Muon Lifetime Measurement

Abstract

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Cosmic ray muons are produced in the upper atmosphere. Some of these muons reach sea level such that their properties can be measured in the laboratory.

The aim of this project is to measure the muon lifetime. Muons are stopped in a large block of scintillator, where they subsequently decay into an electron/positron and two neutrinos. A short light pulse is produced by the stopping muon which is detected and amplified by a photomultiplier tube. When the muon decays a second pulse is produced by the emitted electron or positron. The signals from the photo multiplier are fed into an electronic circuit which determines the time delay between the two pulses. The circuit is connected to a PC which is used to read out the data. The experiment involves the set-up of the equipment, performing the actual measurement and the subsequent data analysis.

The project can be extended to measure the mass of the muon which can be derived at when measuring the energy of the electron or positron emitted in the decay of the muon.

References

- `http://www.ph.ed.ac.uk/~muheim/teaching/projects/index.html`
  `http://www.pp.rhul.ac.uk/muon/index.html`
- T.K. Gaisser & T. Stanev, *Cosmic rays*,
  in Particle Data Group, Reviews, Astrophysics and Cosmology,
  `http://durpdg.dur.ac.uk/lbl/2004/contents_sports.html#astroetc`
- W.R. Leo, *Techniques for Nuclear and Particle Physics Experiments*, 2nd edition, Springer Verlag (1994) Berlin, Heidelberg
- P.R. Bevington & D.K. Robinson, *Data Reduction and Error Analysis for the Physical Sciences*, 3rd edition, McGraw-Hill (2003)

Time Line of the Project

In order to guarantee a successful project you need to be able to plan your work. The following will help you to achieve this goal.

- In week 1 of the semester you will get an introduction to all aspects of the project which will consist of experimental work, data analysis and a literature study.
- At the end of week 2 you are required to hand in a **project plan**. This plan should contain a time line of your project. You will state the measurements that you will attempt and what equipment you will require for this. You should state how you will analyse the data and what results you would like to extract from your data. An outline of your literature study should be included. The project plan may not exceed one page in length, you must sign it and ensure that you attach it to the laboratory book.
- At the end of week 6 you will need to arrange a review meeting with your supervisor. We will compare your actual achievements so far with your project plan and, if necessary, make amendments. Note that the experimental work must be finished by the end of week 8.
- The remaining third of the semester will be required to finalise the analysis, write the report and prepare a poster. The poster session will be in week 11 of semester 2. The date for handing in the project is given in the 4th year project booklet, usually it is the last working day of week 11 of the semester. The hand-in will consist of the project plan, the laboratory book and the written report.

The assessment criteria for the project, the poster and the written report are given in the 4th year booklet and/or by the Senior Honours project coordinator.

Muon Physics

The muon is an elementary particle and one of the fundamental constituents of matter. Muons are very similar to electrons, apart from the fact that a muon has about 200 times more mass than an electron. Due to their mass muons are unstable and decay by the weak force almost exclusively into an electron or positron and two neutrinos, $\mu^- \to e^-\bar{\nu}_e\nu_\mu$ and $\mu^+ \to e^+\nu_e\bar{\nu}_\mu$. The decay time probability for muons follows an exponential decay law. The distribution $N(t)$ of muons with a measured lifetime t can be described as

$$N(t) = N_0 \exp\left(-t/\tau_\mu\right)$$

where τ_μ is the mean muon lifetime and N_0 is a normalisation parameter.

The muon was discovered in 1937 by C.W. Anderson and S.H. Neddermeyer when they exposed a cloud chamber to cosmic rays. The source of muons for this project are also cosmic rays. In the upper atmosphere primary cosmic rays, mainly protons, collide and interact with atomic nitrogen or oxygen nuclei and produce showers of particles. These secondary particles also interact mainly via the strong and electromagnetic force to produce a cascade of more particles, but others will decay via the weak force and some of them produce muons. Many of these particles are very short lived and do not reach sea level. Muons do not interact with matter via the strong force, but only by the electromagnetic and weak force. It can travel a long distance and reach the surface of the Earth.

Muons interact with matter mainly by the electromagnetic interaction and lose energy/momentum along their flight path trough matter. This energy loss is described by the Bethe-Bloch equation. Muons can stop in a scintillator if upon entering their kinetic energy is less than their remaining range. Note that thickness and range are often measured as $x = \rho s$ where s is the thickness in cm and ρ is the density measured in g/cm^3. The effective thickness x has units of g/cm^2 and allows us to compare more easily energy loss and range in materials that have very different densities.

Positive muons that stop in a scintillator await their decay. Negative muons can bind to the atomic nuclei in a scintillator and form muonic atoms. Such bound negative muons can interact weakly with protons in the nucleus before they decay. Thus the effective lifetime of negative muon reduces from the lifetime of free muons of $2.19703 \pm 0.00004\ \mu$s.

Equipment

You need to set up and familiarise yourself with the equipment for this project. The scintillation detectors are read out by photo multiplier tubes, electronics is required to amplify and digitise the signals. The digitised signals from a muon starts a clock and the signal from the electron/ positron emitted in the decay stops this clock. The clock buffer is read from a PC where the data acquisition programme (DAQ) resides.

Use the digital oscilloscope to understand each part of the detector and the electronics. You will need to tune the high voltage applied to the photo multiplier tube. Do never exceed 2400 V for the plastic scintillator rig and 2000 V for the Sodium Iodide crystal scintillator rig, respectively. You also want to optimise the threshold of the discriminator and maybe the gain of the amplifier. The goal is to maximise your measured yield of muon decays while minimising the number of background events. These are random coincidences of signals not arising from muon decays. These are mainly due to natural radioactivity, throughgoing muons and photo multiplier after-pulses.

To measure the energy spectrum of decay electrons you will use electronics to make a coincidence selecting the later pulse of the emitted electron/positron. This signal allows to apply a gate to the ADC card which resides in a PC where the data taking is steered. You will need to calibrate the energy scale of the ADC card using radioactive sources.

A more extensive guide is to be written, but you can also find descriptions of several very similar apparatus on the web.

Data Analysis Methods

There are several ways to extract the muon lifetime from the distribution of muons decay times t. The measured decay spectrum follows the law

$$N(t) = N_0 \exp\left(-t/\tau_\mu\right) + B$$

where τ_μ is the mean muon lifetime, N_0 is a normalisation parameter and B is the number of background events per time bin. The DAQ programme contains a simple least square fit which does not include error bars. How does it work, given that the lifetime distribution is not linear? The result from this approach will be slightly biased (usually towards larger lifetimes) as its assumptions are not exact. Your proper data analysis should be based on one of the following methods or an eqivalent approach:

- Write your own fit function in your favourite programming language. You can learn this method, for example, from the book by Bevington and Robinson. Code in C++ can be downloaded from their website. If you plan a career in science you will be able to use this work again in the future.

- Use Excel's Solver to construct and minimize your own χ^2, see Les Kirkup's webpage. While Excel has limitations for scientific applications, you will find excellent information on its proper use for data handling and plotting in the Experimental Physics 2 Manual by Malcolm McMahon.

- Use a non-commercial fitting programme that allows the user to provide non-linear fit functions, such as xmgrace, gnuplot(?) and root, minuit (or paw and mnfit for fortran afficionados). If you work with any of the above explain the fitting method used. We do not have site license for commercial fitting packages like Origen.

- Use the simple least square approach including errors for each bin in an iterative mode. This is a so-called "poor man's fit", but converges fast to an unbiased result. Carefully select the regions for signal and background.

Note that very early lifetimes need to be excluded from your fit as the lifetime distribution is distorted by the apparatus. Measure the precision and stability of your result as a function of the selected region.

Data Analysis

Your measurement of the muon lifetime in a scintillator is the average lifetime of positive and negative muons. Here you'll find a selection of possible measurements.

- By comparing your measurement with the muon lifetime in vacuum you can measure the ratio r of positively and negatively charged muons at sea level. What assumption do you need to make for this?

- You can also use your measurement to determine the Fermi Coupling Constant G_F of the weak interaction. Always compare your measurements with measured values from the literature.

- The muons are born outside the scintillator and have already lived a considerable time when they stop. Why does the decay time distribution still measure the muon lifetime?

- Show that τ_μ is the mean of the muon lifetime distribution. How is τ_μ related to the muon half-life, a notation used in Nuclear Physics?

- Measure the muon lifetime with the Sodium Iodide detector. What differences do you expect?

- Compare to the theoretical binomial distribution. For example you expect a success rate of $p = 1 - e^{-1} = 0.63$ for the probability of the muon decaying within one lifetime. The probability of failure is $q = 1 - p$. Divide your measured lifetime distribution of N_{total} events into samples of $N = 100$ events each, and count in each group how many have a decay time less than τ_μ. Histogram the values of p. The plot should have a mean of $63 = Np$ and a variance $\sigma^2 = Npq = 23.3$. Are your results consistent with theory?

Literature Study

There is ample literature available about muons and their lifetime. The results of the literature study should be an integral part of the report, but if preferred it could be in form of an appendix in the written report. The literature study will carry a sizable weight in the assessment of the project report. The following motivating questions present possible entry points for your literature study.

- The muon is an elementary particle and one of the fundamental constituents of matter. Muons are very similar to electrons, apart from the fact that a muon has about 200 times more mass than an electron. Muon decay is governed by the charged weak interaction. Take a textbook on particle physics, for example D.H. Perkins, *Introduction to High Energy Physics*,to study muon decay in detail. How are measurements of the lifetime and mass of the muon used to measure the strength of the weak interaction (Fermi's Coupling constant)?

- Cosmic rays are the source of the muons in our experiment. Describe the properties and origin of cosmic rays. How are cosmic ray muons produced in the upper atmosphere? What are the primary particles and what are the production mechanisms for cosmic muons? Describe the kinematic properties of cosmic muons reaching the surface of the earth?

- The muon has a lifetime of $\tau_\mu = 2.197$ μs. According to classical physics, what is the distance that a muon would travel at the speed of light during its lifetime? Why do muons produced in the upper atmosphere, say at 10 km, reach the sea level before they decay? What is the speed $\beta = v/c$ of a muon with an energy of 2 GeV? How far will the muon travel before disintegrating?

- At sea level, what is the total flux of muons and what is their average energy in GeV? You will use a block of plexiglas scintillator with dimensions of $8 \times 16 \times 100$ cm^3 to measure cosmic ray muons. How many muons will pass through this scintillator per unit time?

- Do you expect to measure the same lifetime for positive and negative muons? What are muonic atoms and why are negative muons much likelier to be captured by the nucleus than electrons? The following article will help to understand this problem: T. Suzuki, *Total nuclear capture rates for negative muons*, Physical Review **C35** (1987) 2212.

- Charged particles such as muons lose energy when traversing matter. According to the Bethe-Bloch formula for high energetic particles with $\beta\gamma \geq 4$ this energy loss is roughly constant at about 2 $\mathrm{MeV\,g^{-1}\,cm^2}$. What is the energy loss of such muons in the scintillator block? What is the energy loss of muons in the atmosphere? Note that 1 atm $\approx$ 10^5 N/m^2 $\approx$ g 10^4 kg/m^2, where $g = 9.81\mathrm{m\,s^{-2}}$. You might want to solve example 2.1 of page 33 in the book of W.R. Leo first.

- Try to estimate the maximum energy of muons that will stop in the scintillator block? Find the energy spectrum of cosmic ray muons observed at sea level in the literature and try to estimate how many muon decays you expect to observe in the scintillator block. You might want to solve example 2.2 of page 34 in the book of W.R. Leo first.