MUON PHYSICS THEORY

Overview

The muon is one of nature's fundamental "building blocks of matter" and acts in many ways as if it were an unstable heavy electron, for reasons no one fully understands.
Discovered in 1937 by C.W. Anderson and S.H. Neddermeyer when they exposed a cloud chamber to cosmic rays, its finite lifetime was first demonstrated in 1941 by F. Rasetti. The instrument described in the Muon Physics Instructions document permits you to measure the charge averaged mean muon lifetime in a plastic scintillator and to demonstrate the time dilation effect of special relativity.

Muon Source

The top of earth's atmosphere is bombarded by a flux of high energy charged particles produced in other parts of the universe by mechanisms that are not yet fully understood. The composition of these "primary cosmic rays" is somewhat energy dependent but a useful approximation is that 98% of these particles are protons or heavier nuclei and 2% are electrons. Of the protons and nuclei, about 87% are protons, 12% helium nuclei and the balance are still heavier nuclei that are the end products of stellar nucleosynthesis.

The primary cosmic rays collide with the nuclei of air molecules and produce a shower of particles that include protons, neutrons, pions (both charged and neutral), kaons, photons, electrons and positrons. These secondary particles then undergo electromagnetic and nuclear interactions to produce yet additional particles in a cascade process. Figure 1 indicates the general idea.

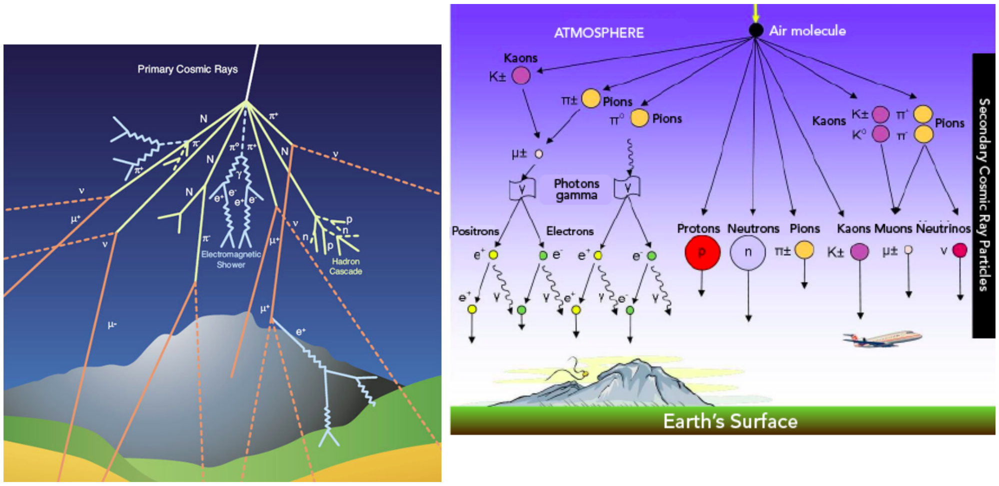

Figure 1. Cosmic ray cascade induced by a cosmic ray proton striking an air molecule nucleus

Of particular interest is the fate of the charged pions produced in the cascade. Some of these will interact via the strong force with air molecule nuclei but others will spontaneously decay (indicated by the arrow) via the weak force into a muon plus a neutrino or antineutrino:

$$\pi+ \rightarrow \mu+ \nu_\mu$$

$$\pi- \rightarrow \mu- \nu_\mu$$

The muon does not interact with matter via the strong force but only through the weak and electromagnetic forces. It travels a relatively long distance while losing its kinetic energy and decays by the weak force into an electron plus a neutrino and antineutrino. We will detect the decays of some of the muons produced in the cascade. (Our detection efficiency for the neutrinos and antineutrinos is utterly negligible.)

Not all of the particles produced in the cascade in the upper atmosphere survive down to sea-level due to their interaction with atmospheric nuclei and their own spontaneous decay. The mean production height in the atmosphere of the muons detected at sea-level is approximately 15 km. Travelling at the speed of light, the transit time from production point to sea-level is then 50 μsec. Since the lifetime of at-rest muons is more than a factor of 20 smaller, the appearance of an appreciable sea- level muon flux is qualitative evidence for the time dilation effect of special relativity.

Interaction of Negative Muons with Matter

The muons whose lifetime we measure necessarily interact with matter. Negative muons that stop in the scintillator can bind to the scintillator's carbon and hydrogen nuclei in much the same way as electrons do. Since the muon is not an electron, the Pauli exclusion principle does not prevent it from occupying an atomic orbital already filled with electrons. Such bound negative muons can then interact with protons according to this reaction:

$$\mu^- + p \rightarrow n + \nu_\mu$$

before they spontaneously decay. Since there are now two ways for a negative muon to disappear, the effective lifetime of negative muons in matter is somewhat less than the lifetime of positively charged muons, which do not have this second interaction mechanism. The muon lifetime we measure with this instrument is an average over both charge species so the mean lifetime of the detected muons will be somewhat less than the free space value, $\tau = 2.19703 \pm 0.00004$ μsec. The interaction probability between the negative muon in the scintillator is proportional to Z^4, where Z is the atomic number of the nuclei, so the lifetime of negative muons in scintillator and carbon should be very nearly equal. This latter lifetime τ_c is measured to be $\tau_c = 2.043 \pm 0.003$ μsec. [Reiter, 1960]

The Muon Physics Manual gives details on the derivation of ρ, the ratio of the number of positive and negative muons, in relation to the observed (measured) lifetime, τ_{obs} and the lifetimes of the positive and negative muons, τ^+ and τ^- respectively:

$$\tau_{obs} = (1+\rho)\left(\frac{\tau^-\tau^+}{\tau^+ + \tau^-}\right)$$

One can also rearrange the equation to be able to compute ρ from the three aforementioned lifetimes:

$$\varrho = -\frac{\tau^+}{\tau^-}\left(\frac{\tau^- - \tau_{obs}}{\tau^+ - \tau_{obs}}\right)$$

Background Radiation/Counts

The detector responds to any particle that produces enough scintillation light to trigger its readout electronics. These particles can be either charged, like electrons or muons, or neutral, like photons, that produce charged particles when they interact inside the scintillator. Now, the detector has no knowledge of whether a penetrating particle stops or not inside the scintillator and so has no way of distinguishing between light produced by muons that stop and decay inside the detector, from light produced by a pair of through-going muons that occur one right after the other. This important source of background events can be dealt with in two ways. First, we can restrict the time interval during which we look for the two successive flashes of scintillator light characteristic of muon decay events. Secondly, we can estimate the background level by looking at large times in the decay time histogram where we expect few events from genuine muon decay.

Fermi Coupling Constant G_F

Muons decay via the weak force and the Fermi coupling constant G_F is a measure of the strength of the weak force. To a good approximation, the relationship between the muon lifetime τ and G_F is particularly simple:

$$\tau = \frac{192.\pi^3 \hbar^7}{G_F^2 m^5 c^4}$$

where *m* is the muon mass. This equation can be used to compute the Fermi Coupling constant from the measured lifetime of the muons. Measuring τ with this instrument and then taking *m* from, say, the Particle Data Group (http://www.pdg.lbl.gov) produces a value for G_F. (*Note: the appropriate units have not been provided herein - you need to make sure you have them in hand when you do this calculation required in the Muon Physics Instruction Document*).

Note: The user manual (found uploaded in LMS) for this experiment has a lot of detailed information regarding the physics behind this experiment. You are encouraged to go through this manual in detail as this theory document is quite concise and may not answer all the questions you have regarding the theory.