Studying cosmic muons using scintillation detectors

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Introduction

Muons are elementary particles and, along with electrons, taus and neutrinos, they make the lepton group of elementary particles. They reach Earth's surface as part of secondary cosmic rays. Secondary cosmic rays are formed by interaction of primary cosmic rays (mostly protons and alpha particles) with atoms and molecules in Earth's atmosphere. The sources of primary cosmic rays are highly energetic processes in the universe - active galactic nuclei, supernovae, gamma ray bursts and also from the Sun. They hit the Earth isotropically because they are randomized through the interstellar medium. Cosmic rays from the Sun are of course not isotropic, but their energies are far too low for them to reach Earth's surface. The goal of our project was to visualize cosmic muons and measure their speed and lifetime.

Visualization

For the construction of our cloud chamber we used a glass aquarium as the basis of our chamber, black plastic sheets to cover the aquarium (to give us better contrast), a rag soaked with 96% ethanol, a metal lid for the bottom, dry ice for cooling, styrofoam for isolation and a projector as a light source. We covered most of the aquarium with black plastic sheets sticking them together with adhesive tape and leaving only two "windows". We sticked our soaked rag on bottom of the aquarium and covered the top with the metallic lid. Then we flipped the aquarium so the rag went to the "top". The aquarium was then placed on dry ice which was in a container made out of styrofoam. Finally, we placed our light source in front of one "window" and observed the process through the other. The top of the chamber was heated to help evaporate the ethanol which then falls down and supersaturates. When charged particles pass through this supersaturated ethanol, they ionize it and these ions then serve as centers for nucleation creating a small "cloud" that can be seen.

Detectors

For detection of cosmic muons we used plastic scintillators and photomultiplier tubes (PMTs).

Organic scintillators are blocks made of aromatic hydrocarbons whose electrons are easily excited by charged particles. When excited, they emit photons. The photons were kept from "leaking" from the scintillator by aluminum foil that we put all around the scintillator except for the part that's connected to the PMT. We also wrapped the scintillators in black plastic sheets so that we exclude any photons that may come from outside and interfere with our results. The photons that are created by muon passage are then directed and sent to the photomultiplier which is directly connected to the scintillator's surface.

In the PMTs, the photoelectric effect occurs first, a photon knocks out an electron from the photocathode. That electron then knocks out more electrons from a dynode and the

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process continues in a cascade, dynode to dynode, to the anode which then sends all the electrons to the oscilloscope in a form of an electric signal.

Measuring muon speed

To measure the speed of muons we used all of the instruments mentioned above plus the discriminator and the time-to-digital converter (the TDC).

The discriminator was used to eliminate unwanted noise by setting the voltage threshold so that only signals whose voltage is high enough (like signals caused by muons) can go through it.

Time-to-digital converter is a device that converts the time delay between two signals to a channel number (each time delay gets its channel and the TDC we used has a maximum of 8192 channels per 50 ns). We first needed to calibrate the TDC and that was done using a very accurate signal generator. The generator was connected to the TDC and the TDC to the computer. We sent out signals from the generator in specific time delays to see which channel corresponds to which time delay. In figure 2 we can see that the dependence of the time delay on the channel number is linear and by fitting a linear function we get:

$$t = 0.00625 \cdot channel\ number + 0.16$$

Then we can use this formula to calculate the delay of two signals if we know the channel number.

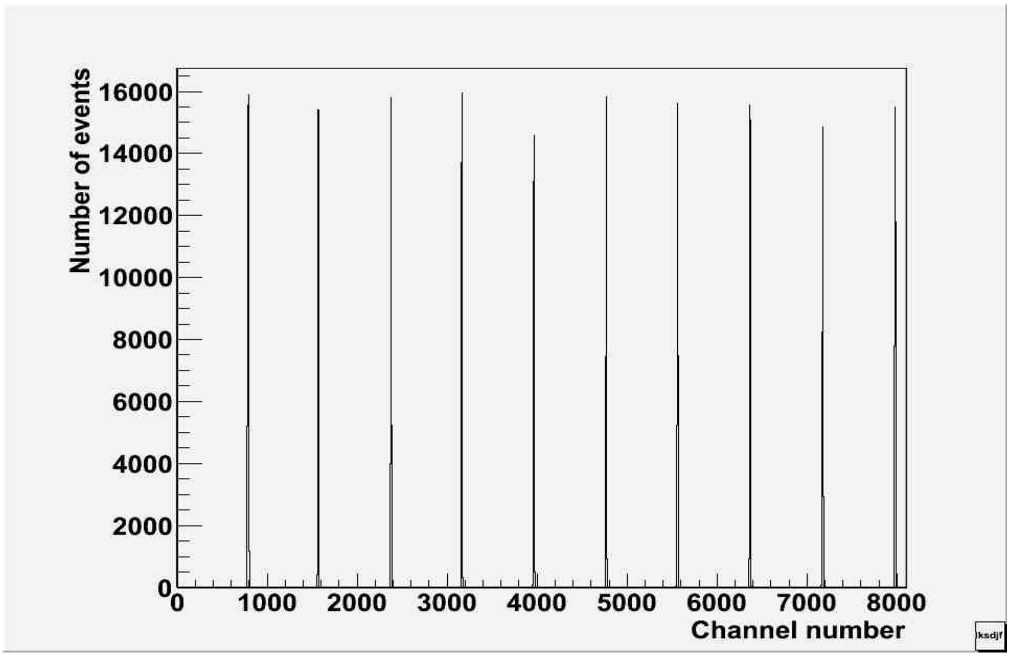

Figure 2: TDC calibration

After the calibration process was done, we began with the measurements. One scintillator was placed above the other and this enabled the same muon to pass through both scintillators producing two signals with time delay between them equal to the time it took the muon to get from one scintillator to the other. We did two measurements, one with the distance of 20±4 cm between the two scintillators and another with the distance of 70±1 cm. We connected our detectors to the discriminator to get rid of the noise, the discriminator to the TDC to convert the time delay between two signals to a channel number.

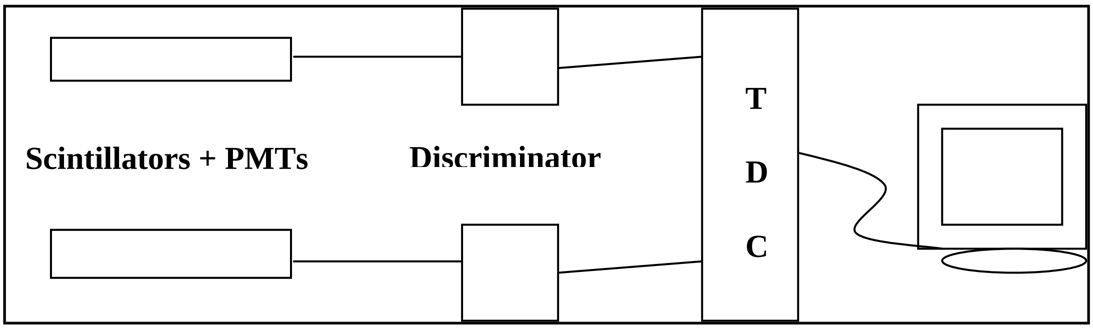

Figure 1: Setup of experiment 1

When we obtained the data we needed in form of a channel number, we could start the data analysis. First, we fit our channel distribution with a Gaussian curve to get a mean value. Using this method we were able to get the specific time that an average muon needed to pass between the scintillators.

The time delay obtained from every signal pair has some systematic error which is caused by the scintillators, the PMTs and the wires. Those systematic errors were a problem to us because their values significantly affected our results. Because both of our time delays (from the first and second measurements) had those errors, we subtracted the time delays and obtained the time difference without systematic errors by the following formula:

$$\Delta t = \Delta t_2 + \Delta t_{se} - (\Delta t_1 + \Delta t_{se})$$

This time difference was then used to calculate the speed of our muons using:

$$v = \frac{\Delta s_2 - \Delta s_1}{\Delta t}$$

Since we measured the distance between our scintillators and obtained the time delay between the scintillators using the above mentioned method of eliminating the errors, we were able to calculate the average speed of muons which is:

$$v = (3 \pm 1) \cdot 10^8 \frac{m}{s}$$

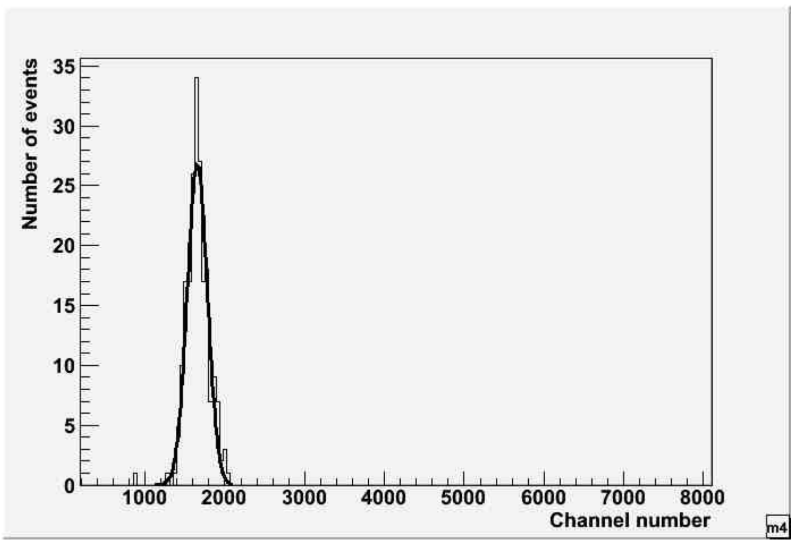

Figure 3: Muon speed measurements for 20 cm distance

There are few reasons for the high error value of our measurement. First of all, the scintillators were damaged and the surfaces through which the photons passed to the PMTs were blurred. A part of the reason could also be in the PMTs, but the majority of the error was caused by small distances between the scintillators because we had a limited amount of time to do the measurements so some of the muons did not pass vertically through the scintillators but with some inclination and because of that the errors for distances were very high. Because of the same reason we had a relatively small number of events which also increased the error.

Measuring muon lifetime

Some of the muons that enter the scintillator are of low enough energy to stop in it. If that happens, it will soon decay to an electron (or positron), and two neutrinos.

$$\mu^{+} \longrightarrow e^{+} + \bar{\nu}_{\mu} + \nu_{e}$$
$$\mu^{-} \longrightarrow e^{-} + \nu_{\mu} + \bar{\nu}_{e}$$

Both the muon that hit the scintillator and the electron created by the decay create signals in the PMT. The PMT is connected to the discriminator and the discriminator to the TDC.

Lifetime was measured by measuring the time delay between the signal caused by the muon and the signal caused by the electron created by the decay. Each signal from the PMT was split into two which lead to the discriminator. To prevent both the start and the stop signals from coming at the same time and thus giving us no time delay, the start cable was longer. The stop signal would arrive first at the TDC but it would not trigger anything and, soon afterwards, the same signal (muon created) would arrive through the longer (start) cable and the timer would be triggered. A signal created by an electron would also first come through the shorter (stop) cable after splitting and would finish the timing. The electron start signal that would come afterwards would not be of any importance because the time between two different signals is usually greater than the maximum time the TDC was set to measure (10µs).

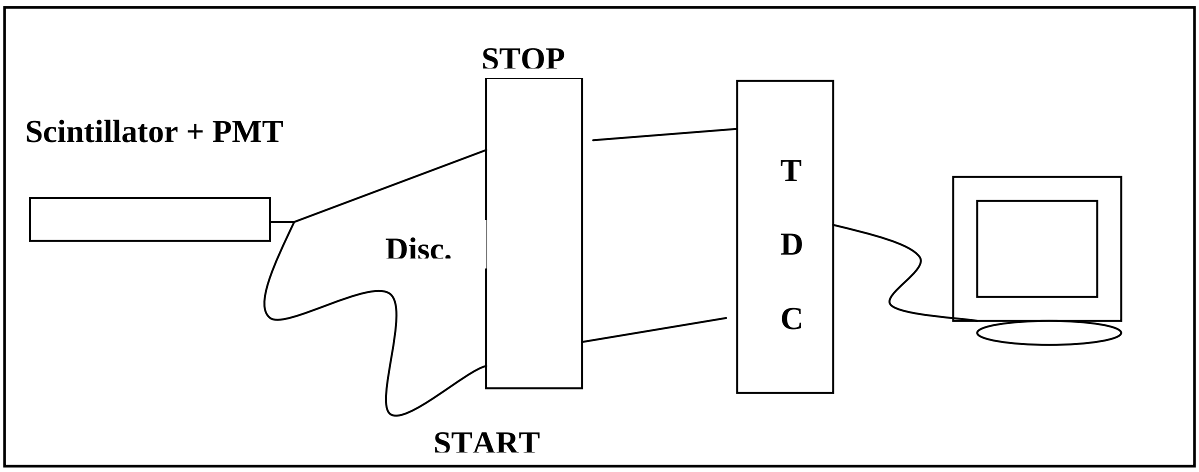

Figure 4: Setup of experiment 2

The number of muons remaining after time t is

$$N(t) = N_0 e^{-t/\tau}$$

where N_0 is be the initial number of muons and τ is the decay constant.

We were collecting data for muon lifetime during 12 hours. We rebind measured number of events (we decreased number of channels from 8190 to 10 and summed number of events from every of the 10 divisions) and thus obtained exponential function good enough to analize. Because we measured number of decayed muons we fitted the data to the function

$$N_{decayed}(t) = N_0(1 - e^{-t/\tau})$$

and so obtained the muon lifetime:

$$\tau = 1.97 \pm 0.04\ \mu s\,.$$

We didn't take into account the fact that μ^+ and μ^- don't have the same lifetime inside of a scintillator and we neglected the fact that two muons can come into the scintillator at the same time because these events are very rare.

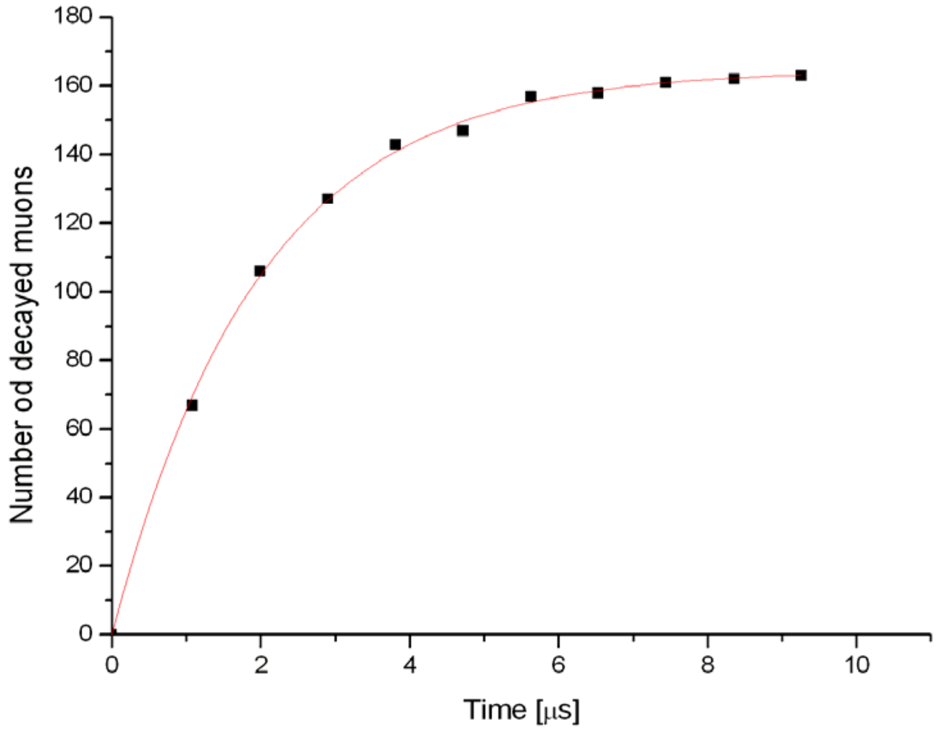

Figure 5: Number of decayed muons by time t

Discussion

Although the error is high, the mean result is within our expectations because cosmic muons are high energy particles and according to the special theory of relativity we know that:

$$v = c\sqrt{1 - \frac{m^2c^4}{\left(mc^2 + T\right)^2}}$$

For very high kinetic energies (T) speed is concentrated close to the value of the speed of light, and that is what we get.

Even though it seems to be too short a period of time to reach us, they do so due to their very high speeds and the time dilatation they experience which gives them more time to reach Earth's surface.

Acknowledgments

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References

Particle Data Group – Review of particle physics
William Leo – Techniques for nuclear and particle physics experiments