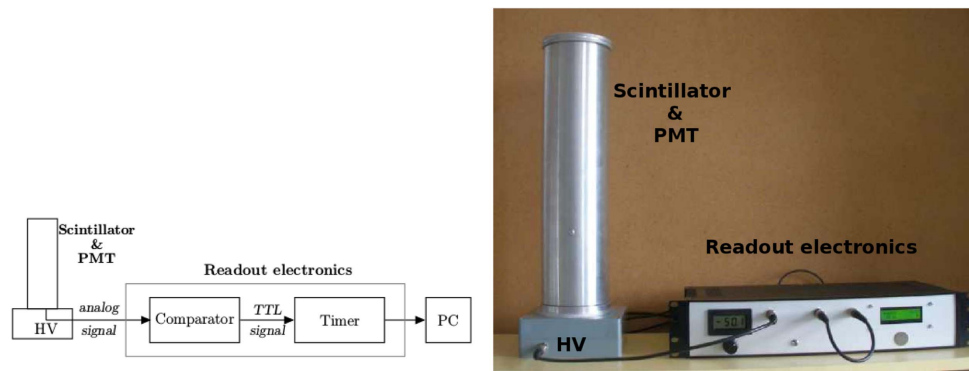


Figure 2. The scheme of the assembled setup (left). The scintillation detector and the readout electronics mounted in the box (right).

signals with a time resolution of 12.5 ns. The range of time measurement is approximately 54 s ($2^{32} \times 12.5$ ns). After this time period, the time is reset to zero and the measurement continues automatically until it is stopped by the user. The module can be programmed to transfer the recorded data to a computer or a memory card and also to perform simple operational tasks on the data. In our case, once 16 events have been recorded, the whole block of 16 time stamps is sent via serial/USB connection to the computer.

The PIC32 module was programmed to show the total number of registered events during the measurement. It was also programmed to calculate the time differences between subsequent events and to show the number of events for which the time difference is less than a given selected time window, usually several muon lifetimes. This number indicates the number of registered muon decays in the selected time window, as will be explained below.

The scheme of the assembled setup is shown in figure 2 (left), and the scintillation detector and electronics mounted in the box are shown in figure 2 (right). The most expensive part in our setup is the scintillation detector, the standard part for the detection of incoming muons and electrons from the decays in the majority of muon lifetime setups. However, the electronic components for signal processing and data acquisition are more than an order of magnitude cheaper compared to the classical nuclear physics equipment. Also, this electronics is much simpler and more compact.

5. Data analysis and results

From the recorded time stamps of the registered events in the scintillation detector we can determine the muon lifetime. As the first step, we have to calculate the time differences between every pair of subsequently registered events. Decays of the stopped muons can be selected by constraining these time differences to be smaller than a selected time window, e.g. 10 μ s. In this way we obtain the time distribution of muon decays $I(t)$ defined in equation (3).

In principle, we can determine the muon lifetime by fitting the exponential function to the obtained time distribution. However, in the real measurement we have to take final time intervals ΔT in which we count the number of muons that decay, N_i , in order to have a statistically significant number of counts. It is desirable that the duration of the time interval ΔT is less than $\frac{\tau}{4}$. It can be also shown that systematic uncertainty in determination of τ is less than 0.2% if $\Delta T \leq 0.1\tau$ [19]. On the other hand, if the time intervals are too small, this means

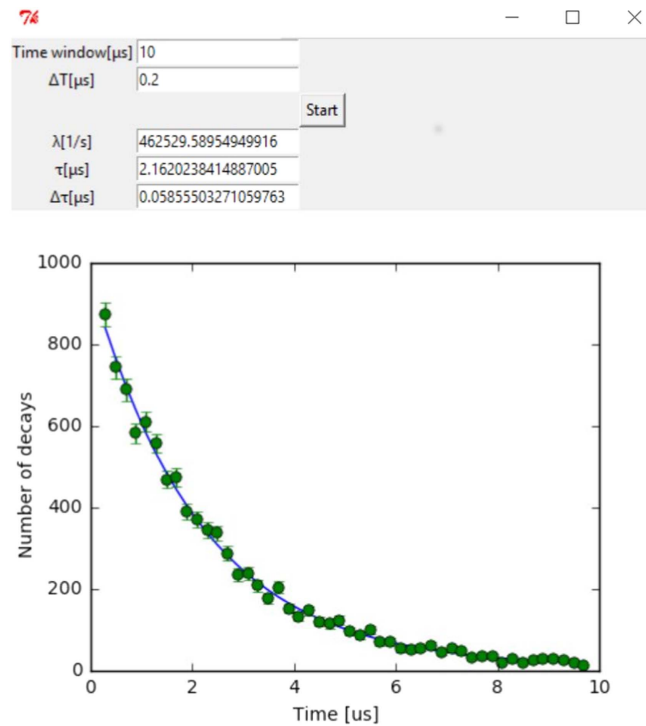


Figure 3. The graphical user interface (GUI) for the data analysis and the representation of the results. In this case we took the events that have time differences less than $10 \mu\text{s}$ and ΔT was $0.2 \mu\text{s}$. The number of muon decays in the given time interval, N_i , are presented by green solid points, and for each point was calculated the statistical uncertainty as $\sqrt{N_i}$. The fitted curve is presented and the values of λ , τ and the uncertainty of τ are given.

a longer measurement to collect sufficient statistics, and a compromise should be found. The statistical uncertainty of the number of muon decays in each time interval is calculated as $\sqrt{N_i}$.

Finally, we have to fit the exponential function to the obtained data distribution to determine the muon lifetime τ . The fit can be done either by using a simple exponential function (in this case we neglect a possible constant background) or by using a simple exponential in combination with a fixed term which takes into account the background [3].

Students can program their own software package for data analysis with different levels of complexity or use one of the existing analysis tools. We have developed a software package using a simple exponential function of the form given by (3), and a GUI based on the Python software [18] for the analysis of the collected data and the graphical representation of the results.

During a single day of measurement with the settings described above, we collected approximately 1700 events in the time window of $10 \mu\text{s}$. The value of the time window in the analysis can be set by using the GUI. To collect sufficient statistics, measurement needs to be performed during a course of several days.

In figure 3 we present the data collected in approximately 5 days of measurement, which could be a reasonable time for a lab exercise. The time interval for counting the number of muon decays, ΔT , which can also be set using the GUI, was $0.2 \mu\text{s}$ (this is a little less than

0.1τ). The data distribution, the exponential fit on this data distribution and the values of obtained λ , τ and the uncertainty of τ are presented as the results on the GUI screen. The obtained result for the muon lifetime is $\tau = 2.16 \pm 0.06 \mu\text{s}$ (statistical uncertainty only).

We have also seen that we can expect slight, but not by much, improvements of the result with the increased statistics. On the other hand, our setup has limitations caused by its very simple construction. The signals are clean and above some (indeed very low) threshold there is no noise from the scintillation detector and we have observed no noise from the electronics. But, the biggest disadvantage is that we do not have particle identification, so both muon and electron are detected by the same scintillation detector. However, this is not so critical if we do not have any radioactive source in the vicinity of our detector, which means that we make a measurement in an ordinary environment. In such an environment, cosmic muons are the main source of the radiation which is detected by the detector. The condition that the second event appears in the chosen time window, in our case $10 \mu\text{s}$, after the muon entrance actually ensures that we have detected the electron from the decay of a muon stopped in the detector. Using the statistics of random events and knowing the rate of incoming cosmic rays, as well as the dimensions of our scintillator, one can show that there is very small probability that the second detected particle in the time window of $10 \mu\text{s}$ is a cosmic ray particle; see, e.g. [3]. We have estimated that there is less than ten wrongly identified muon decays in a thousand detected real decays. A possible background can be taken into account by using different fitting functions, such as exponential plus constant term.

One of the sources of systematic uncertainty is also the different lifetime of negative muons in matter compared to a vacuum, which is smaller because of possible muon capture by the nucleus; see, e.g. [8]. Another possible source of systematic uncertainty is the finite size of the time window in which we seek the decays of muons. However, a larger size of this time window means also a bigger chance for a second muon to appear in it, and also at some point fluctuations in the background become comparable with the number of muon decays. The selected time window of $10 \mu\text{s}$ in our analysis is slightly more than 4τ , which is the time interval in which approximately 98.2% of muons should decay.

6. Conclusions

We have assembled a simple and inexpensive setup for measurement of the lifetime of cosmic muons. In our setup, as in the majority of other realizations of this experiment, we have retained a scintillation detector for the detection of incoming muons and electrons from the decays, but we have substituted classical nuclear physics equipment with inexpensive and simple electronics for signal processing and data acquisition. This electronics is an order of magnitude cheaper but still possesses the required properties for measurement, and it is also simpler to use. This feature could enable much broader employment of this experiment, not only in undergraduate laboratory exercises but also in secondary schools, although in some cases assistance for the construction and operation could be needed. All PCBs we have designed and programs we have developed, as well as additional information, can be obtained on request.

Another feature which differentiates our setup from, according to our knowledge, all other existing setups is the principle on which the measurement is done. We register time stamps of all events which are detected in the scintillation detector and in off-line analysis, by making appropriate cuts, the events which correspond to the decays of muons are selected. Since we have a kind of ‘off-line TDC’, the time window in which we seek the decay of a muon can be varied in the analysis.

The software for the analysis can be developed either by the users themselves or they can use one of the existing tools. We have developed analysis software and a GUI for the presentation of data and results using a Python software package. In our analysis software, the time intervals in which muon decays are counted can be varied as well as the time window in which we seek the decays of muons. We have used only a simple exponential function for the extraction of the muon lifetime. In the analysis of a measurement of approximately five days, with a time interval of $0.2\ \mu\text{s}$ and time window of $10\ \mu\text{s}$, we obtained a satisfactory result with a statistical uncertainty less than 3%. But more advanced fitting procedures or the influence of the size of the time window in which we observe the decays of muons, or the size of the time interval in which we count the decays, can also be investigated.

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