Cherenkov Detector

Cosmic Rays Cherenkov Detector

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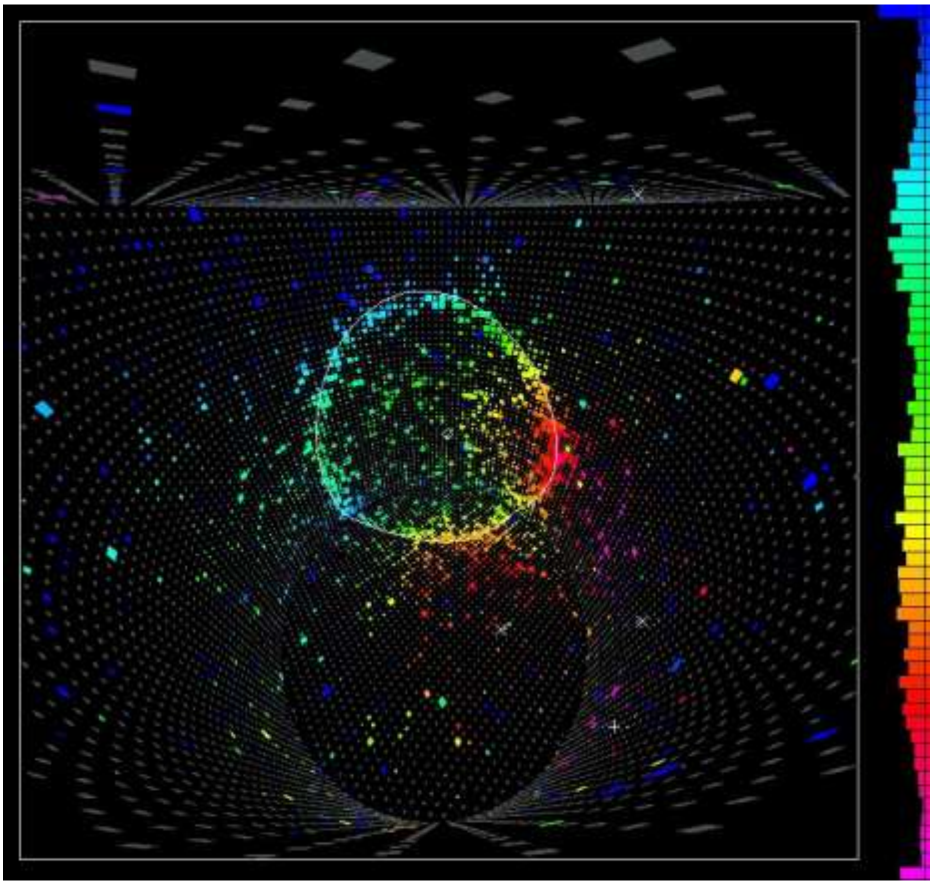


In the picture you see the trace of a cone of Cherenkov light produced in the Japanese experiment Kamiokande, based on 50000t of water kept “observed” by 11000 photomultiplier tubes. The interaction of a neutrino with electrons or nuclei of water can produce a charged particle that **moves faster than the light in water** (but obviously, more slowly of light in vacuum) . This fact generates a flash of light due to the **Cerenkov radiation**, that is the optical equivalent of the sonic boom. This flash of light creates distinctive tracks that are recorded and provide information about the direction and type of incident neutrino.

In this document we propose the construction of a DIY Cherenkov detector for the detection of cosmic particles, mainly muons.

Introduction on Cherenkov Effect

While electrodynamics holds that the speed of light *in a vacuum* is a universal constant (*c*), the speed at which light propagates in a material may be significantly less than *c*. For example, the speed of the propagation of light in water is only 0.75*c*.

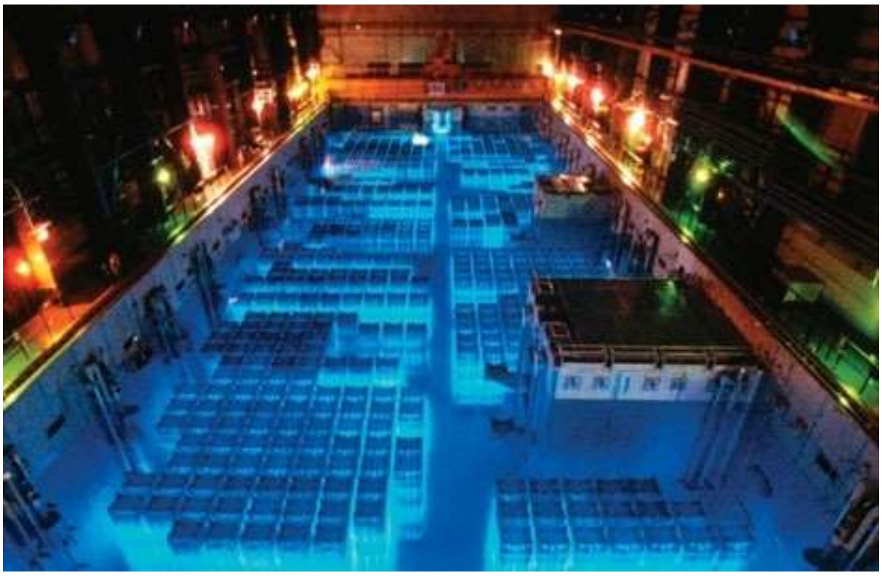
Matter can be accelerated beyond this speed (although still to less than *c*) during nuclear reactions and in particle accelerators. Cherenkov radiation results when a charged particle, most commonly an electron, travels through a dielectric (electrically polarizable) medium with a speed greater than that at which light propagates in the same medium.

As a charged particle travels, it disrupts the local electromagnetic field in its medium. In particular, the medium becomes electrically polarized by the particle's electric field. If the particle travels slowly then the disturbance elastically relaxes back to mechanical equilibrium as the particle passes. When the particle is traveling fast enough, however, the limited response speed of the medium means that a disturbance is left in the wake of the particle, and the energy contained in this disturbance radiates as a **coherent shockwave**.

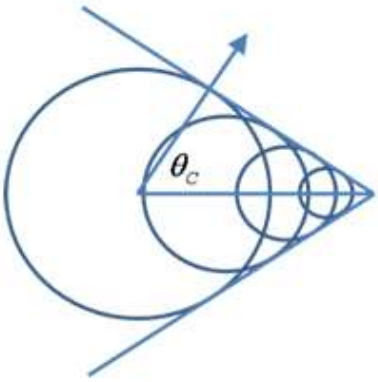
A common analogy is the sonic boom of a supersonic aircraft or bullet.

The sound waves generated by the supersonic body propagate at the speed of sound itself; as such, the waves travel slower than the speeding object and cannot propagate forward from the body, instead forming a shock front. **In a similar way, a charged particle can generate a light shock wave as it travels through an insulator**.

The Cherenkov light is also observed within the containment pools in nuclear reactors and it is caused by the Cherenkov light emitted by the beta radiation which travels inside the water.

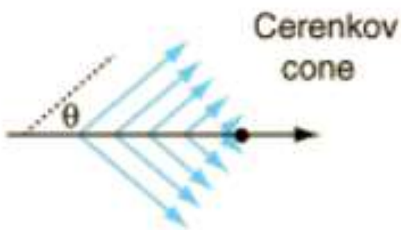


Characteristic of Cherenkov radiation is the so-called Cherenkov angle, indicated in figure with the letter θ, and can be calculated using the relationship shown in the figure, where n is the refractive index of the medium, and β is the ratio between the particle speed and the speed of light in vacuum $\beta = v / c$.



$$\theta_C = \cos^{-1}\left(\frac{1}{\beta n}\right)$$

It can be seen that the maximum angle is reached when the particle is moving at approximately the speed c. In the case of water, where n = 1,33, the maximum angle is 41.2°. From the same equation it can be calculated the minimum speed (energy) in order to produce the Cherenkov emission, the minimum energy for an electron is **0,26MeV**, for a muon instead the minimum energy to produce Cherenkov emission is **160MeV**. The scheme below illustrates this calculation in the case of an electron.



$$\cos\theta = \frac{c}{vn}$$

v = particle velocity
n = index of refraction of the medium

For water with n=1.33, the limiting angle for high speed particles is given by:

$$\theta = \cos^{-1}\frac{1}{1.33} = 41.2°$$

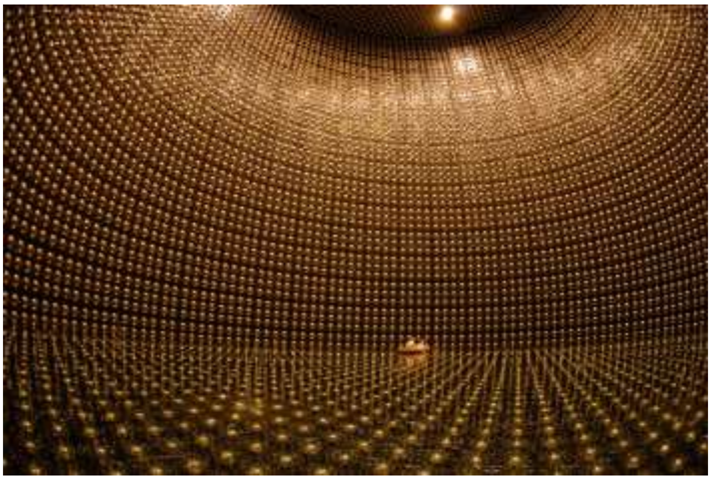
The threshold particle speed for Cerenkov radiation is v = c/n, which for an electron in water gives a threshold particle kinetic energy of 0.26 MeV.

$$\beta = 0.752,\ E_{electron} = \gamma m_e c^2 = \frac{1}{\sqrt{1-\beta^2}} m_e c^2 = (1.52)(0.511\ \text{MeV}) = .775\ \text{MeV}$$

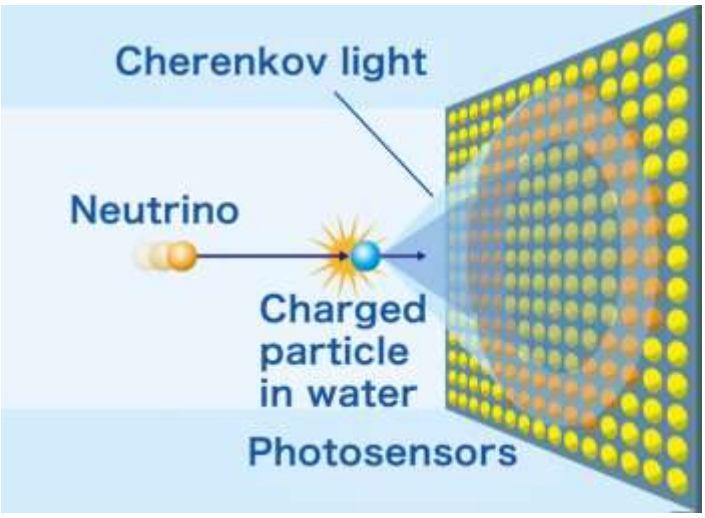
Kinetic energy = 0.775 MeV - 0.511 MeV = 0.26 MeV

Super - Kamiokande

Super-Kamiokande (abbreviated to **Super-K** or **SK**) is a neutrino observatory located under Mount Ikeno near the city of Hida, Japan. The observatory was designed to search for proton decay, study solar and atmospheric neutrinos, and keep watch for supernovae in the Milky Way Galaxy. The Super-K is located underground in the Mozumi Mine in Hida's Kamioka area. It consists of a cylindrical stainless steel tank that is 41.4 m tall and 39.3 m in diameter holding 50,000 tons of ultra-pure water. Mounted on the superstructure are 11,146 photomultiplier tubes (PMT) 50 cm in diameter.



A neutrino interaction with the electrons or nuclei of water can produce a charged particle that moves faster than the speed of light in water (not to be confused with exceeding the speed of light in a vacuum).**This creates a cone of light known as Cherenkov radiation**, which is the optical equivalent to a sonic boom. The Cherenkov light is projected as a ring on the wall of the detector and recorded by the PMTs. Using the timing and charge information recorded by each PMT, the interaction vertex, ring direction and flavor of the incoming neutrino is determined. From the sharpness of the edge of the ring the type of particle can be inferred. The multiple scattering of electrons is large, so electromagnetic showers produce fuzzy rings. Highly relativistic muons, in contrast, travel almost straight through the detector and produce rings with sharp edges.



Construction of Detector

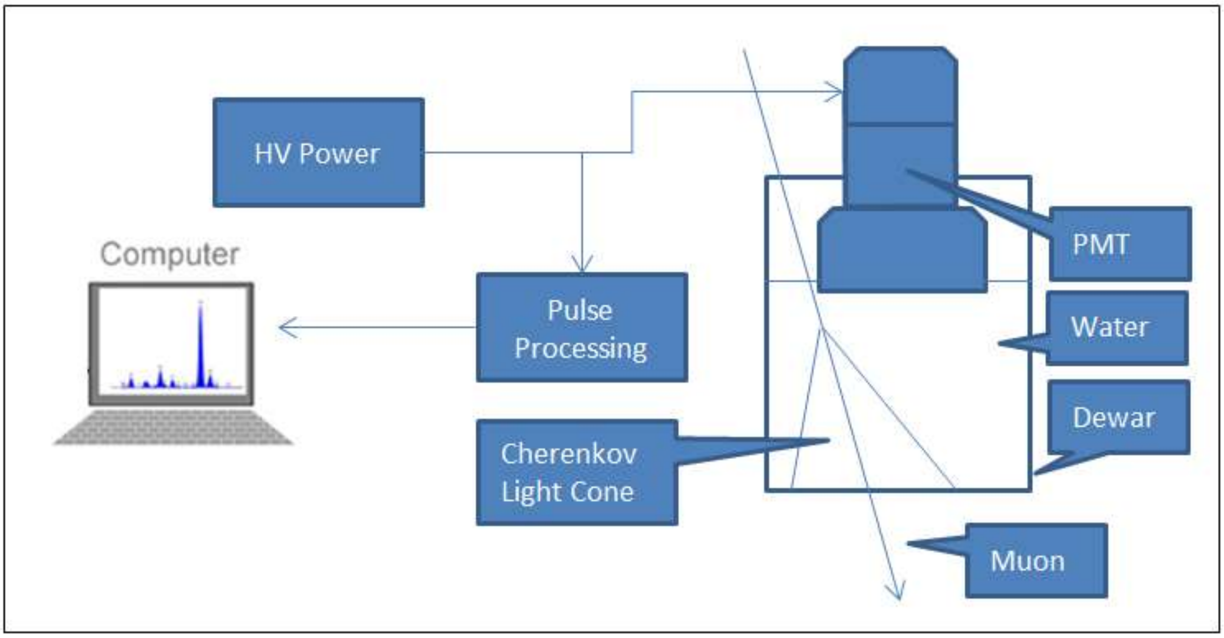
To realize the detector we chose a photomultiplier widely used in scintillation detectors, the model R6233 of Hamamatsu, with a large photocathode of 70mm, thus able to cover a fairly large area.

Specification of PMT R6233

Type : Head-On
Size : 76mm
Photocathode : Bialkali
Max Voltage : 1500V
Peak Sensitivity Wavelength : 420nm
Rise Time : 9,5ns
Gain : 270000

For the water tank it has been used a Dewar vessel scavenged from a food thermos. The Dewar vessel is made of glass and inside it is covered with a silver layer as a mirror, in this way the Cherenkov radiation which is produced downwards is reflected upwards by the walls of the Dewar and reaches, even if partially, the photo-cathode of the PMT.
In the images below you can see the Dewar vessel and the detector with the PMT :

To reduce internal reflections the PMT was placed so that the photo-cathode is immersed within the water. Water must be distilled and purified so that internal absorption inside the liquid is minimized.

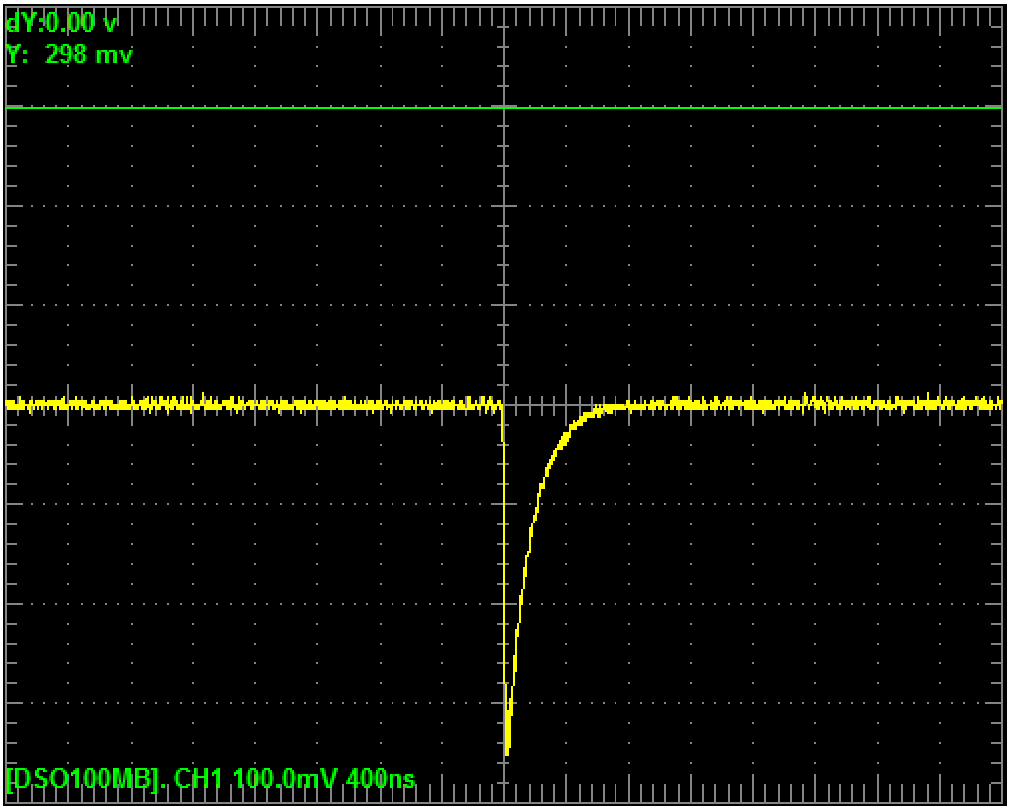


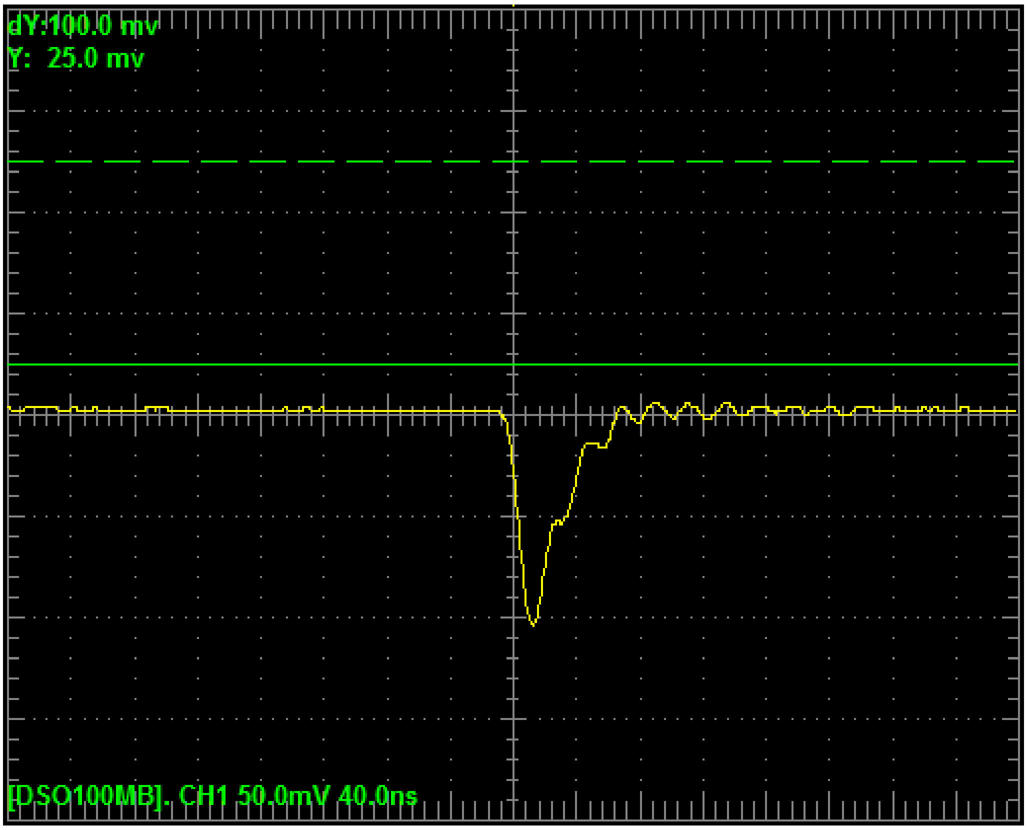
To prevent that the PMT is reached by ambient light, the detector has been inserted inside a light-proof container, provided with a BNC connector for the high voltage connection. The signal is taken from a "splitter T ", provided with the decoupling capacitor.

Cherenkov Light Pulses

Using the setup described above we have acquired signals pulses from the PMT produced by Cherenkov radiation. The PMT has bee polarized at a voltage between 1000V and 1400V. As output load resistance on the splitter we used the values of 1k and 50Ω. The greater value allow to have a fairly high amplitude signal but with a duration of almost 1µs, while with the 50Ω resistance, the pulse duration is very short, approximately **20ns** and the amplitude is about **50mv**. In both cases the signals that are obtained are **well distinguished by the thermal noise of the PMT** that has values with significantly lower amplitudes. This allows to make quite good counting measures.

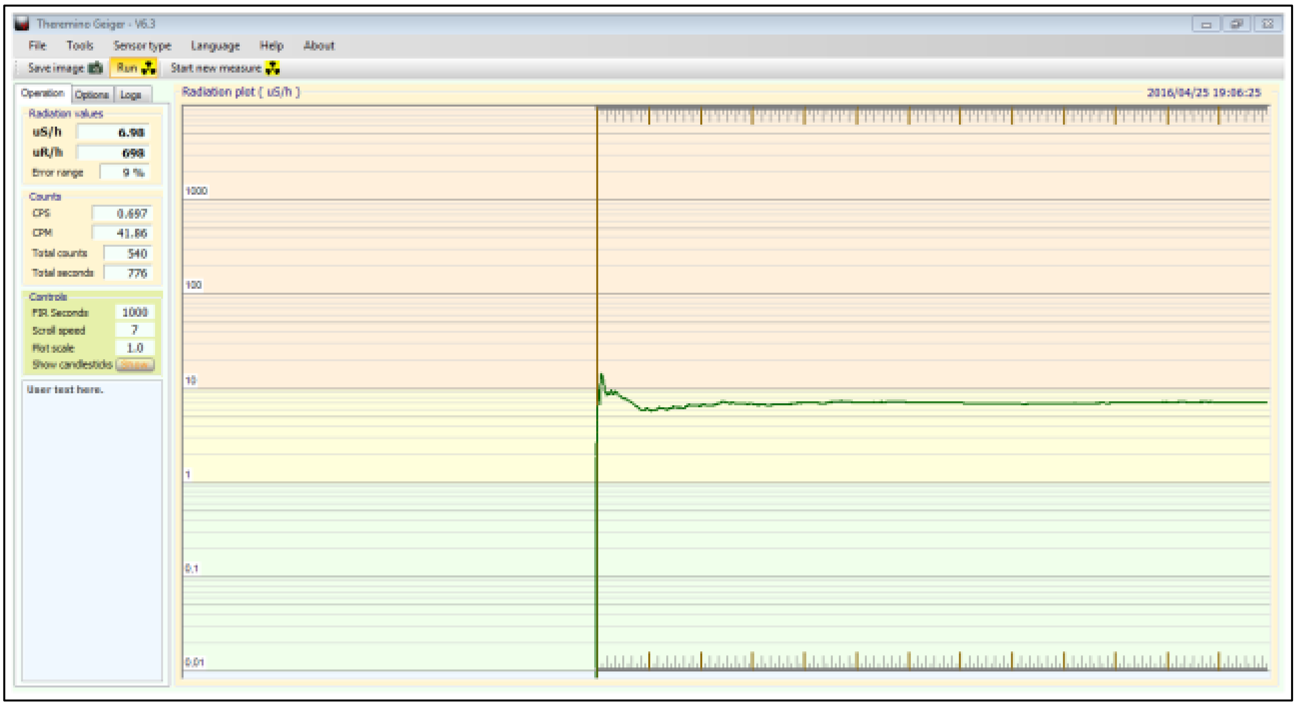
In the first picture it is shiwn the pulse with 1 kΩ resistor, while in the second with resistor of 50Ω.





By sending the signal produced by the PMT to a pulses processing unit and suitably setting the discriminator threshold to exclude the pulses generated by the thermal noise of the PMT you get a count value of about **40CPM.** Considering the surface area/volume occupied by the water and the PMT geometry this value seems consistent with the expected value of the **muon flux**. In the image below it is presented the result of the count performed with the Theremino Geiger software : **10 min running : 40 CPM**.

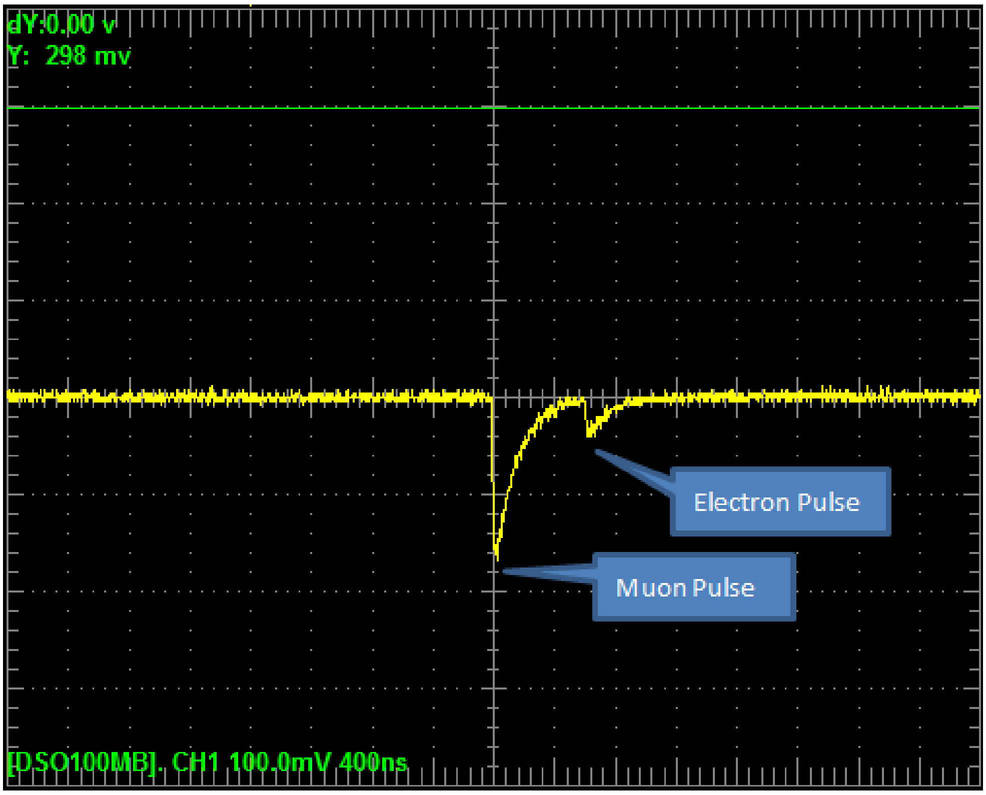
We also tried to shield the detector with a screen of about 2cm of lead, with the aim to verify if the count undergoes changes. The image on the left shows the measurement setup with the screen. The result of the count is about **42CPM**, slightly higher than the configuration without the screen. This is in line with the expected result due to the contribution of secondary particles generated inside the lead shield by the interaction of the soft component of cosmic rays (**electromagnetic cascade**); while the hard component is not absorbed the lead shield.

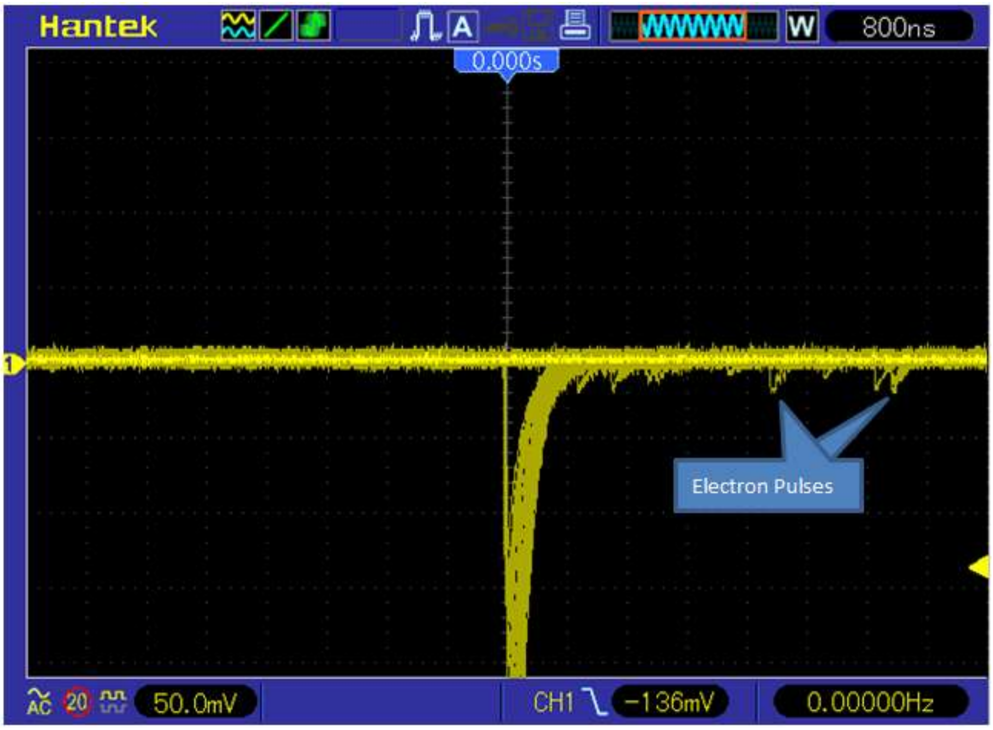


Muon Decay

As seen above, the Cherenkov detector records the passage of **cosmic muons** through the water detector. The **muon is an unstable particle** which naturally decays into an electron and a pair of neutrino, with an average life of about **2,2μs**. The decay of the muon is an event that can be recorded in our DIY Cherenkov detector. When the muon interacts with the water, it can be slowed down almost to a stop, then it can

undergo decay while still inside the detector. In this case the electron that is produced can in turn give rise to a Cherenkov pulse, immediately after the pulse produced by the muon.
The figures below show the traces of muon decays recorded in our DIY detector.





Coincidence Pulses

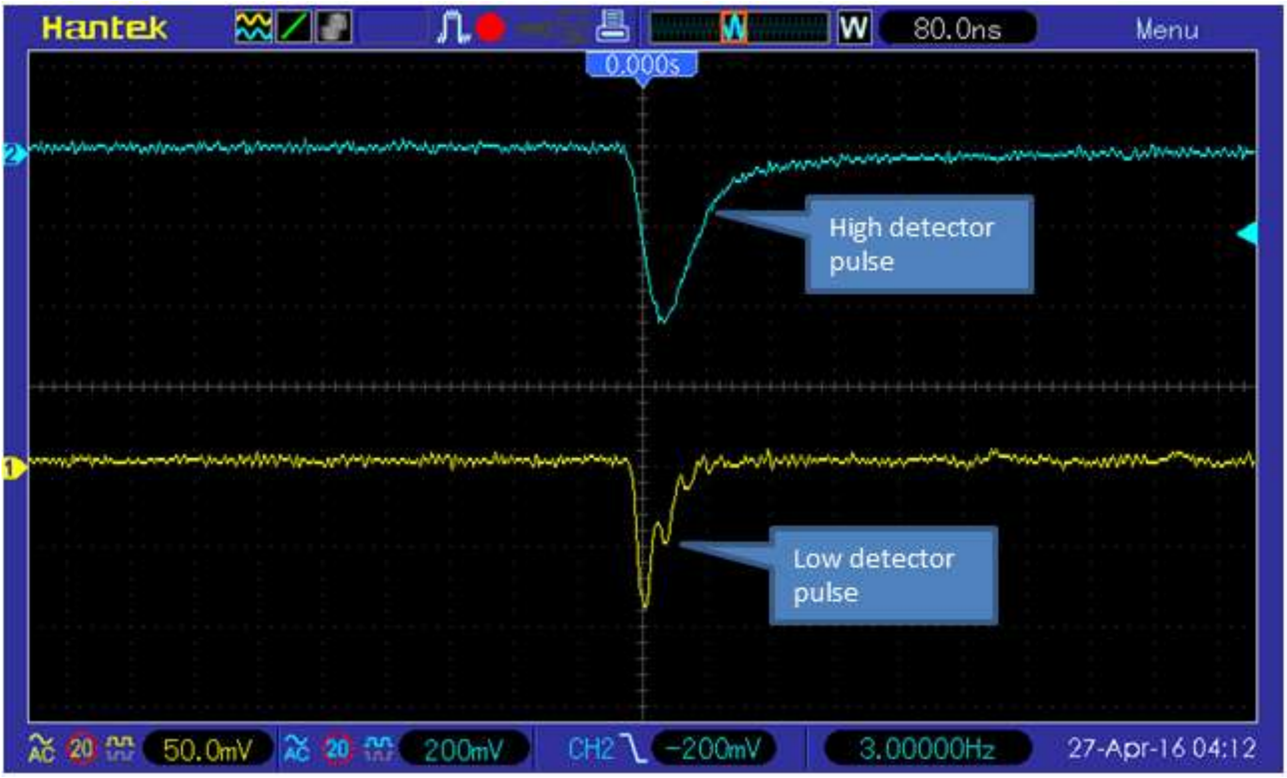
By using the Cherenkov detector and the plastic scintillator it has been made a setup for the detection of coincident pulses.

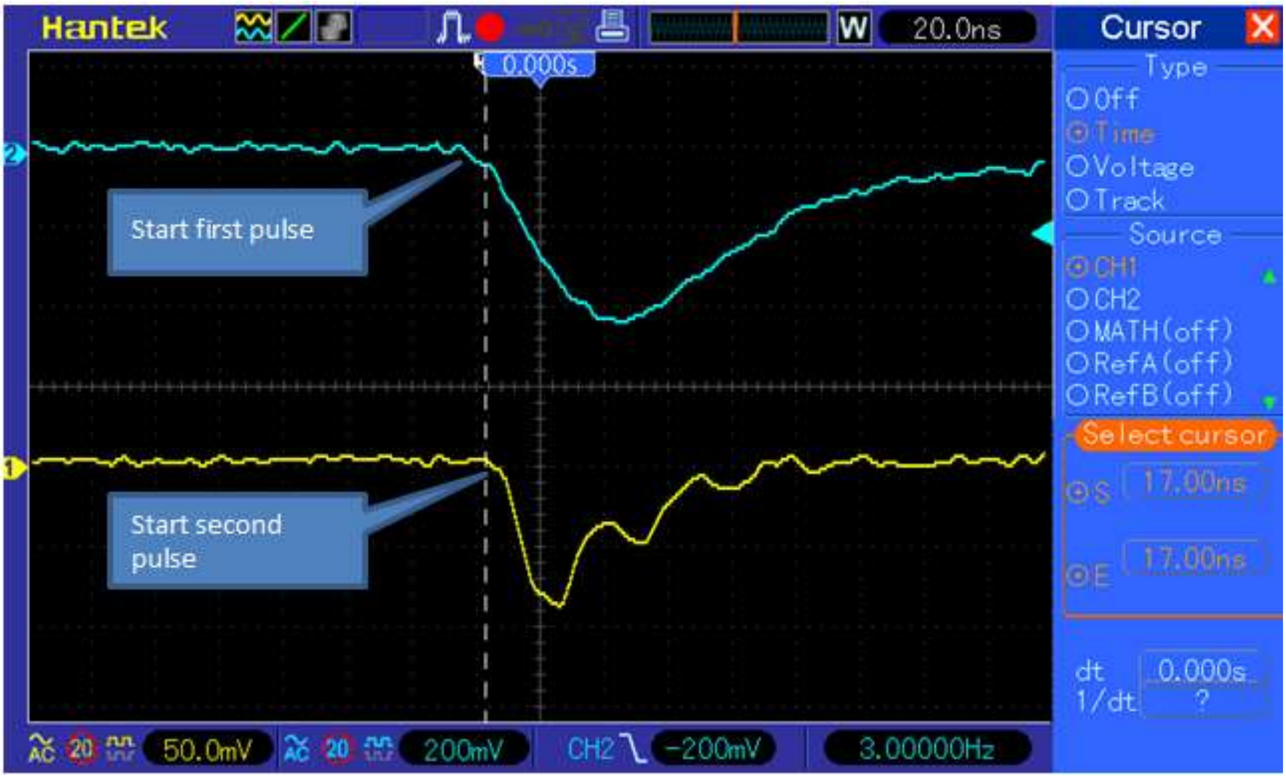
These pulses are produced by cosmic muons that pass through both detectors which are placed vertically, one above the other. The image at the side shows the positioning of the two detectors.

The two detectors are placed at the distance of about 1m, with this geometry the number of events in coincidence is rather low : less than **1CPM**, this is natural because the positioning of the two detectors at this distance greatly reduces the solid angle of the detection .

Whereas muons can have speeds between c and 2/3c (2×10^8 m/s – 3×10^8 m/s),**the time taken by muons to cover the distance of 1 m should be between 3ns and 5ns.**

In the images below we show some examples of coincidence pulses, in which it is clear that the order of magnitude of the delay of the second pulse is in accordance with what expected.




Hantek
20.0ns
0.000s
Cursor
Type
Off
Time
Voltage
Track
Source
CH1
CH2
MATH(off)
RefA(off)
RefB(off)
Select cursor
S 17.00ns
E 17.00ns
dt 0.000s
1/dt ?
Start first pulse
Start second pulse
50.0mV
200mV
CH2
-200mV
3.00000Hz