Muon Lifetime

In class we discussed evidence for time dilation by considering the number of muons that would reach Earth if time dilation was not taken into account. (Problem 1-11, Spacetime Physics text.) If muons start at 60 km above the surface of the Earth traveling at 0.99, how long would it take them to reach Earth?

The muon half-life is 1.5×10^{-6} s in its rest frame. If time dilation is ignored, how many half-lives would have passed?

However, if time dilation is taken into account, about 1/8 of the muons reach sea level and only three half-lives have passed.

Since a lot of muons reach the surface of the Earth, we can stop them in a plastic scintillator and measure the muon lifetime.

<u>The decay process</u>

The decay process of muons is probabilistic in nature. One cannot predict whether a particular muon will decay or not, but we can predict how many will decay on average within a given time period. This is the rate of decay. Given some number N of muons, we expect that the number of decay events dN in some time interval *dt* should be proportional to the number of muons we started with. So, the rate of decay is:

$$dN = -\lambda N \, dt$$

where λ is a proportionality constant.

This is a first order differential equation that can be solved for N(t), the number of undecayed radioactive nuclei as a function of time. Let the number of undecayed nuclei at time t = 0 be N_0 and use integration to solve this equation for N(t). Show and discuss your solution with the teaching assistant (TA).

The constant λ is often written as $\lambda = 1/\tau$, where τ is the mean lifetime of the muons.

So, we can write the number of decayed muons in the time interval *dt* as

$$dN = -\lambda N_0 e^{-\lambda/\tau} \, dt$$

and the fraction that would decay on average in the time interval *dt* as

$$dN/N_0 = -\lambda e^{-\lambda/\tau} \, dt$$

The probability of decaying in a time interval *dt* is

$$D(t) = -\lambda e^{-\lambda/\tau}$$

The probability of decay in a time interval *dt* does not depend on the starting value N_0. and it is the probablility of decay whether we are looking at the number of muons that enter our detector or the number of muons that start at a specific height.

Muon detecton

We will detect muons with a plastic scintillator. The muons will slow down and then stop in the scintillator.

As the muons pass through the scintillator, some of their energy is transferred to the molecules in the scintillator, exciting them to higher energy levels. When the molecules de-excite to a lower energy level, light is emitted. The light passes into a photomultiplier tube attached to the scintillator.

In the photomultiplier tube, the photons eject electrons via the photoelectric effect. Instead of just collecting the few electrons ejected, the electrons are accelerated through a series of electrodes called dynodes. At each dynode, more electrons are ejected, amplifying the signal, so that a cascade of electrons is finally detected at the anode, as in the Figure below. This yields a current pulse.

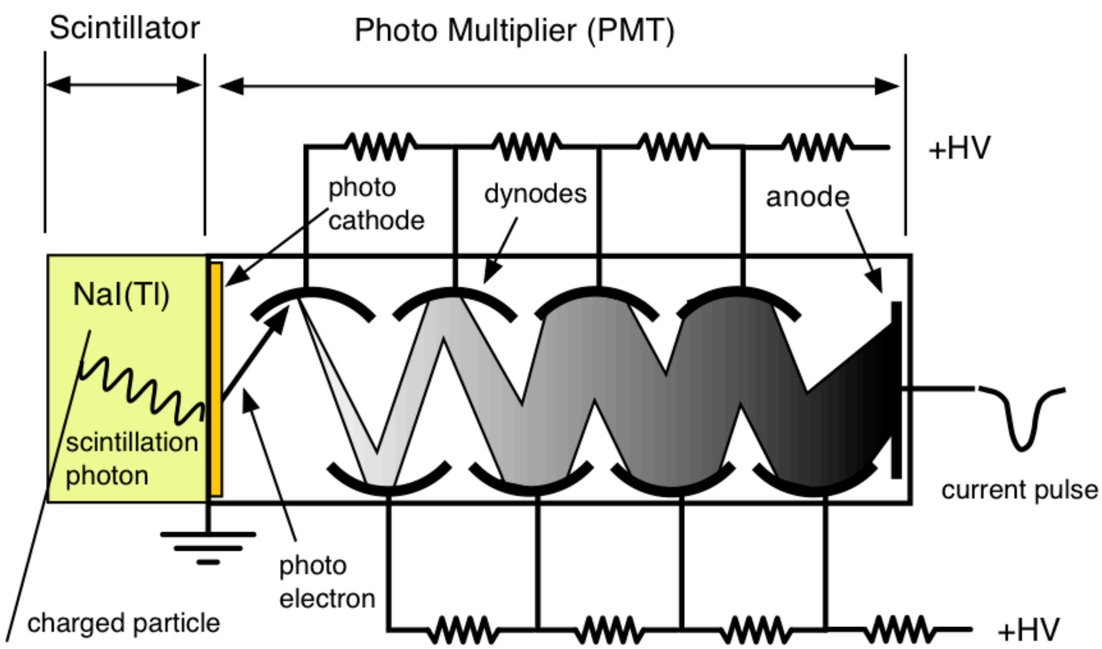

Figure from
http://wanda.fiu.edu/teaching/courses/Modern_lab_manual/_images/PMT.png

After the muon stops, it decays into an electron, a neutrino and an anti-neutrino. The electron is very energetic and also produces light as it passes through the scintillator.

So two bursts of light are produced in the scintillator and detected through the photomultiplier tube. The first burst is the stopping of the muon. The second is the decaying of the muon. The time between those two pulses produced in the photomultiplier tube is then the lifetime of the muon *in its rest frame* (as it has now stopped and then decayed).

You are going to measure the distribution of decay times for those muons entering the detector

$$D(t) = -\lambda e^{-\lambda/\tau}$$

and the muon lifetime τ.

Explain your understanding of the muon lifetime measurement and how the scintillator detection process works to a TA before proceeding.