Experiment 1

Muon Lifetime

1.1 Introduction: The Muon

The μ lepton (muon for short) has played a central role in the history of elementary particle physics since its discovery in 1937 by cosmic ray physicists, who mistakenly identified it with the famous “meson” hypothesized by Yukawa in 1935 to be the carrier of the strong force. The excitement per capita caused by that misidentification has rarely been exceeded in the myriad “elementary” particle discoveries since; it is probably for this reason that some people (including many former Soviet physicists) still refer to the muon as a “meson” today.

Technically speaking, a *meson* is now defined as a strongly interacting particle (a “*hadron*”) with zero or integer spin (therefore a “*boson*”). The muon, with spin $\frac{1}{2}$ (therefore a “*fermion*”) and weak nuclear interactions but no strong interactions, is properly classed as a “*lepton*”, but the colloquial notion of “mesons” as “medium-mass” particles is hard to forget, and the muon certainly satisfies this criterion, being about 207 times heavier than the electron but only about 1/9 as heavy as a proton.

Most of the muons produced on Earth today are still of natural origin, despite the best efforts of accelerator physicists. The cosmic rays that arrive at the Earth’s surface are almost all muons, whereas the “primary” cosmic rays in space are almost all extremely high energy ($> 10^{10}$ eV) nucleons — mostly protons. No one is sure where these ultra fast protons come from, but for many years their mysterious source provided the only high energy particles available for experiments, and even today’s best accelerators cannot match their highest energies. In this lab we will put their products to good use.

The conversion of primary cosmic rays (protons) to muons begins when the former collide with oxygen or nitrogen nuclei in the upper atmosphere. The products of these collisions are mainly fragments of nuclei (nucleons, alpha particles, smaller nuclei, *etc.*), gamma rays, positrons, electrons and mesons (mostly π mesons or “*pions*”). All of these “secondary” cosmic rays, if they have enough energy, can collide with new nuclei and form more of the same, in what is known as a “shower”. It is the pions that are of most interest; indeed, this has always been true, since the pion actually is the famous “Yukawa meson” that acts as the “nuclear glue” in most strong interactions. Once this was demonstrated in 1947, the fanfare around muons died away and almost everyone went off to study pions.

Pions come in three charge states, π^+, π^0 and π^-. The muon, like the electron, has only two: The μ^- and its antiparticle the μ^+. The π^0 has a lifetime of only about 8×10^{-17} s, decaying almost always into two gamma rays; whereas charged pions almost always decay into muons and neutrinos (primarily *via* $\pi^+ \to \mu^+\nu_\mu$ or $\pi^- \to \mu^-\bar{\nu}_\mu$) with a mean lifetime of about 26 ns (one ns [*nanosecond*] $= 10^{-9}$ s).

About one $\pi^\pm$ in ten thousand will decay into a positron(electron) and an (anti)neutrino instead (*e.g.* $\pi^- \to e^-\bar{\nu}_e$), which illustrates the marked similarity (except for mass) between muons and electrons. Muons (at least the negative variety) are often referred to as “heavy electrons”, and considerable theoretical effort has been devoted to the mystery of why nature should have several "*generations*", as they are now known, of leptons.[1] No one knows yet, but there is no doubt that nature knows the difference and keeps very careful track of it; otherwise a muon could just "de-excite" to an electron and a gamma ray ($\mu^- \to e^-\gamma$), which has not been observed to occur within at least 10^{11} muon decays.

The muon and electron have their own associated neutrinos: ν_e and ν_μ are definitely not the same particle, although the difference between them is even less apparent than that between muons and electrons.[2] These "conservation rules" are kept track of by assigning conserved quantum numbers: the μ^- and the ν_μ have "muon number" +1; the electron and its neutrino have "electron number" +1. Their respective antiparticles (μ^+, $\bar{\nu}_\mu$, e^+, $\bar{\nu}_e$) have lepton number −1.

Almost all the secondary cosmic rays eventually stop in the upper atmosphere; it is mainly the "tertiary" particles — muons and neutrinos — that make it all the way down to the Earth's surface. This is because these "leptons" *do not interact strongly*. They can zip right through nuclear matter without more than an electrostatic deflection. (Neutrinos have not even that, and usually keep on going right through the Earth.) This explains the mainly (about 75%) muonic composition of the highly penetrating cosmic rays detected at sea level. Muons, like electrons, come with + or − charges and therefore interact electromagnetically. By analogy with electrons, the μ^- is conventionally called the particle and the μ^+ the antiparticle, and the μ^+ is some what more plentiful in practice. Unlike electrons, muons are themselves unstable. (Otherwise they would accumulate and eventually take the place of electrons in normal matter.) Although $\mu^- \to e^-\gamma$ is forbidden by lepton number conservation,

$$\mu^- \to e^-\bar{\nu}_e\nu_\mu \qquad \text{and} \qquad \mu^+ \to e^+\nu_e\bar{\nu}_\mu$$

are not. In free space, both types of muon decay with the same mean lifetime, $\tau_\mu = 2.19703(4)$ μs.

The interaction governing μ decay is obviously not very strong or muons would not last so long; it is, in fact, the same "weak interaction" that governs nuclear β-decay. One property of the weak interaction that manifests itself dramatically in the π-μ-e decay sequence is "parity violation"; this feature led to the muon's second period of notoriety in physics. Prior to 1956, parity ($\mathcal{P}$) or inversion symmetry (in which all position vectors $\vec{r}$ are replaced by $-\vec{r}$) was one of the most sacred "Laws of Physics" — the process you see in a mirror when looking at the reflection of some normal process is supposed to be just as likely and have the same strength as the original process. In 1956 Lee and Yang proposed that the mysterious decay properties of strange mesons called *kaons* could be understood if weak interactions maximally violate inversion symmetry — *i.e.* the process in the mirror does not exist in nature. In 1957 this theory was confirmed in nuclear β-decay and (simultaneously, in the same issue of the *Physical Review*) in the π-μ-e decay sequence. This caused quite a shock, since at that time people assumed that physics was as invariant under inversion as we still believe it to be under rotation or translation.

This property has useful applications — it causes muons to be born 100% spin polarized and to decay asymmetrically themselves, with (in the case of the μ^+) the positron tending to exit preferentially along the muon's spin direction; one can thus detect any interactions of the muon's spin and magnetic moment with its surroundings during its lifetime by observing the directions of the positrons from the decay of an ensemble of muons. This technique is called μSR (by analogy

[1] A third "generation" of lepton, the τ^- (with its associated neutrino the ν_τ), is nearly 3500 times heavier than the electron and correspondingly short-lived (about 3×10^{-13} s) because there are so many lighter particles it can decay into.

[2] If you want to see more details about any sort of elementary particles, see the Website `http://pdg.lbl.gov/` of the Particle Data Group at Lawrence Berkeley National Laboratory. (Normally Website are considered unreliable references, because anyone can put one up and say whatever they like; this one is an exception.) You can also inspect the informative and colourful posters in the stairwell on the West side of Hennings.

with NMR and ESR) and is actively pursued at TRIUMF as a means of probing internal magnetic fields in normal matter; in this lab, however, we will concern ourselves only with the *lifetime* of the muon.

While positive and negative muons decay at the same rate in vacuum, it is difficult to *stop* muons in vacuum. In condensed matter, where experiments like these are normally performed, positive muons last longer than negative muons. This is because the latter are subject to the additional process of nuclear capture, $\mu^- p \to n\nu_| mu$, where the proton is part of the nucleus around which the μ^- orbits as one would expect a "heavy electron" to do. The μ^+, which is repelled by nuclei, behaves more like a "light proton" and is not subject to such interactions. Consequently, the μ^- lifetime is shorter than that of the μ^+ by an amount depending upon the atomic number Z of the nuclei of the stopping medium. For heavy nuclei like Pb, the μ^- lifetime can be as short as 80 ns. For carbon it is around 2.0 μs, and in plastic scintillator it is typically about 1.8 μs on average, although of course each element present will exhibit a different μ^- lifetime "component".

1.2 Reading

Consult the available literature[3] to find out about

1. properties of muons;
2. rate of anival of cosmic-ray muons at sea level;
3. typical cosmic-ray muon energies;
4. the spectrum of electron energies in muon decay.

1.3 Apparatus and Procedure

The equipment is shown schematically in Figure 1.1. Scintillators A and B are large (respectively 20 cm OD × 20 cm high and 35.6 cm OD × 27.95 cm high) cylindrical blocks of plastic scintillator (density $\rho \approx 1$ g/cm^3) which are optically isolated, covered with a highly reflective surface coating. These scintillator are "observed" by photomultiplier (PM) tubes provided with a high voltage (HV) power supply (PS). The PM tubes should be operated at about +1400 V.

As scintillators A and B are of different sizes and are viewed by different types of PM tubes, the pulse heights and counting rates are not the same. Most cosmic-ray muons pass completely through the scintillators. In order to identify those few that stop in A it is almost completely surrounded by B and the signal from B is used as a veto.[4] The electronics for measuring the time interval between the arrival of a muon in scintillator A and its decay in the same scintillator is shown schematically in Fig. 1.2.

The negative pulses from the anodes of the photomultiplier tubes are of variable amplitude (up to ~ -1 V), and length (typically several microseconds). These "raw counter pulses" have a relatively fast "rise time" and a long exponential-looking decay; it is important to define the *time* of the pulse by triggering on the leading edge at some "threshold" (minimum pulse height) and then eliminating their variability in the subsequent logic. The *discriminators* trigger on all pulses

[3] A good (though old) reference is the three-volume set "*Muon Physics*", Ed. V.W. Hughes and C.S. Wu (Academic Press, 1975). And don't forget the LBNL Website: `http://pdg.lbl.gov/`

[4] The "uncovered" part of A is at the top. Thus (to the extent that B is an efficient "anti counter") only muons coming *down* from the zenith and stopping in scintillator A will produce this "μ stop" pulse A$\bar{\text{B}}$. Although cosmic ray muons arrive from all directions except "down", the flux is highest from the zenith, so this is a good choice.

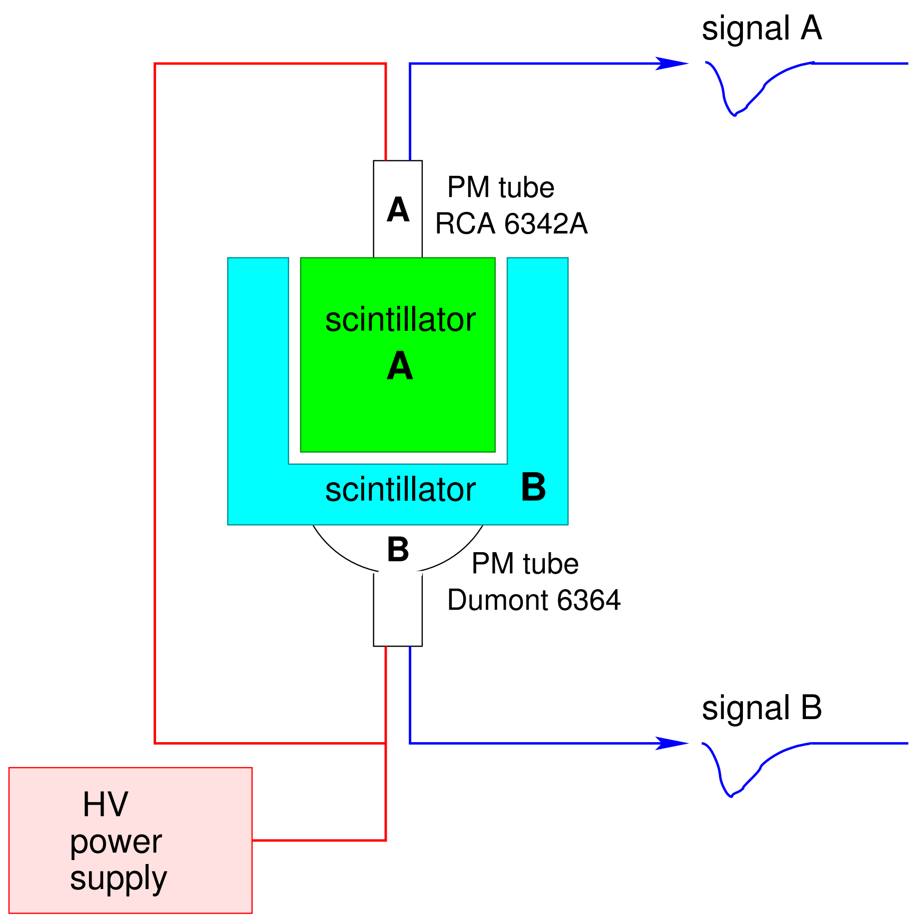

Figure 1.1: Sketch of muon detectors.

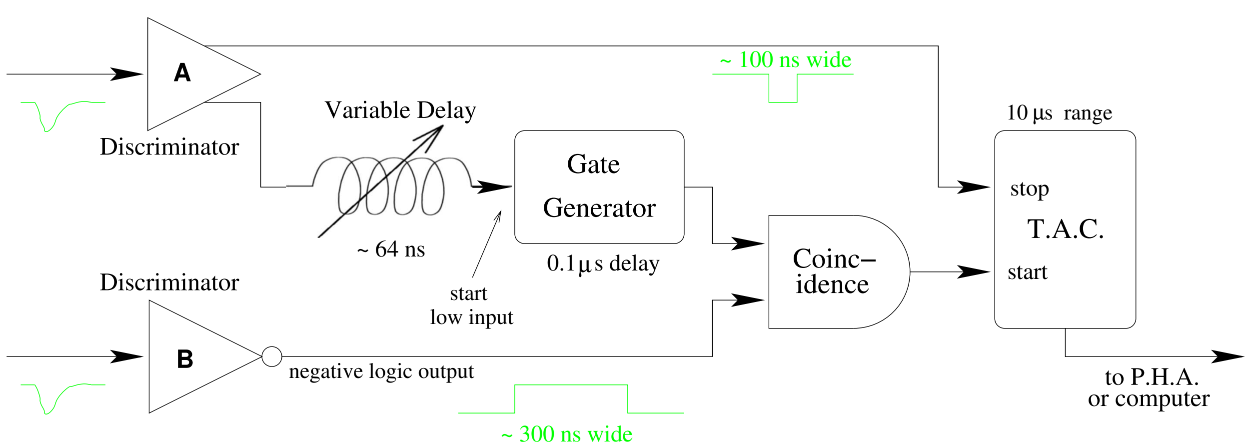

Figure 1.2: Schematic diagram of electronics for muon lifetime experiment. All unused outputs must be terminated with 50 ohms. Photomultiplier tube voltage = +1400 V.

greater than a threshold (T adjustment screw) of about −0.1 V and produce uniform −0.7 V logic pulses as output. The A discriminator output pulse should have a width (W adjustment screw) of about 0.1 μs. Discriminator B should produces a pulse approximately 0.3 μs wide.

The A logic signal is fed through a variable *delay* of about 64 ns and into the "–" input of the *gate and delay generator*,[5] which should be set for a delay of about 0.1 μs. The delayed output of the gate generator then goes to one of the inputs of the *coincidence* unit. The other input to the coincidence is the negative logic[6] output from the B discriminator, *i.e.* $\bar{\text{B}}$. Thus the output of the coincidence unit is what we call the $\text{A}\bar{\text{B}}$ logic pulse. The combination of the variable delay and the gate generator provide sufficient delay so that the pulses from a muon passing through *both* scintillators arrive at the coincidence unit with the time sequence shown in Fig. 1.3. (Otherwise the $\text{A}\bar{\text{B}}$ statement, "I got a signal from A when there was none from B," would not be very significant!)

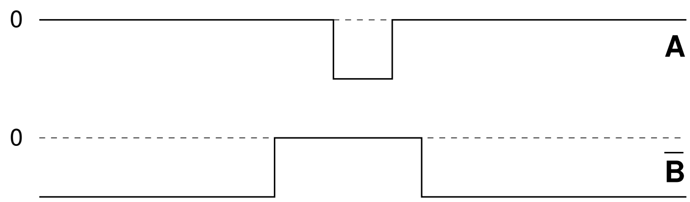

Figure 1.3: Timing sequence of input pulses at the coincidence unit.

The $\text{A}\bar{\text{B}}$ logic pulse is used as the START for the time to amplitude converter (TAC). A second pulse from A, caused by muon decay, provides the STOP for the TAC. The output of the TAC is processed using a pulse height analyzer (PHA) function in the computer. The whole system can be calibrated using the calibration unit provided. It is triggered with a positive pulse of greater than 1 microsecond duration.

Note: Most logic units with multiple output channels are designed to have "loads" of 50 Ω input impedance connected to at least two of their outputs. If you are only using one output, you should terminate another one with a 50 Ω terminator.[7] This would be needed for the B discriminator and on the unused AND output of the coincidence unit.

1.4 Analysis

The stopped muon decay rate can be described by the equation

$$\frac{dP}{dt} = -\frac{P}{\tau_\mu}$$

where P is the probability of a muon surviving decay until time t and τ_μ is the muon lifetime. Integration of this equation and multiplying by the number N_0 of muons tested gives

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

[5] We will assume you are using an ORTEC 416A Gate and Delay Generator. If you use some other brand or model it may have slightly different labels or choices of settings, but it should have the same functionality.

[6] By "negative logic" we don't mean negative volts; all the logic pulses are either −0.7 V or zero. The *negative logic* pulse from the B discriminator is the one that is at −0.7 V *all the time* **except** when B is "on" — then it is zero. This is what we mean by "$\bar{\text{B}}$".

[7] Generally, 50 Ω terminators are *yellow*.

where N_0 is the total number of muons stopping during the experiment and $N(t)$ is the number that survive until time t. The number which decay *at* time t (within dt) is

$$\frac{dN}{dt} = -\frac{N_0}{\tau_\mu} e^{-t/\tau_\mu} = n$$

and the uncertainty of the measured number n is $\sigma_n = \sqrt{n}$.

The way that the electronics is configured minimizes the number of components required but there is a background caused by events in which the decay can be simulated by a second muon entering the detectors before the original muon has decayed. The resulting background is flat. The muon lifetime can still be extracted from the data by fitting it to the function

$$n = a - be^{-t/\tau_\mu}$$

where a and b are constants.

A set of programs for plotting and analysis of the data are described in the laboratory manual and available from the computer ID P352. From your data you should be able to estimate the ratio of positive to negative muons in cosmic rays.