Muon Detector

PMT coupled Plastic Scintillator for Cosmic Muons Detection

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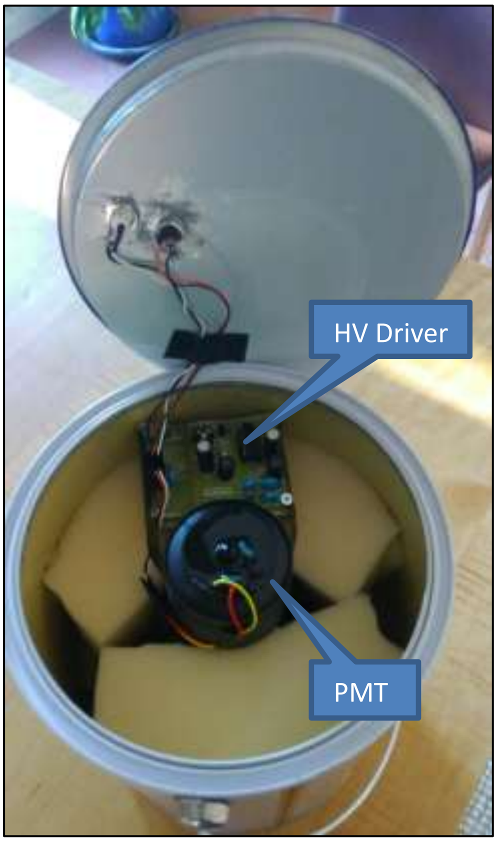
Cosmic Muons Scintillation Detector

The muon detector we are going to use is based on a **plastic crystal scintillator** coupled to a **photomultiplier**. Plastic crystal and PMT have been inserted inside a cylindrical metal housing. Inside the container it has been placed also the driver of high voltage for the photomultiplier tube. The signal from the anode of the PMT is picked up by means of a decoupling capacitor and sent to a BNC connector on the container lid. On the lid is also placed the connector for the low voltage power supply at 5V. In the images below you can see the finished detector closed and opened.



This detector is sensitive also to background radioactivity but you can easily select the pulses generated by cosmic muons since the latter have a much greater amplitude of the pulses produced by background gamma radiation. To optimize the yield for the muon particles the plastic scintillator type **BC412** has been chosen. It is particularly suited to detect charged particles such as **electrons or muons**. The area of the scintillator, 119cm2 has been chosen wide in order to obtain a high number of events per second due to cosmic muons, also the thickness of the scintillator has been chosen quite big, 114mm, so as to increase the stopping power and thus increase the likelihood that the muons are slowed down and come to a rest inside the scintillator.

Plastic Scintillator

Technical Data

Type : Bicron BC412
Base : Polyvinyltoluene
Density : 1.032 g/cc
Refractive Index : 1.58
Solubility : Soluble in aromatic solvents, chlorine, acetone, etc. Insoluble in water, dilute acids, lower alcohols, silicone fluid, grease and alkalis.

Radiation Detected	Scintillator
< 100 keV X-rays	BC-404
100 keV to 5 MeV gamma rays	BC-408
>5 MeV gamma rays	BC-400 BC-416
Fast neutrons	BC-408 BC-412
Alphas, betas	BC-400 BC-404
Charged particles, cosmic rays, muons, protons, etc.	BC-408 BC-412 BC-416

Properties

Light Output, % Anthracene : 60
Rise Time, ns : 1.0
Decay Time, ns : 3.3
Pulse Width, FWHM, ns : 4.2
Light Attenuation Length, cm* : 210
Wavelength of Max. Emission, nm : 434
No. of H Atoms per cm3 , ($x10^{22}$) : 5.23
No. of C Atoms per cm3 , ($x10^{22}$) : 4.74
Ratio H:C Atoms : 1.104
No. of Electrons per cm3 , ($x10^{23}$) : 3.37
Principal uses/applications : large area
Dimensions : **123mm diameter (119cm^2) / 114mm side**

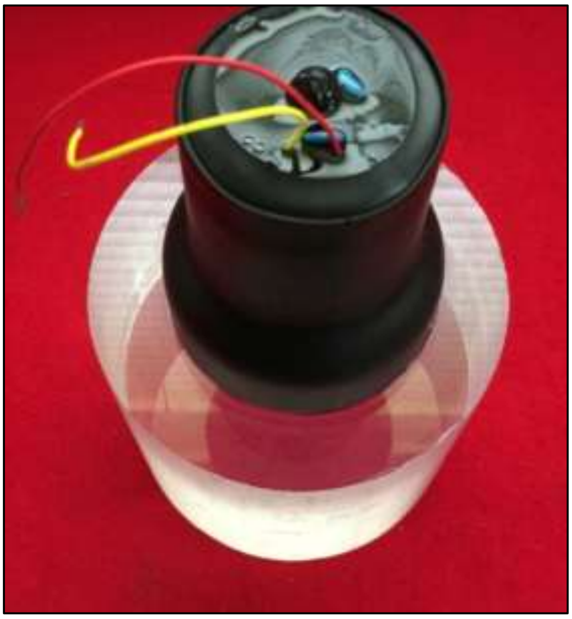
Photomultiplier Tube

Type : Hamamatsu R6233

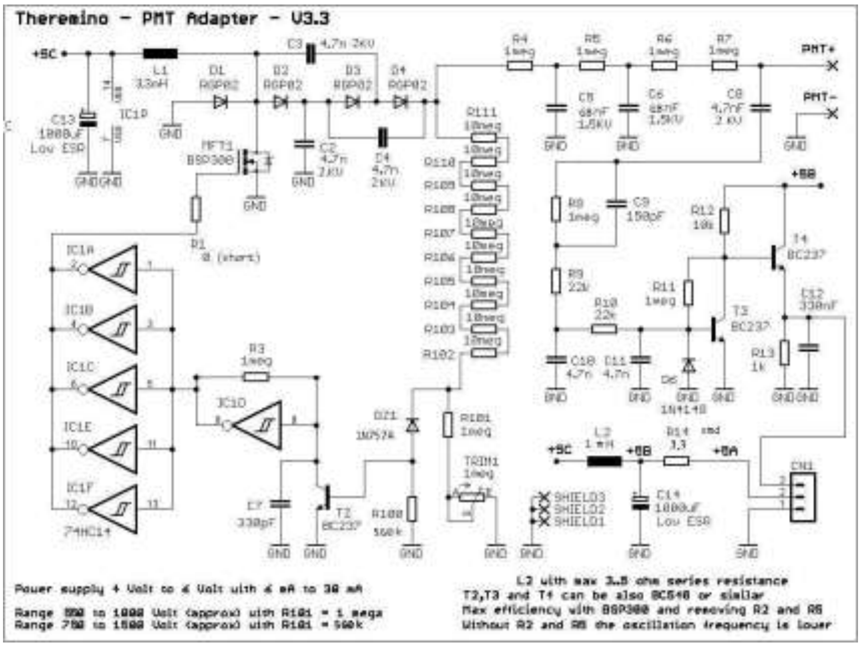
General : 76mm dia., Head-on type, Bialkali photocathode (Effective area : 70 mm dia./Spectral response : 300 to 650 nm)

Type	Head-on type
Tube Size	Dia.76 mm
Photocathode Area Shape	Round
Photocathode Area Size	Dia.70 mm
Wavelength (Short)	300 nm
Wavelength (Long)	650 nm
Wavelength (Peak)	420 nm
Spectral Response Curve Code	400K
Photocathode Material	Bialkali
Window Material	Borosilicate glass
Dynode Structure	Box-and-grid+Linear-focused
Dynode Stages	8
[Max. Rating] Anode to Cathode Voltage	1500 V
[Max. Rating] Average Anode Current	0.1 mA
Anode to Cathode Supply Voltage	1000 V
[Cathode] Luminous Sensitivity Min.	80 µA/lm
[Cathode] Luminous Sensitivity Typ.	110 µA/lm
[Cathode] Blue Sensitivity Index (CS 5-58) Typ.	12.0
[Cathode] Radiant Sensitivity Typ.	95 mA/W
[Anode] Luminous Sensitivity Min.	3 A/lm
[Anode] Luminous Sensitivity Typ.	30 A/lm
[Anode] Radiant Sensitivity Typ.	2.6 x 104 A/W
[Anode] Gain Typ.	2.7 x 105
[Anode] Dark Current (after 30min.) Typ.	2 nA
[Anode] Dark Current (after 30min.) Max.	20 nA
[Time Response] Rise Time Typ.	9.5 ns
[Time Response] Transit Time Typ.	52 ns

PMT coupled Scintillator



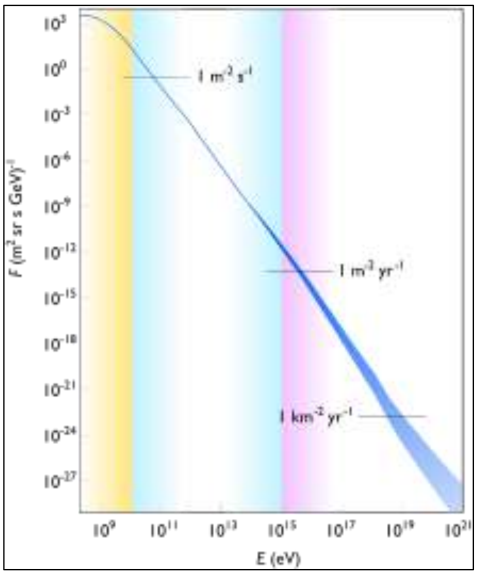
PMT HV Driver



The photomultiplier tube is fed by means of a Theremino PMT adapter placed inside the metal container. Actually it is used only the high voltage generation part. The signal is taken from the capacitor C8, while the entire part of " pulse shaping " has not been assembled. The HV driver power supply is via 5V low voltage, which can be easily provided by a series of 4 1,5V batteries, the voltage can reduced a bit with a diode connected in series.

Cosmic Rays Theory

Cosmic rays are energetic particles coming from outer space. The Earth and any other spatial body, as well as satellites and astronauts in orbit, are exposed to cosmic rays. The cosmic rays nature is very diverse (the kinetic energy of the particles of cosmic rays is distributed over fourteen orders of magnitude), as well as the origin : the Sun, other stars, novae and supernovae (example of energetic phenomena), and even remote objects as quasars.



Cosmic Rays flux vs Particle Energy

The part on the yellow background is believed to be from the sun, the part on the blue background of galactic origin, the higher energy part of extragalactic origin.

On average, every second a particle hits every square centimeter surface area on Earth.
Most cosmic rays arriving on Earth are secondary products of swarms formed in the atmosphere by primary cosmic rays, with interactions that typically produce a cascade of secondary particles starting from a single energetic particle.

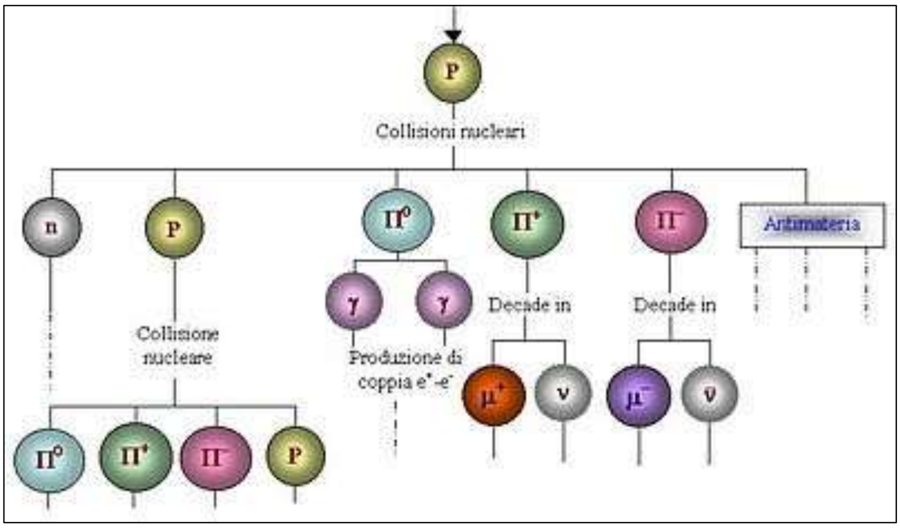
Primary Cosmic Rays

Outside of Earth's atmosphere primary cosmic rays are composed primarily of protons and alpha particles (99%), with a small amount of heavier nuclei (~1%) and an extremely minute proportion of positrons and antiprotons. Arrived in Earth's atmosphere, these particles interact with the nuclei of the molecules of the atmosphere, thus forming, in a cascade process, new particles moving forward, which are called secondary cosmic rays.
The composition and the energy spectrum have been studied in detail for the primary cosmic radiation. The Hydrogen flux is slightly more than 90%, a little less than 10% Helium, 7×10^{-4} for light elements such as lithium, beryllium and boron, and 5×10^{-3} for other elements Carbon from the Neon.
The energy spectrum follows a power law in the form :

$$\phi \propto E^{-\alpha}$$

with $\alpha = 2.7$ for energy values less than $\approx 10^{15} eV$.

Secondary Cosmic Rays



structure of the secondary cosmic radiation

The secondary radiation at sea level is made of two components (soft and hard) that behave differently when passing through very dense materials (iron, lead , ...).
The soft component (about 30% of the secondary radiation), which is made of electrons and photons and in small part by protons, kaons and nuclei, is able to pass through only a few inches. While the hard component (about 70%), composed of **muons**, can penetrate thicknesses of absorbent materials of more than one meter.
The average flux of the particles that make up the radiation which reach the level of the sea , is estimated :

$$100 \times \frac{particelle}{m^2\,s} \approx 0.01\frac{particelle}{cm^2\,s}$$

Cosmic rays have an angular distribution with respect to the normal to the Earth surface that can be described by the function :

$$f(\theta) = \frac{4}{\pi} \cdot cos^2\theta\,, \quad \theta \in \left[0, \frac{\pi}{2}\right]$$

The particles that make up the radiation have high energy. It is estimated that the average flux at sea level has an average energy of 3 GeV. The μ lepton (muon), the main component of the secondary cosmic rays, is an elementary particle with spin 1/2, mass :

$$105,658389 \pm 0,000034 MeV/c^2$$

(about two hundred times the mass of the electron), and an average life :

$$\tau_\mu = 2,19703 \pm 0,00004 \mu s$$

As mentioned in the introduction, the μ are produced mainly in the upper atmosphere by the decay of π :

$$\pi^+ \to \mu^+ + \nu_\mu$$
$$\pi^- \to \mu^- + \bar{\nu}_\mu$$

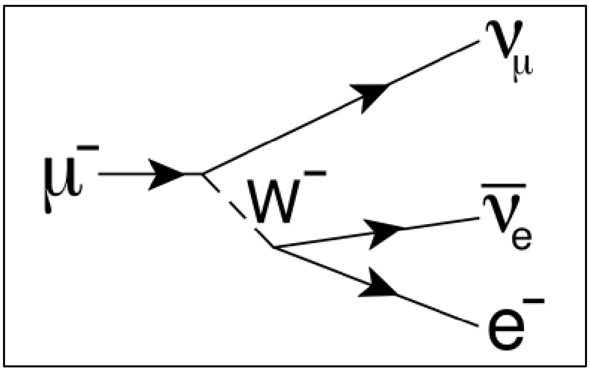
At the production time they have **relativistic speeds and because of the phenomenon of time dilation** they can reach the sea level, where it is observed that the μ + are about 20 % more of the μ- .
The muons does not interact with matter via the strong force but only through the weak and electromagnetic forces. It travels a relatively long instance 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.
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 flux of sea-level muons is approximately 1 per minute per cm2 with a mean kinetic energy of about 3-4 GeV.
Careful study shows that 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.

Muon Decay

Muons were the first elementary particles to be found unstable, i.e. subject to decay into other particles. At the time of Rossi's pioneering experiments on muon decay, the only other fundamental" particles known were photons, electrons and their antiparticles (positrons), protons, neutrons, and neutrinos. Since then dozens of particles and antiparticles have been discovered, and most of them are unstable. In fact, of all the particles that have been observed as isolated entities, the only ones that live longer than muons are photons, electrons, protons, neutrons, neutrinos and their antiparticles. Even neutrons, when free, suffer beta decay with a half-life of 15 minutes, in the decay process.

$$n \rightarrow p + e^- + \bar{\nu}_e$$

Similarly, muons decay through the process :



The decay times for muons are easily described mathematically. Suppose at some time t we have N(t) muons. If the probability that a muon decays in some small time interval dt is λdt, where **λ is a constant "decay rate"** that characterizes how rapidly a muon decays, then the change dN in our population of muons is just **dN = −N(t)λdt**, or **dN/N(t) = −λdt**. Integrating, we have :

$$N(t) = N_0 \, e^{(-\lambda t)}$$

N(t) is the number of surviving muons at some time t
N_0 is the number of muons at t = 0
The "lifetime" t of a muon is the reciprocal of **λ, τ = 1/ λ**.

This simple exponential relation is typical of radioactive decay.

Now, we do not have a single clump of muons whose surviving number we can easily measure. Instead, we detect muon decays from muons that enter our detector at essentially random times, typically one at a time. It is still the case that their decay time distribution has a simple exponential form of the type described above. By decay time distribution D(t), we mean that the time-dependent probability that a muon decays in the time interval between t and t + dt is given by D(t)dt. If we had started with N_0 muons, then the fraction $-dN/N_0$ that would on average decay in the time interval between t and t + dt is just given by differentiating the above relation:

$$-dN = N_0 \lambda \exp(-\lambda t)dt$$
$$-dN/N_0 = \lambda \exp(-\lambda t)dt$$

The left-hand side of the last equation is nothing more than the decay probability we seek, so $D(t) = \lambda \exp(-\lambda t)$. This is true regardless of the starting value of N0. That is, the distribution of decay times, for new muons entering our detector, is also exponential with the very same exponent used to describe the surviving population of muons. Again, what we call the muon lifetime is $\tau = 1/\lambda$.
Because the muon decay time is exponentially distributed, it does not matter that the muons whose decays we detect are not born in the detector but somewhere above us in the atmosphere. An exponential function always "looks the same" in the sense that whether you examine it at early times or late times, its e-folding time is the same.

Cosmic Rays Measures

The flow of particles that reach the detector (at sea level) should have the following value :
Detector Surface = 119cm^2
119cm^2 x 0,01 muons/s cm^2 = 1,19 muons/s = 71cpm

Actually, the measured value is higher because the plastic scintillator is achieved by cosmic particles also through the sides. Also measurements were made at altitudes above sea level.
The table and graph below shows the obtained results :

Altitude (m)	CPM
195	217
375	225,1
810	273,95
1070	286,22
1565	349,17

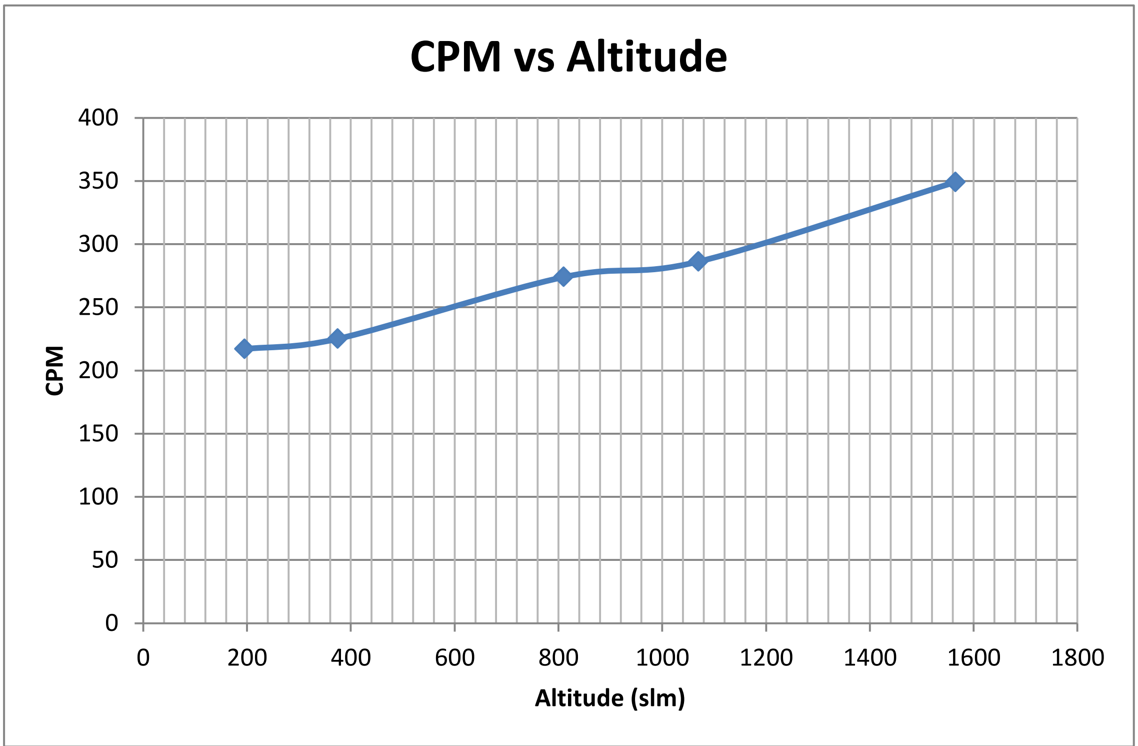
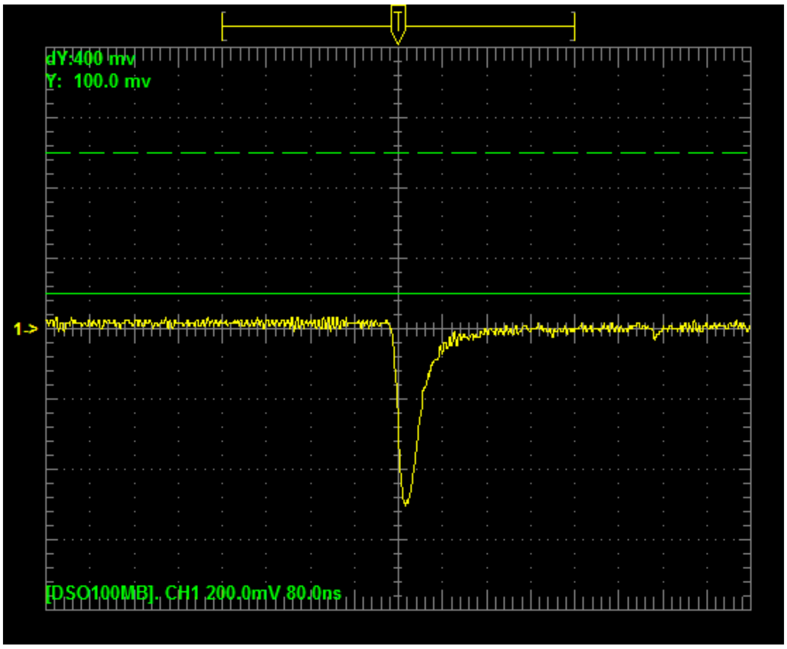


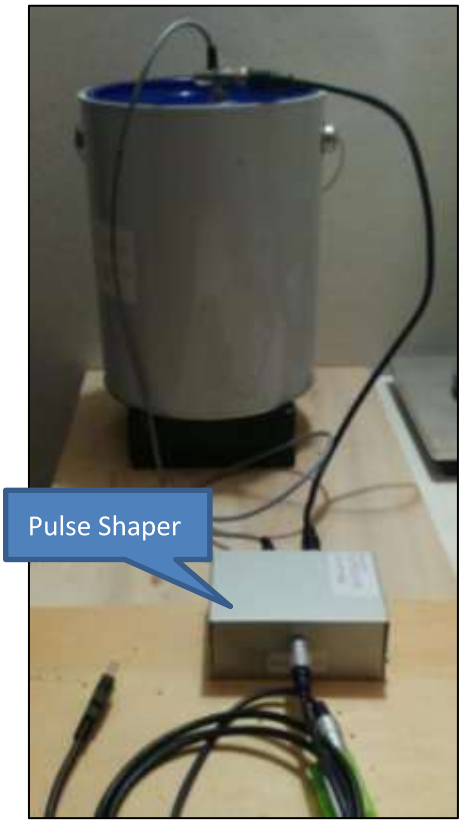
Chart showing the muon flux at different altitudes. It is clear that the more the altitude the higher the muon flux value. The increase of the altitude increases the flow because it decreases the thickness of atmosphere traversed by the muons and therefore it reduces the likelihood of absorption and spontaneous decay.

The typical high-energy muon passes right through the scintillator, but in doing so, it causes some ionization, and deposits about **50 MeV** of its energy in the scintillator. And some fraction of that energy gets converted to photons of light (that's what scintillator material is good at), and some fraction of that light reaches a photomultiplier tube, which converts the brief flash of light to a detectable pulse of electrons. Fortunately, the much more frequent events due to background radiation of the earth from ambient beta and gamma rays, have an initial energy of 1 MeV or less. A discriminator easily filters out the weak light pulses they create.

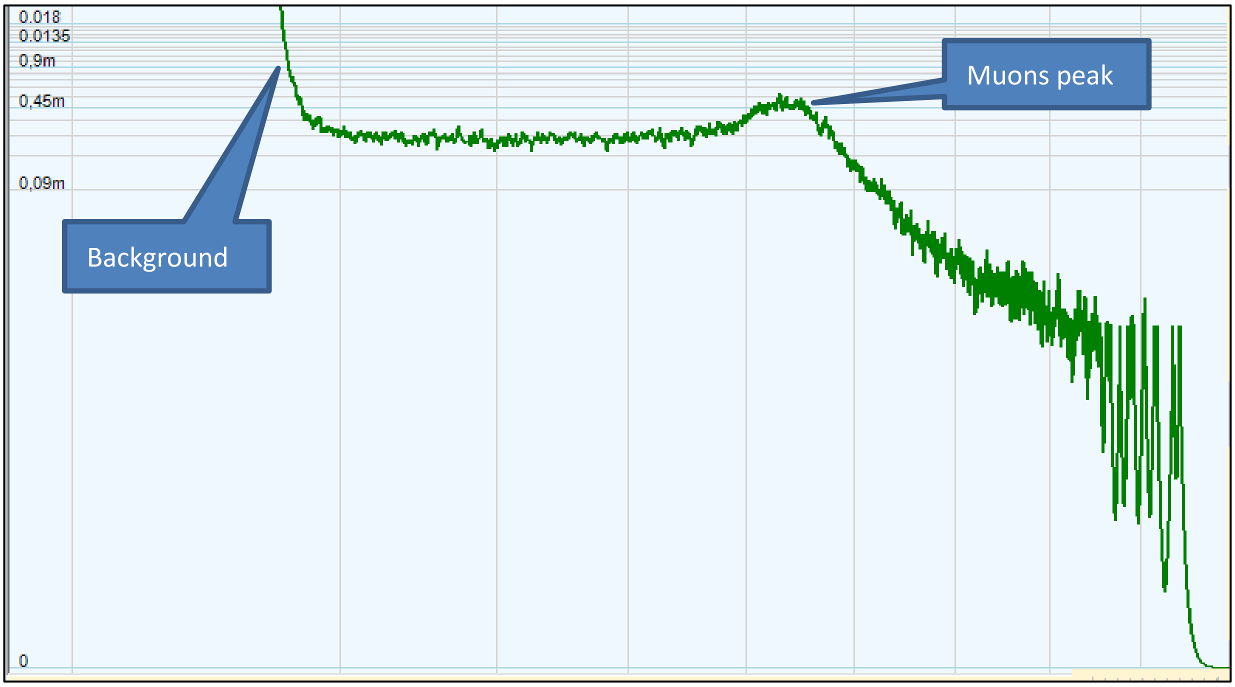
by adjusting the supply voltage of the photomultiplier to around 1000V, the typical pulse produced by a muon passing through the scintillator crystal has a width of about 200-400mv; adjusting the threshold to trigger the oscilloscope to 200mv automatically selects only the pulses produced by the muons.



Typical pulse caused by the passage of a muon. The FWHM width of the pulse is about 40ns, in line with the characteristics of the plastic scintillator and the photomultiplier



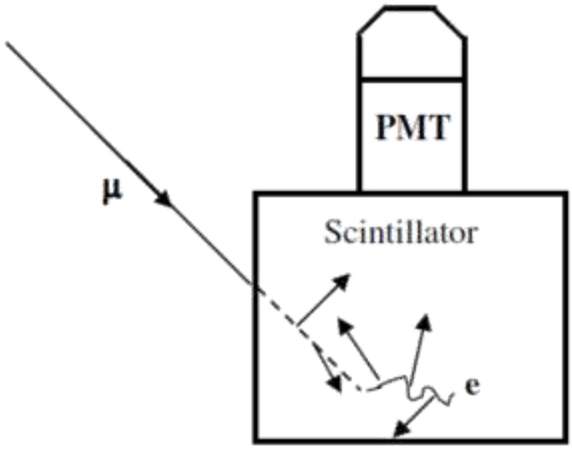
The pulses produced by the scintillation detector may be conveniently displayed by a software MCA. To do this connect the BNC output of the detector with the "pulse shaper" PMT Theremino adapter, its audio output is then connected to a PC running the software Theremino MCA. The gamma spectrum obtained shows a peak at high energies (tens of MeV) , higher than the peaks of the normal gamma energies. This peak corresponds to the energy deposited by muons interacting with the plastic scintillator. For a muon with vertical path the maximum deposited energy is about **50 MeV**. Of course the peak you get does not match the actual energy of the muon, since muons with higher energy pass through the scintillator crystal and continue their path, while muons with lower energy are stopped within the crystal and undergo the consequent decay.



Spectrum obtained with a software MCA in which it is shown the peak at high energies due to the absorption of muons in the plastic scintillator crystal .
The peak value of energy is estimated at about 40-50 MeV

Muon Lifetime Measures

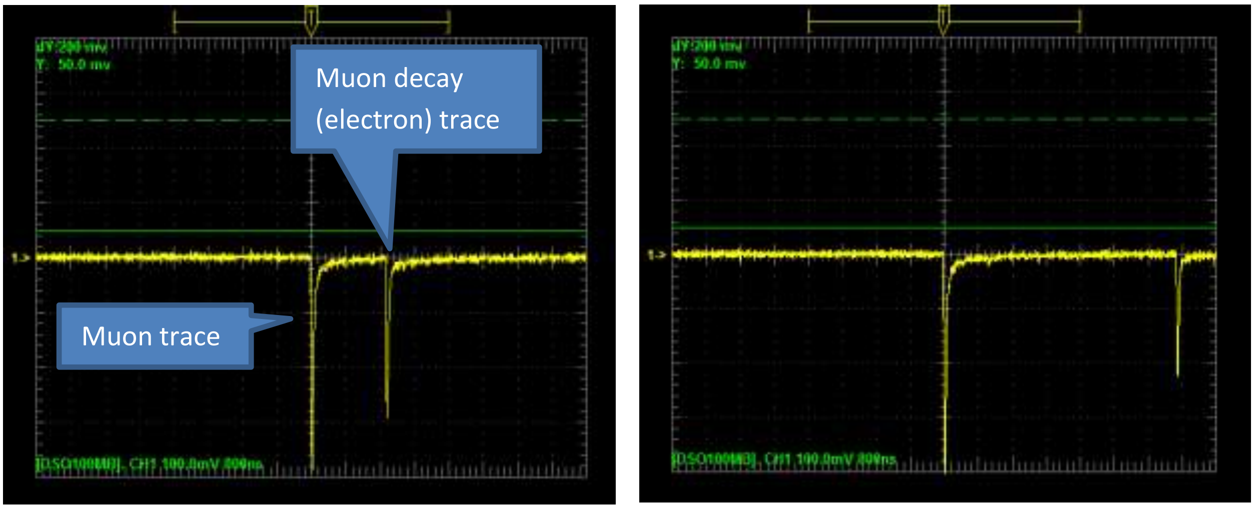
So the scintillator/photomultiplier assembly, when properly configured, produces several electronic events every second, almost all of which are due to muons passing through the scintillator. But the truly exciting fraction of those events is due to the muons which arrive with much-less-than-average kinetic energy, because such muons can lose enough energy in the scintillator to come to rest inside it. In coming to rest, they will deposit the last of their kinetic energy, typically of order 50 MeV, so they will still produce a scintillator flash as they come to rest.



Schematic showing the generation of the two light pulses (short arrows) used in determining the muon lifetime. One light pulse is from the slowing muon (dotted line) and the other is from its decay into an electron or positron (wavy line)

The muons that come to rest then live a relatively long time, on the order of order microseconds, inside the scintillator; but eventually each of them decays in an electron (positron) plus a neutrino and a antineutrino. Nearly all of the rest energy (105 MeV) of the stopped muons appears as kinetic energy of the three particles; on average, the electron (positron) gets a third of this energy, about 35 MeV. (The two neutrinos carry away the rest of the energy undetectably.) But such an electron is a charged particle, itself certain to cause ionization as it moves through the scintillator. Conveniently, the typical energy deposited in this ionization process is about the same as that deposited by a muon-in-transit, or a muon stopping, so the very same scintillator/PMT configuration is also suitable for detecting stopped muons subsequently decaying at rest.

To measure the muon's lifetime, we are interested in only those muons that enter, slow, stop and then decay inside the plastic scintillator. Such muons have a total energy of only about 160 MeV as they enter the tube. As a muon slows to a stop, the excited scintillator emits light that is detected by a photomultiplier tube (PMT), eventually producing a logic signal that triggers a timing clock. A stopped muon, after a bit, decays into an electron, a neutrino and an anti-neutrino. Since the electron mass is so much smaller that the muon mass, $m_\mu/m_e \sim 210$, the electron tends to be very energetic and to produce scintillator light essentially all along its path. The neutrino and anti-neutrino also share some of the muon's total energy but they entirely escape detection. This second burst of scintillator light is also seen by the PMT and used to trigger the timing clock. The distribution of time intervals between successive clock triggers for a set of muon decays is the physically interesting quantity used to measure the muon lifetime.



Examples of pulses caused by the passage of a muon and the subsequent decay into an electron. The electron has high kinetic energy, and then leaves a trace of amplitude similar to that of the muon. In the first case the time interval is approximately 1600ns, in the second case approximately 5600ns.

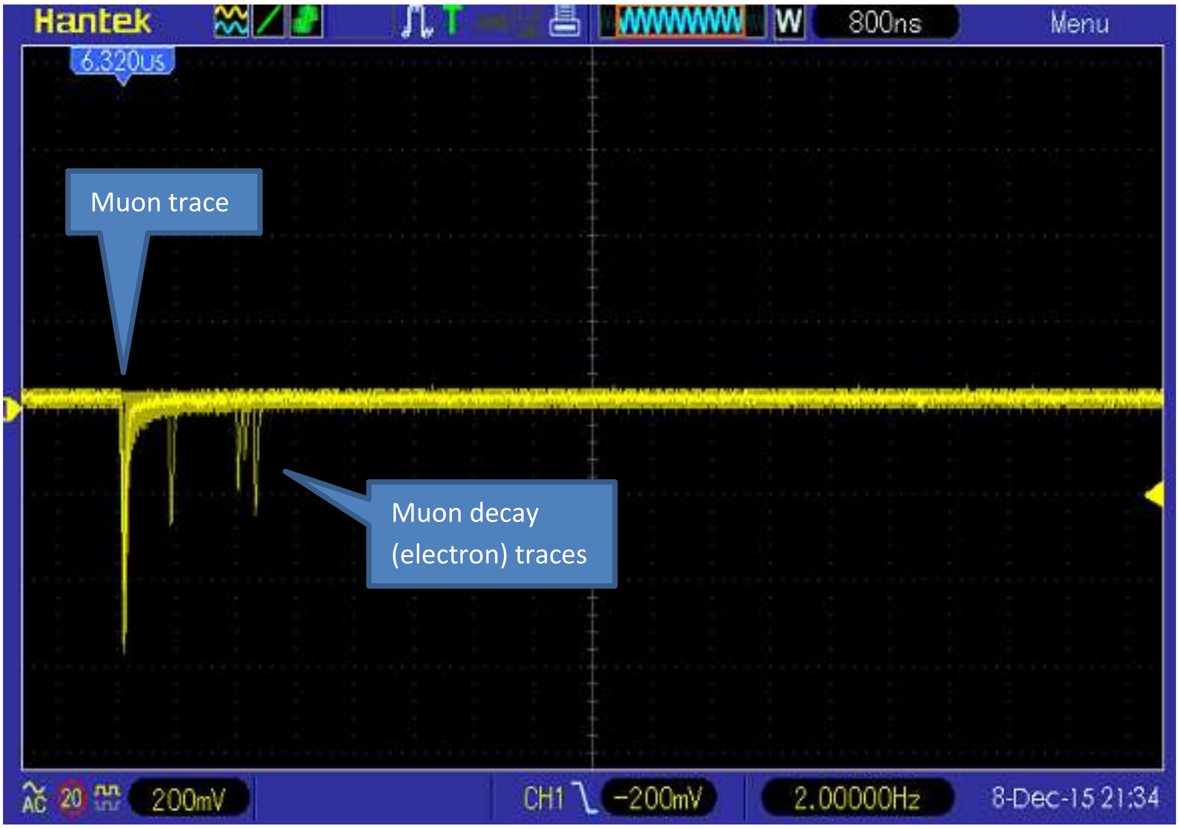
The muons whose lifetime we measure necessarily interact with matter. Negative muons that stop in the scintillator can bind to the scintillator's carbon and hydrogen nuclei in much the same way as electrons do. Since the muon is not an electron, the Pauli exclusion principle does not prevent it from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

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

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

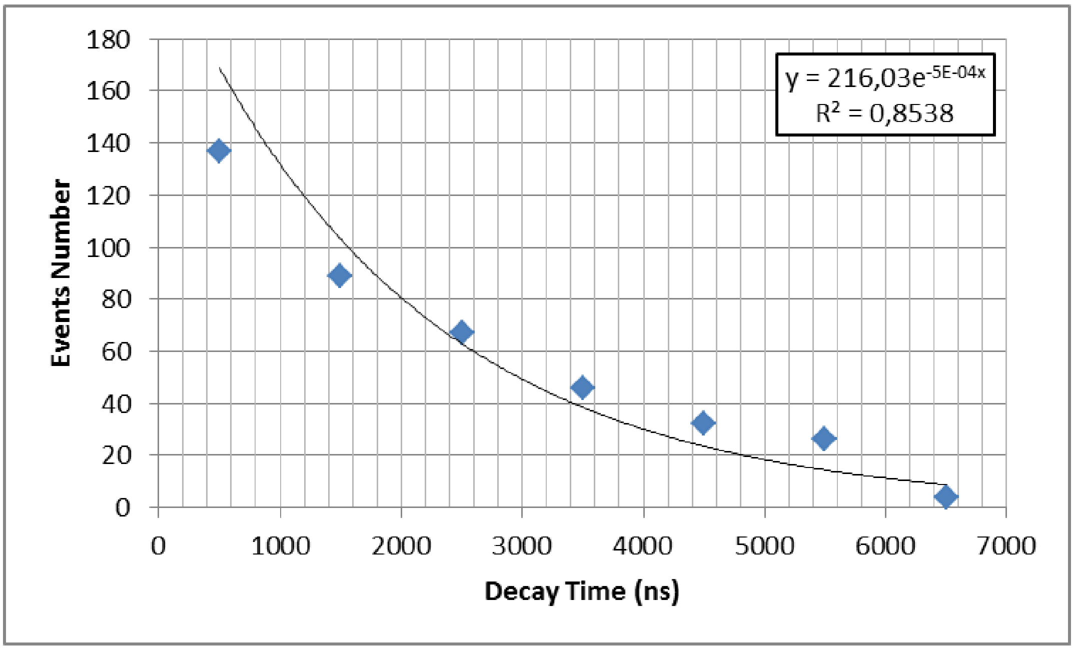
$$\tau_\mu = 2{,}19703 \pm 0{,}00004\ \mu sec$$

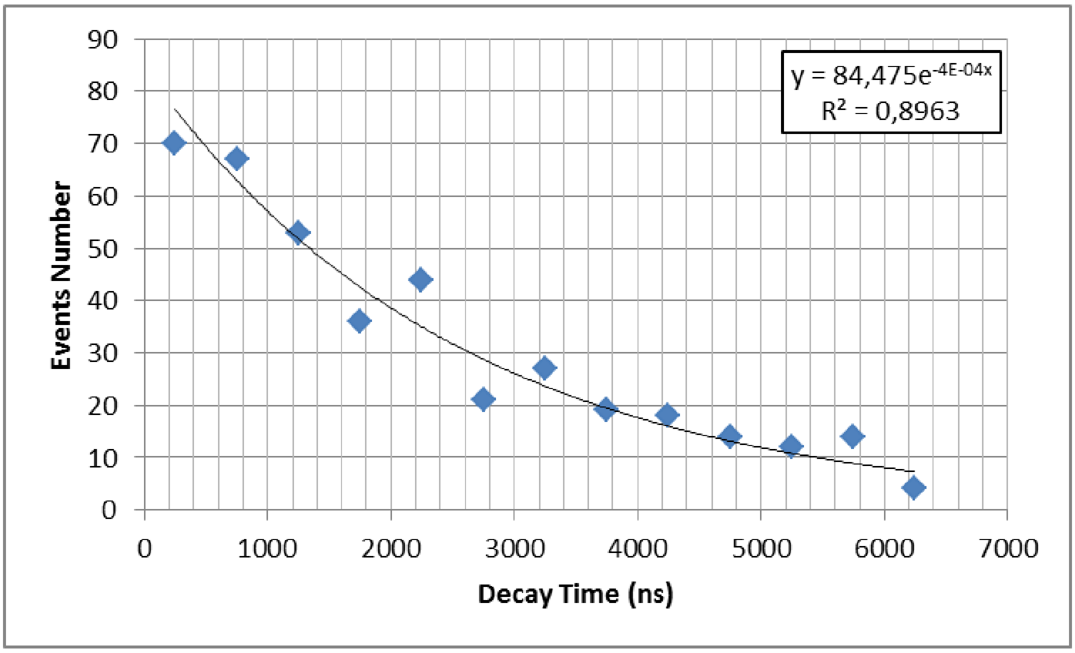
For the data acquisition of muon decay we used an oscilloscope with time of persistence set to "infinite" : in this way the pulses due to muons decay remain displayed and can be measured.
In detail the trigger threshold should be set to **200mV,** in mode **“peak detect”** so as to acquire even the shortest pulses, the time base should be set to **400ns** or to **800ns**, and the graph must be moved to the left part of display so as to be able to use all the right with a width of about **10µsec**.
Time measurement is made using the measurement cursors normally available on the oscilloscope.



Oscilloscope image that shows, with the display setting of infinite persistence, the muon trace on the left and on the right some electron traces produced by the muon decay

With the detector and the process above described we have acquired **400 events**.
Distributing them in bin with temporal width of 1 μsec we obtain the first chart shown below, from which we obtain with exponential fit a value of **τ_μ =2 μsec**.
Distributing them in bin with temporal width of 0,5 μsec we obtain a value of **τμ =2,5 μsec**.





Esteem method	τ_μ
Exponential fit with bin 1 μsec	**2 μsec**
Exponential fit with bin 0,5 μsec	**2,5 μsec**

Using the statistic method MLE (maximum Likelihood Estimation) for the exponential time constant, it can be shown that :

$$\tau = \frac{\sum_{j=1}^{n} x_j}{n}$$

The most likely value of the time constant of the exponential decay is equal to the average of the measurements.
The variance associated with the estimate is obtained with the following formula :

$$\sigma = {\tau^2}/{n}$$

For n = 400 (400 events have been acquired) we obtain the values :

τ_μ = 2,078 (measurements average)
σ = 0,011

The value that is obtained is probably slightly underestimated since the frame window taken into examination had up to 7 usec. This value is, however, in agreement with the result that you should get which stays between the theoretical value of **2,2 µsec for positive muons** which is equal to the value measured in empty space and the value of **2,04 µsec for negative muons** which are affected by the interactions with the nuclei of the scintillator material.

Esteem method	τ_μ
MLE Statistic	2,078 ± 0,011 µsec