Muon Lifetime

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Abstract

Goal of this experiment is to measure the life time of muons. Muons are so-called Leptons, the heavier “brothers” of the electrons you are familiar with. They are fundametal but unstable constituents of matter. They are not composed of any other sub-particles. You will be able to experimentally verify that the decay of these particles is decribed by an exponential decay rate, just as the decay of the Radon daughters which are composite objects.
This will be done by measuring distribution of time intervals between entry of a cosmic ray muon into a scintillator (in which it stops) and its subsequent decay. A fit to this distribution then yields the muon lifetime. We will use contemporary instrumentation and expriemental techniques.

1 Tasks

1. Setup the counting electronics. Find the appropriate setting for the high voltage, counting threshold and maximum correlation time.
2. Perform a time calibration of the electronics using a cable delay.
3. Collect a suitable sample of muon decays. You will need to run the experiment for at least one day to have sufficient statistics.
4. Analysze the data using PAW. Determine: the muon life time, the total number of muon decays you observed and the signal to background ratio of the experiment.
5. Do you get the tabulated muon life time? If not try to explain why it is different.

2 Introduction

We understand today that the world around us is composed of a limited number of fundamental particles. The interactions of these particles are mediated by four fundamental forces:

1. Electromagnetic force: governing the interaction of charged particles.
2. Weak force: converting particles into each other.
3. Strong force: holding the atomic nuclei together.
4. Gravitation: attraction of masses governing the dynamic of the universe.

While all massive particles are subject to (the VERY weak) Gravitational and Weak Interactions only some experience the strong force. These are called **Hadrons**. They are understood as various combinations of **Quarks**, of which we know today 6 (plus their anti-particles):

$$\begin{pmatrix} up \\ down \end{pmatrix} \begin{pmatrix} charm \\ strange \end{pmatrix} \begin{pmatrix} top \\ beauty \end{pmatrix}$$

These particles carry +2/3 and -1/3 charge and spin 1/2, respectively. They cannot exist freely but are instead always bound (by the strong force) in groups of three called **Baryons** or two (always as quark

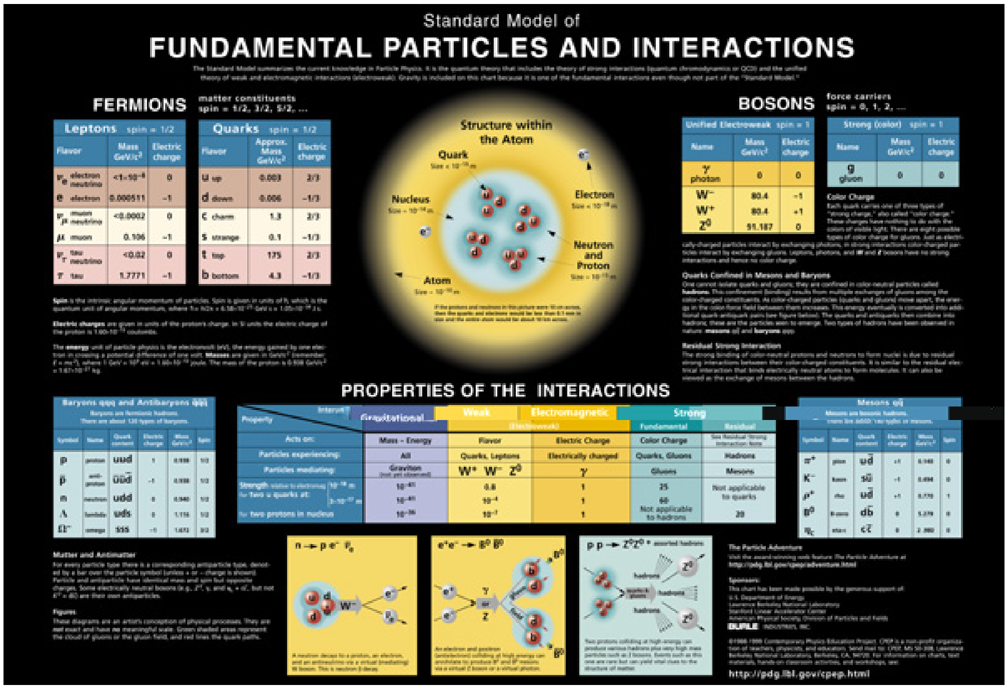

Figure 1: Sketch of the particles and their interactions. This chart has been taken from the web site of the Particle Data Group.

anti-quark pair) called **Mesons**. The world around us (neutrons and protons) is entirely made of the lightest species **u** and **d**. The other heavier quarks are only found in unstable particles.
The particles not subject to the Strong force are called **Leptons**. They also come in three groups (plus their associated anti-particles):

$$\begin{pmatrix} e \\ \nu_e \end{pmatrix} \begin{pmatrix} \mu \\ \nu_\mu \end{pmatrix} \begin{pmatrix} \tau \\ \nu_\tau \end{pmatrix}$$

Leptons have spin 1/2. The particles listed in the upper row have charge -1. The so called neutrinos ν are neutral. As for the quarks stable matter only contains electrons. Its heavier relatives μ and τ are unstable. Their decays are a manifestation of the weak force which always acts on pairs of the particle doublets listed above.
In this experiment we will determine the lifetime of the muon which is 207 times heavier than the electron. Due to their large mass muons

are not produced in any radioactive decay. Large particle accelerators are usually needed to create heavy Leptons. Fortunately muons are quite abundant in the cosmic radiation. That's also how people have demonstrated their existence in 1937.
The temporal development of the decay of Radon daughters is well described by a simple exponential function. This has been demonstrated in one of the previous experiments. In this experiment a complex nucleus, composed of many protons and neutrons was decaying. Is the decay of the much simpler muon, which is in fact a point-like fundamental particle, also described by such an exponential decay law?

2.1 Cosmic Radiation

Where do we get the muons from? The earth's upper atmosphere is constantly bombarded by very energetic extra-terrestrial particles. Most (about 85%) these are protons, α-particles and a few light nuclei. These particles can reach extremely high energies even beyond the reach of today's most powerful particle accelerators. The largest energy ever measured for a microscopic particle is a few times 10^{21} eV; equivalent to the energy of a speeding tennis ball.
The cosmic ray protons (u, d, d) create π-Mesons $(u, \overline{d})$, $(\overline{d}, u)$ through the strong interaction:

$$\begin{aligned} p + p &\rightarrow p + p + \pi^0 \\ &\rightarrow p + n + \pi^+ \\ &\rightarrow p + n + \pi^+ + \pi^- + \pi^+ \\ p + n &\rightarrow p + n + \pi^0 \\ &\rightarrow p + p + \pi^- \\ &\rightarrow n + n + \pi^+ \\ &\rightarrow p + p + \pi^- + \pi^+ \pi^- \end{aligned}$$

At sufficiently large energies many pions may be produced. Pions are unstable. The charged variety decays by means of the weak interaction with a lifetime of $\tau = 2.55 \cdot 10^{-8}$ s:

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

Due to their short lifetime most of the pions decay in the atmosphere and do not reach the earth's surface.

The muons are again unstable and decay weakly:

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

with a lifetime of $\tau = 2.2 \cdot 10^{-6}$ s. Owing to their relatively long lifetime (at least compared to pions), many secondary muons created in the upper atmosphere actually do reach the surface of the earth. These particles are ultra relativistic (kinetic energies of GeV to several hundred GeV are quite common) which means that their clocks go slower than those in the laboratory. Without this we wouldn't expect to see many muons on the earth's surface. Goal of this experiment is to verify the above value for the muon lifetime.
The quoted lifetime applies strictly only for *free* particles. Negative muons, bound in an atomic orbit, may also be captured by nuclei: $\mu^- + p \rightarrow n + \nu_\mu$. Negative muons have hence a shorter effective lifetime τ_e: $\frac{1}{\tau_e} = \frac{1}{\tau_\mu} + \frac{1}{\tau_{capt}}$. The energy of muons bound in atomic shells is calculated analogous to electrons. Due to their 200 times larger mass the orbital radii are hence 200 times smaller. After being bound the muon drops immediately to the tightest bound shell (not forbidden by Pauli principle). The capture probability scales approximately as: $\frac{1}{\tau_{capt}} \approx Z^4$. Already for Z=11 τ_μ and τ_{capt} are of similar magnitude reducing the observed lifetime for μ^- by a factor 2. That's why the detection material chosen for this experiment is liquid scintillator, composed of hydrogen and carbon; both low Z.

2.2 Measurement

To measure the muon lifetime it is not necessary to know the time elapsed between its creation and decay (just like in the Rn decay measurement performed in this lab). It suffices to chose a time zero t_0 for which we know for sure that the muon did exist. We may then evaluate $e^{\frac{t-t_0}{\tau_e}}$, the probability that the muon survived the time t. The experimental task is now to define the reference time t_0 and measure the time t until the muon decays.
The detector used in this experiment is a large drum filled with liquid scintillator. Minimum ionizing muons deposit a $\frac{dE}{dx}$ of 1.7 MeV/cm. A muon passing through the drum will typically deposit many MeV in the liquid. Such large energy deposits are beyond most detector

backgrounds. A *large* energy deposit defines t_0. A fraction of the muons will stop in our detector drum and subsequently decay. The decay electrons (or positrons) have a continuous energy distribution just as in the case of the three body beta decay. Due to the large muon mass the kinetic energy of the electron can reach up to 53 MeV; again beyond the energy of most detector background. A second large energy deposit in the detector in short succession to the first hit will signal a muon decay. We will associate two large energy deposits within a short time with decaying muons. A measurement of the time t between two such hits will allow us to derive the effective muon life time τ_e by means of a statistical analysis of their time distribution:

$$N(t) = N(t_0) \cdot e^{-\frac{t-t_0}{\tau_e}} + B(t) = \underbrace{N(t_0) \cdot e^{\frac{t_0}{\tau_e}}}_{constant} \cdot e^{-\frac{t}{\tau_e}} + B(t) \qquad (1)$$

We will fit the time distribution to obtain τ_e. Although the choice of a high counting threshold greatly reduces the detector background it is not exactly zero. The leading componet is caused by so called "random coincidences". These are caused by two independent muons which just happen to cross our detector within a short period of time. The corresponding high energy deposits just look like a muon decay using our event selection criterion (two large energy deposits in a short succession). We would naively expect that such "random coincidences", occurring at a constant rate, should result in a time independent offset B. However, this is not the case. You can easily understand this when examining the probability of observing *no successive hits* within a given time difference. This probabilty is obviously decreasing with longer waiting time. Let the average number of events in any given time period Δt_w be μ. At a constant rate R_μ of muons hitting the detector we expect $\mu = R_\mu \cdot \Delta t_w$. The probability of observing *no successive hits* within Δt_w is given by the Poisson distribution:

$$P(x, \mu) = \frac{\mu^x}{x!} e^{-\mu}, \qquad (2)$$

where x denotes the number of successive hits observed. As in our case we are intersted in $x = 0$ we see that $P(0, \mu) = e^{-\mu} = e^{-R_\mu \Delta t_w}$. We thus expect an exponential time distribution for the background events. A fit to the combined muon-background event distribution will hence allow us to actually measure the background.
We have to arrange the time measurement in such a way as to allow

a precise measurement of the random background B. The number of background counts B is given by:

$$B(t) = B(t_0) \cdot e^{-(t-t_0)R}, \tag{3}$$

where R denotes the background counting rate.

3 Experimental Procedure

We will have to find the proper compromise between low background (high threshold) and low counting rate. As a measurement of both takes about a day the table below lists previously measured signal to background ratios and muon decay rates as a function of the detector threshold. These measurements were done using a high voltage of -1300 V and the analog sum of two of the tree PMTs of the detector. The rate of muons impinging on the drum is about 67 s^{-1} of which

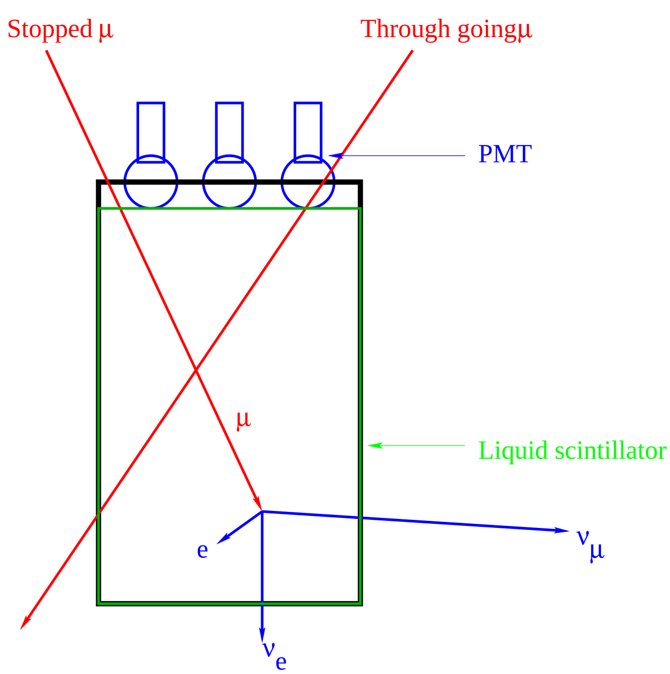

Figure 2: Cross sectional view of the muon decay detector.

our enegry threshold slects an unknown fraction.