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Muon Lifetime

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Abstract

This experiment aims to measure the lifetime of muons that originate from cosmic rays and make their way to the Earth's surface. Detection of these muons is accomplished using a stack of three scintillators equipped with photomultipliers. The muon lifetime is determined through statistical analysis of the collected data and subsequently compared to established literature values.

Contents

1 Theory

1.1 The Standard Model of Particle Physics

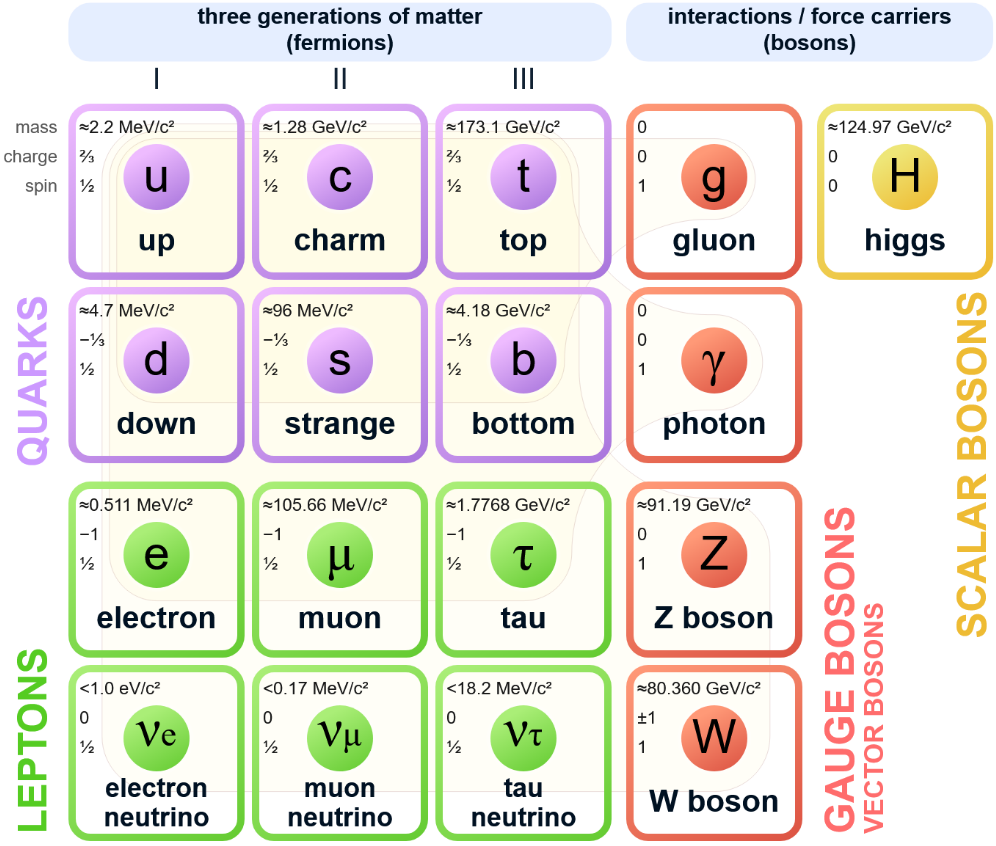

Figure 1: The particles and field quanta in the Standard Model [1].

The standard model describes the elementary particles and their interactions. The strong, weak and electromagnetic interactions can be explained with the Standard Model. Gravity, however, cannot be described using the Standard Model, which is why theorists are looking for new models (e.g. superstring theory). The Standard Model is able to explain all previous observations of particle physics. It states that matter is composed of quarks and leptons. The interaction between the particles is caused by the exchange of field quanta (bosons). Figure 1 shows all particles of the Standard Model, for each matter particle there is also the corresponding antimatter particle. For example, the proton consists of two up quarks and one down quark, and the neutron consists of one up quark and two down quarks. Particles consisting of three quarks are called baryons, those consisting of one quark and one antiquark are called mesons. The muon is an elementary particle like the electron but 206 times heavier, hence its famously referred as "the heavy sister of the electron".

1.2 Formation of Muons

The muons are formed from the decay of pions (π^+ and π^-) and kaons (K^+).

$$
\begin{aligned}
\pi^+ &\rightarrow \mu^+ + \nu_\mu \\
\pi^- &\rightarrow \mu^- + \bar{\nu}_\mu \\
K^+ &\rightarrow \mu^+ + \nu_\mu
\end{aligned}
\tag{1}
$$

The pions and kaons, for their part, arise from the collisions of the primary cosmic rays (high-energy protons, α-particles) with the air molecules of the upper atmosphere.

$$
\begin{aligned}
p + p &\rightarrow p + n + \pi^+ \\
p + n &\rightarrow p + p + \pi^- \\
p + p &\rightarrow p + n + K^+
\end{aligned}
\tag{2}
$$

At sea level, the rate of high-energy cosmic muons is about 1 $\frac{Muon}{cm^2 min}$. Figure 2 shows their energy, altitude and angular dependence.

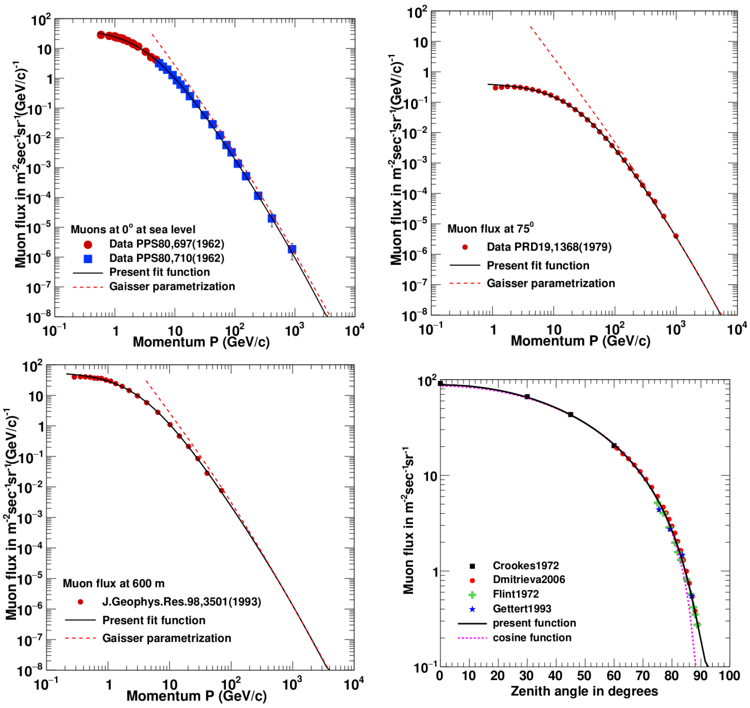

Figure 2: From top left to bottom left, clockwise: muons at sea level at 0º, with zenith angle of 75° at sea level, the dependence of the flux with zenith angle and at 600m altitude at 0º. Figures were taken from [4].

1.3 The muon decay

Muons decay by exchanging a W-Boson (weak interaction) with an average lifetime of 2.197 μs [3] in:

$$\begin{aligned} \mu^+ &\rightarrow e^+ + \nu_e + \bar{\nu}_\mu \\ \mu^- &\rightarrow e^- + \bar{\nu}_e + \nu_\mu \end{aligned} \tag{3}$$

Figure 3 shows the Feynman graph of muon decay.

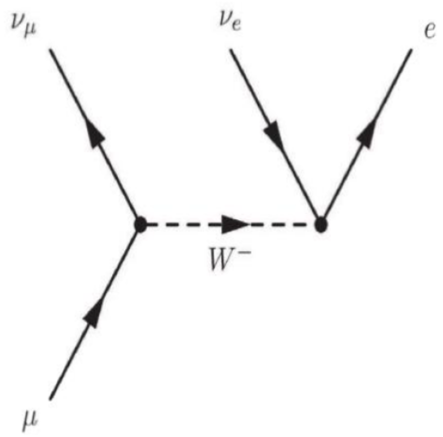

Figure 3: Feynman graph of muon decay.

Positive muons decay exclusively according to the scheme above. Negative muons can also be captured by an atom and orbit on Bohr's orbits. Because of their greater mass, there is a cascade of electron transitions until the muon is on the innermost shell. There it can be captured by the core.

$$\mu^- + p \rightarrow n + \nu_\mu \tag{4}$$

This process reduces the lifetime of the negative muon. The lifetime depends on the core mass of the target material.

1.4 Muon technology applications

Muon imaging has recently gained a lot of traction since the discovery of big void in Khufu's Pyramid in Egypt [5]. The technique employed is usually referred as muon radiography, essentially analogous to x-ray radiography, but using cosmic muons.

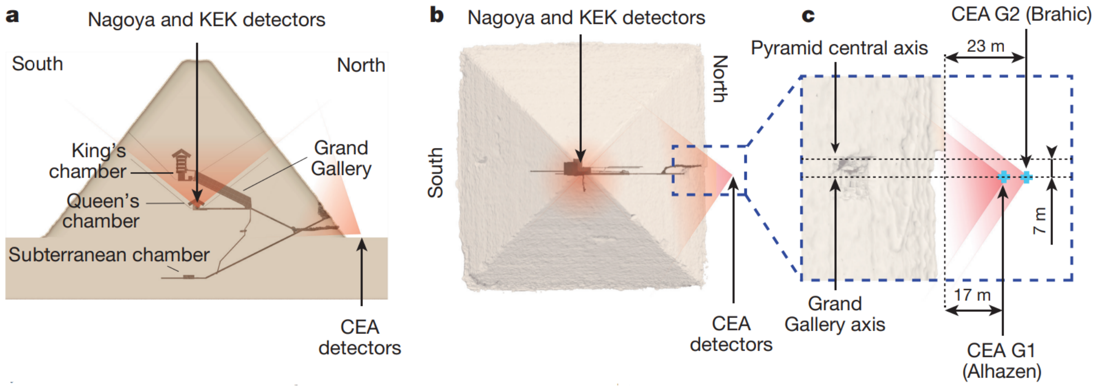

Figure 4: Schematic of Khufu's Pyramid showcasing the Queen's chamber, the void that was discovered. Image taken from [5].

There's two crucial physical properties that make muon radiography, and in general this kind of muons applications, possible: The continuous flux of high energy cosmic muons and their ability to penetrates huge distances before being absorbed. Every negatively charged particle loses energy by subsequent deflection with positive nuclei, there's a lot of energy loss mechanisms that are happening during this interaction, one of them, "bremsstrahlung" is when during this process photons are created. As a negative charged particle, an electron transversing a material will be deflected and then absorbed much faster than a muon given their mass differences. Because of this, cosmic muons traveling at almost light-speed (high momentum) having a huge penetration distance.

Other applications are: Volcanology, homeland security, nuclear reactor and waste imaging, underground exploration (mineral detection) and civil engineering. More about this field, referred globally as "Muon imaging" can be found in [6].

2 Experimental Setup

⚠ **Be careful when handling the high voltage of the detectors. The voltages are deadly ! Don't touch the detectors when the high voltage is applied. Slowly ramp up the voltage to the detectors and slowly ramp it back to zero. Never switch off the power supply as long as high voltage is still applied to the detectors.**

The muons are detected in an arrangement of three scintillators arranged one above the other. Each scintillator is connected with photomultipliers, responsible for the transduction between the luminous signal to an electrical signal. A layer of lead, a material with high stopping-power, is placed between the first two scintillators to slow down the muons. The target is located between the second and third scintillator. A muon decay in the target is registered if the first two detectors respond, but the third does not. The decay electron or positron is then measured in the second or third detector. The first detector must not respond because the electron or positron cannot fly through the lead. The constant fraction discriminator generates a logical signal as soon as the input signal exceeds a certain level. Because the input signal is proportional to the energy of the incident particle, we can filter out the low-energy particles and reduce the background of the measurement. The start and stop signals for the Time to Amplitude Converter TAC are then generated with the logical signals. The TAC generates a bipolar Signal which is proportional to the time difference between start and stop signal. The TAC signal is used as a trigger for the oscilloscope, with which the time difference between the start and stop signal is measured. The oscilloscope is read out by the measuring computer. Figure 5 shows the signals on the oscilloscope. Figure 6 shows a schematic representation of the experiment.

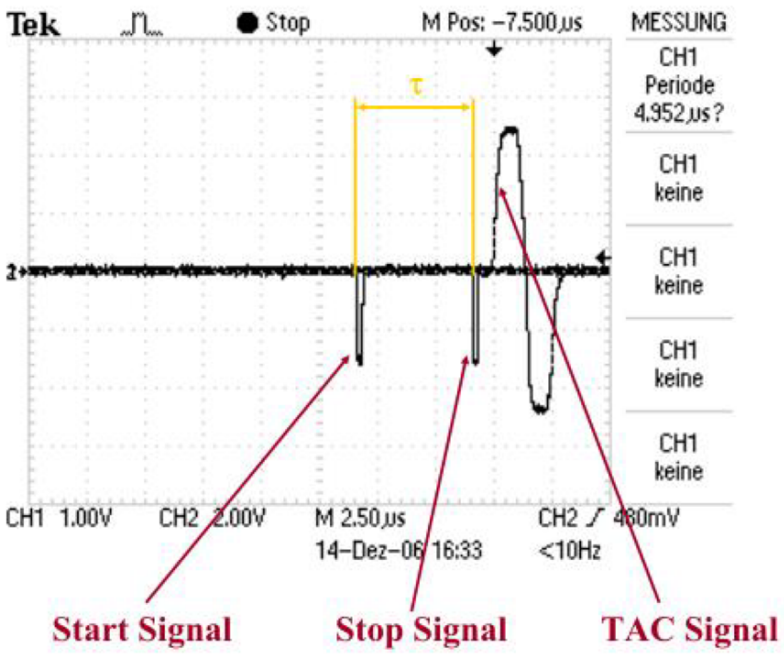

Figure 5: Start, stop and TAC signal of a muon decay.

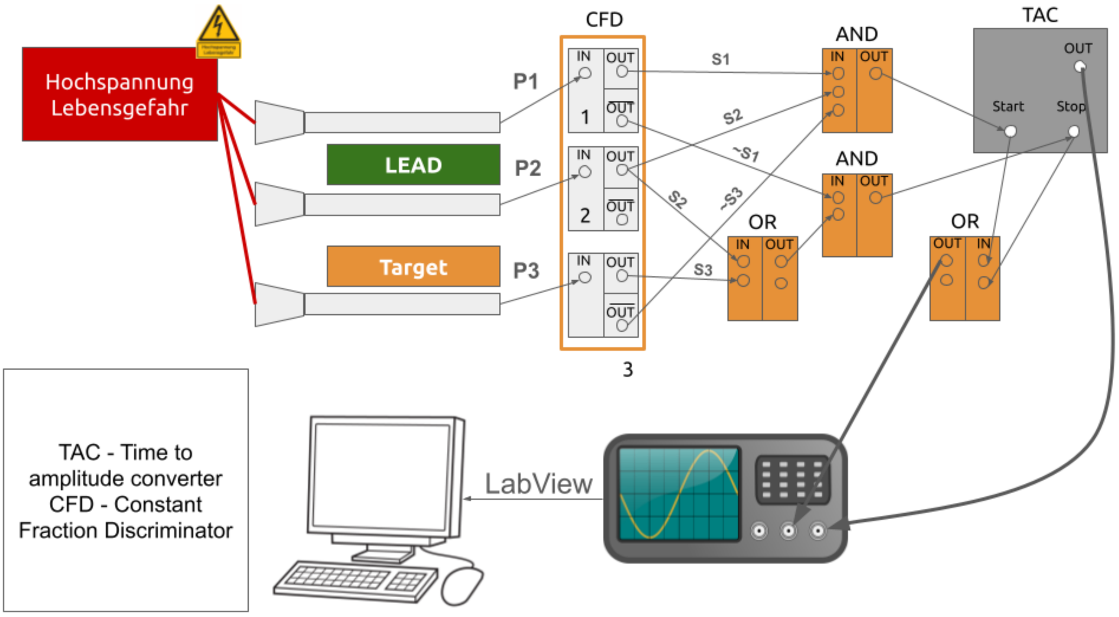

Figure 6: Schematic representation of the experiment.

3 Measurement of disintegration time

The task is to measure the mean lifetime of the muons. The rate of these type of events is one per minute, so, in order to get reasonable counts, each measurement takes one week.

A muon decays according to the decay law (cf. radioactivity). A decay cannot be predicted, we only know the probability that a muon will decay. It is specified with the decay constant (λ). n muons will decay in the time interval dt.

$$dn = -\lambda dt \tag{5}$$

As a solution of the differential equation we get:

$$n = n_0 e^{-\lambda t} \tag{6}$$

The inverse of the decay constant $\tau = 1/\lambda$ is the mean lifetime and it is to be determined in this experiment.

4 Tasks

4.1 Theoretical tasks

1. How can a muon even get to the Earth's surface if its average lifetime is only 2.2 s? The speed of light multiplied by the lifespan is only about 660 m.
2. Explore the interaction of muons with different materials. How does the composition and density of a material affect the attenuation and absorption of muons passing through it?
3. Analyze the statistical nature of cosmic ray muon detection. How can you ensure that your measurements are statistically significant, and what methods can be used to minimize error?
4. Compare the efficiency and characteristics of different types of detectors (e.g., scintillators, gas detectors) in the detection of cosmic ray muons. What are the advantages and disadvantages of each type in your experimental setup?
5. Discuss the importance of shielding and background radiation in muon experiments. How can you differentiate between muons and other background radiation to ensure accurate measurements?

4.2 Experimental tasks

1. Record spectra from all three detectors with the multichannel analyzer (MCA). Using a 90Sr source or cosmic ray muons adjust the detector voltage (i.e. photomultiplier voltage) so that the spectra have similar aspect.
2. Set the discriminators correctly. To do this, measure the count rate of the coincidence of the upper and middle detector. What value do you expect?
3. Familiarize yourself with the use of the oscilloscope.
4. Perform a digital circuit design of the signals from the scintillators until the TAC inputs: Start and Stop. Confirm that this makes sense with the physics to measure (check the paragraph in section 2)
5. Perform a time calibration of the system. Take the start signal and delay it for a certain amount of time. Use these signals to test the accuracy of the measurement setup.
6. Measure the mean lifetimes of the muons. Take the target you feel like. If there is enough time, measurements can be made with different targets.

References

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