SiPM & Plastic Scintillator

Silicon photomultiplier coupled to plastic scintillator

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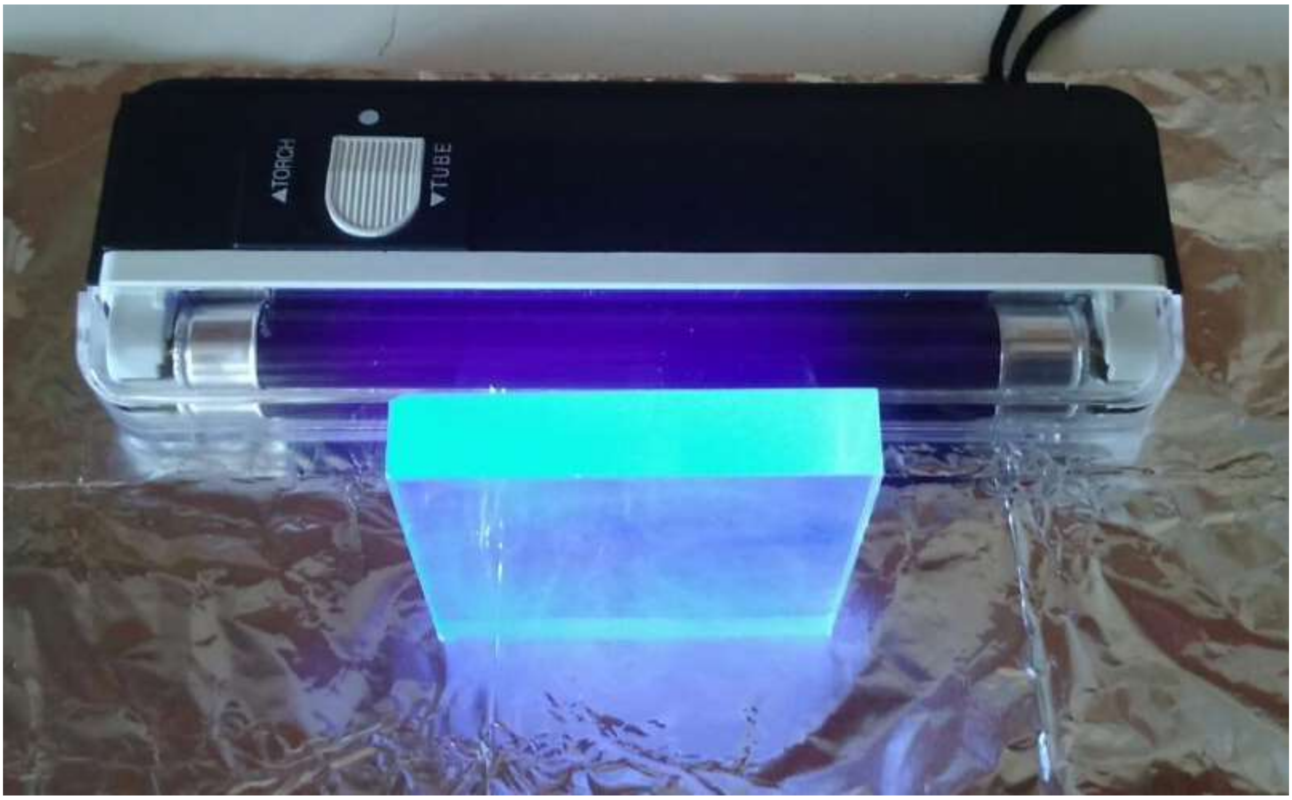
Table of contents

Introduction



In this document we propose the use of plastic scintillators coupled to SiPM for the detection of particles. A detector of this type is particularly sensitive to charged particles and thus can be used for the detection of cosmic muons and for the detection of electrons produced by β radioactivity.

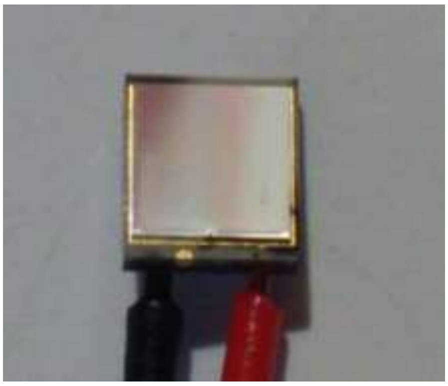
Plastic Scintillators

The term “plastic scintillator” typically refers to a scintillating material in which the primary fluorescent emitter, called a fluor, is suspended in the **base**, a solid polymer matrix. While this combination is typically accomplished through the dissolution of the fluor prior to bulk polymerization, the fluor is sometimes associated with the polymer directly, either covalently or through coordination, as is the case with many Li6 plastic scintillators. Polyethylene naphthalate has been found to exhibit scintillation by itself without any additives and is expected to replace existing plastic scintillators due to higher performance and lower price.

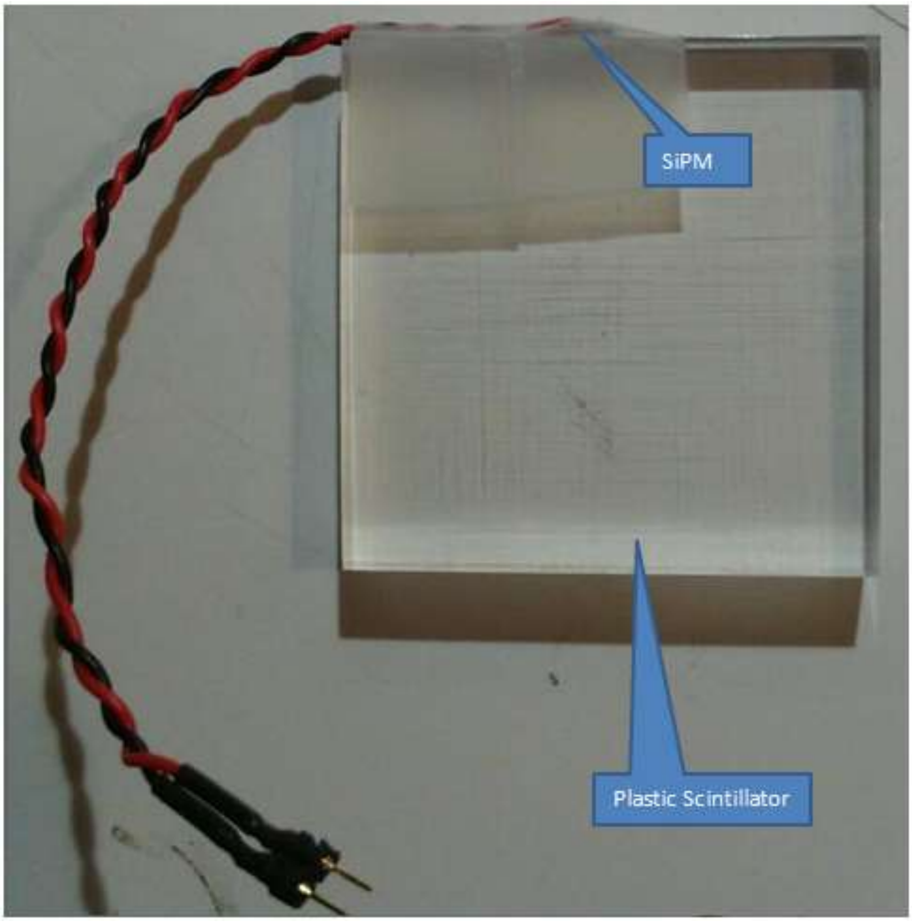
The advantages of plastic scintillators include fairly high light output and a relatively quick signal, with a decay time of 2–4 nanoseconds, but perhaps the biggest advantage of plastic scintillators is their **ability to be shaped**, through the use of molds or other means, into almost any desired form with what is often a high degree of durability. Plastic scintillators are known to show light output saturation when the energy density is large (Birks’ Law).

Building the Detector

The detector has been assembled by coupling a SiPM sensor with a scintillator crystal. The SiPM have been described in other documents. The sensor is a SiPM of AdvanSiD, sensitive in the near ultraviolet, with an effective area of 4x4mm, shown below :

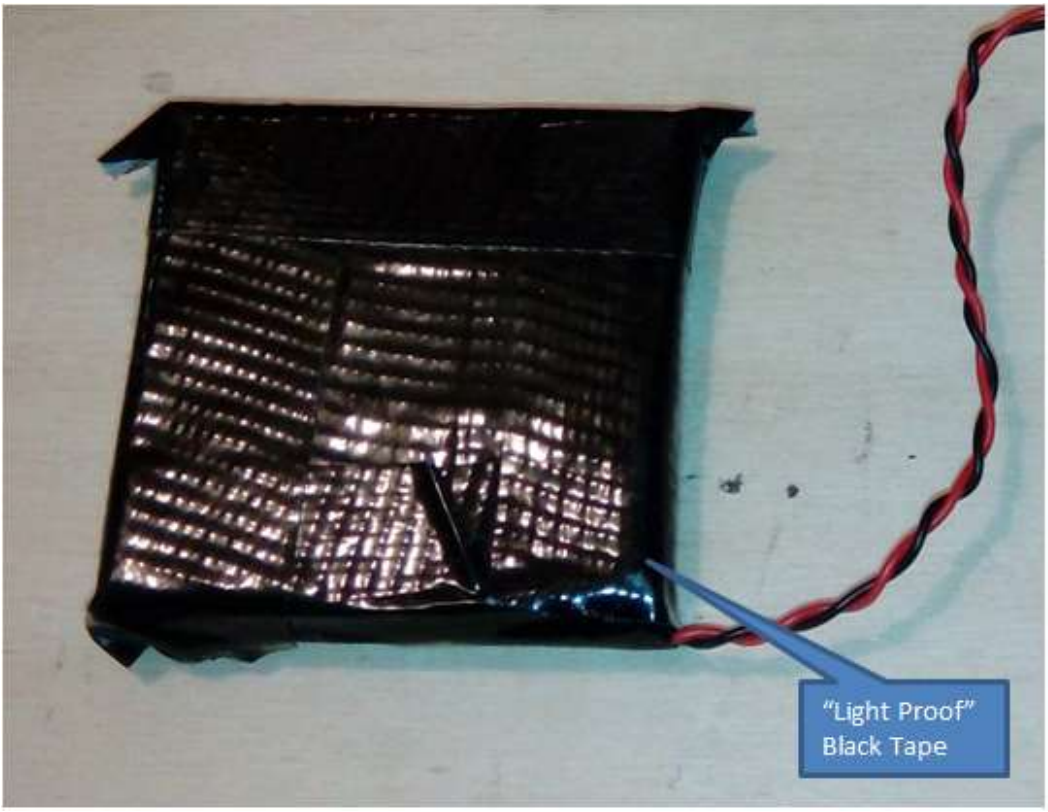


The SiPM sensor has been placed on a side of the scintillator crystal and fixed with transparent adhesive tape, to increase the optical coupling efficiency, between the SiPM and the crystal a layer of silicon Optical grease has been spread :



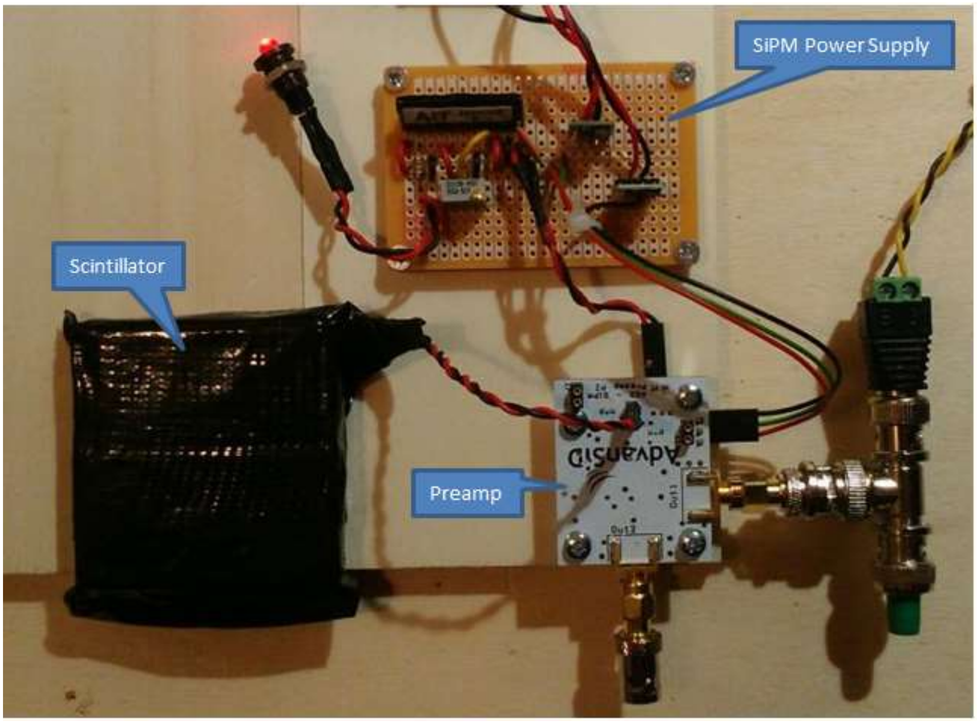
The plastic crystal with SiPM was wrapped in reflective aluminum foil in order to increase the probability that the photons produced in the scintillation are captured by the sensor SiPM :

To prevent the SiPM can be reached by ambient light, the whole detector was wrapped with black opaque tape.

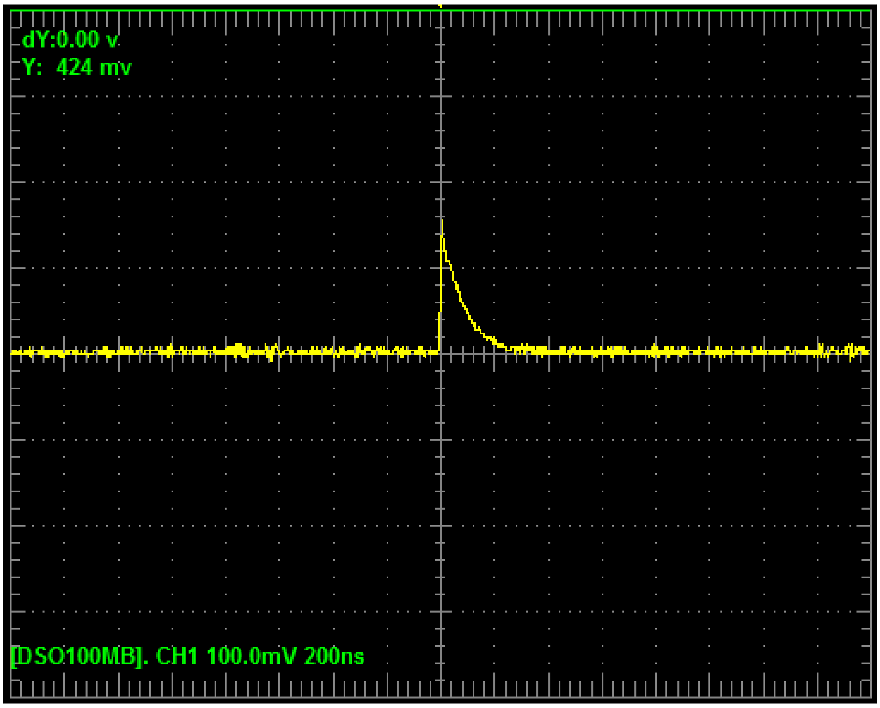


Experimental Setup

For the first tests with the plastic scintillator coupled to the SiPM the AdvanSiD preamplifier has been used. The images below show the connection of the device :



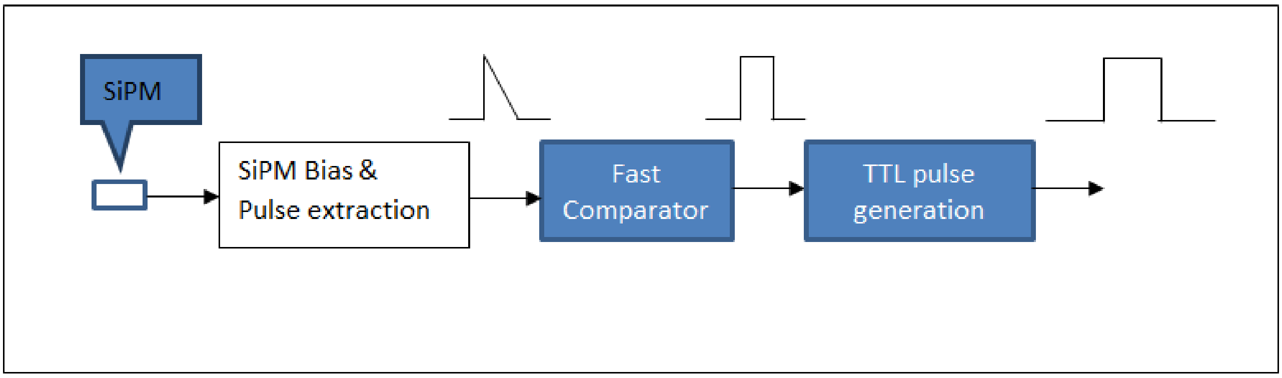
The image below shows the trace of a pulse generated by the plastic scintillator and acquired by the oscilloscope.

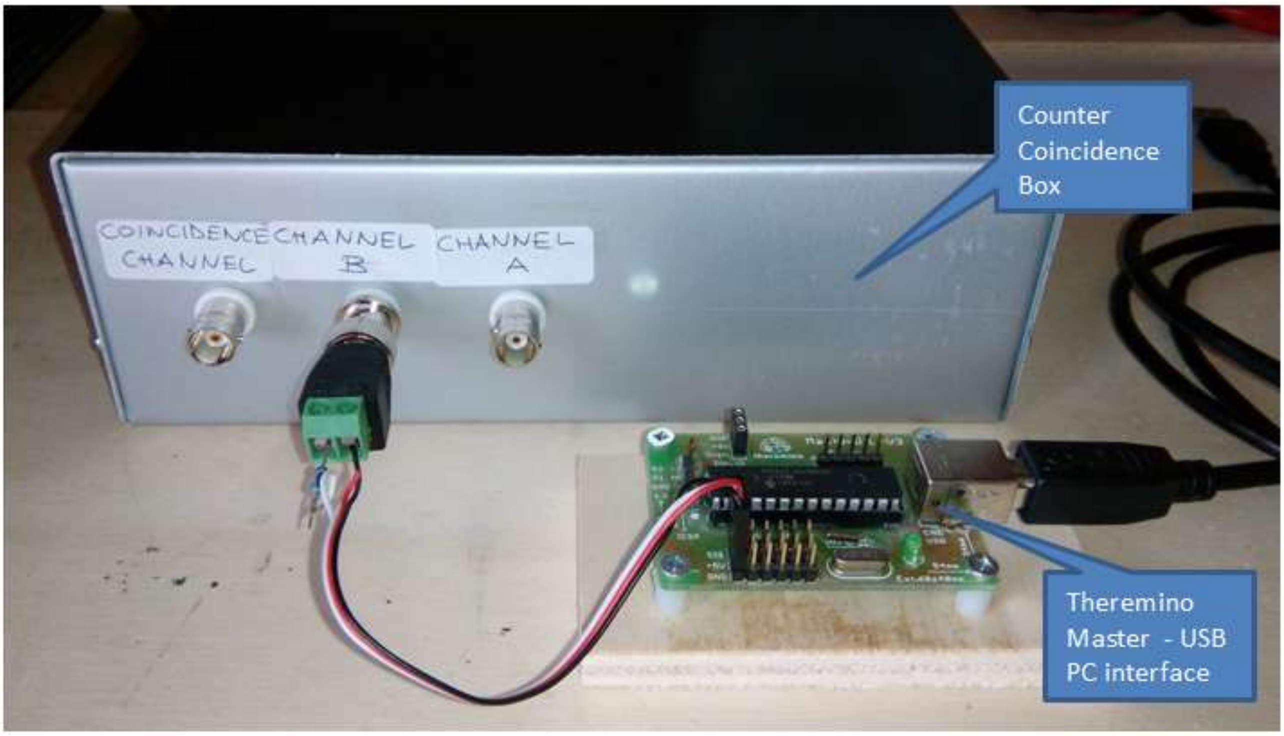


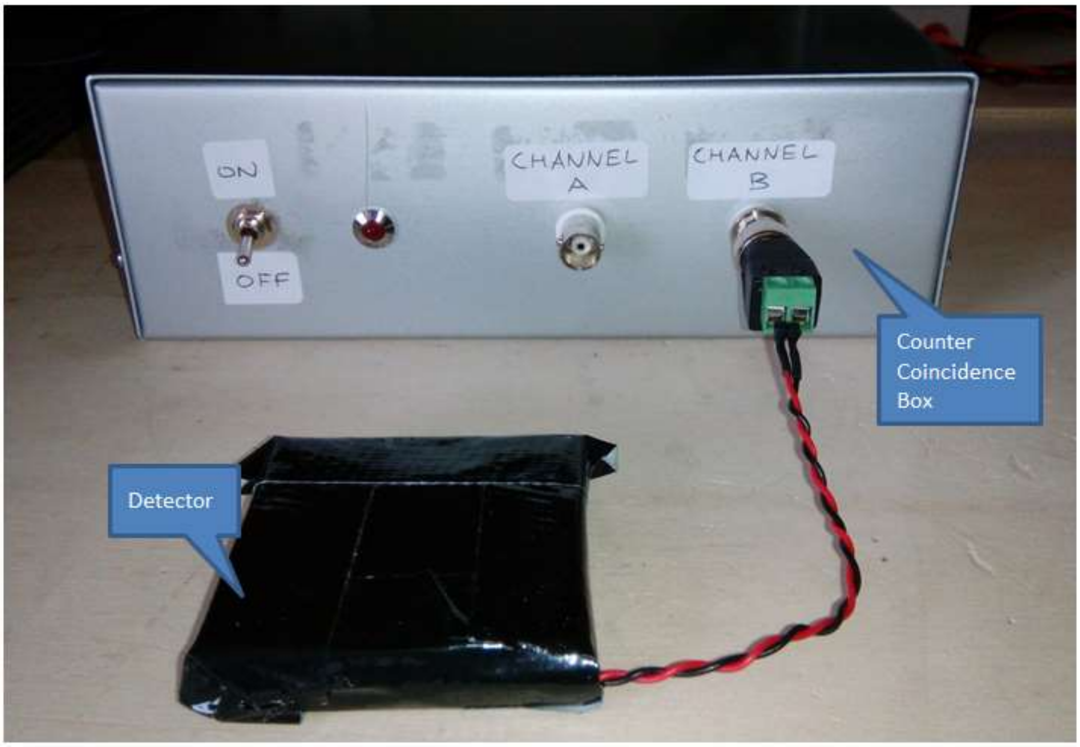
The plastic scintillator is sensitive to charged particles then the pulses generated by this scintillator are very probably caused by **cosmic muons** interacting with the crystal. The low-amplitude pulses (**10-20mV**) on the other end are due to the noise of SiPM sensor. The pulses produced by the passage of charged particles through the crystal have amplitude of **100-200mV**, so they are easily distinguishable by the pulses due to noise. In addition to the pulses generated by cosmic rays, the scintillator crystal responds also, but to a much weaker extent, to the gamma rays which are present in the background radiation.

Counting Measurements

To make counting measures a circuit has been used which makes the polarization of SiPM and the pulse extraction, the pulse is then processed by a **fast comparator** with a threshold of **100mV** that produces at the output a pulse of about **200ns** , which is further processed in order to produce in output a **TTL pulse of+ 5V and 10µs duration**. This pulse is sent to the “Theremino Master” which carries out the counting of the pulses, which are then displayed by the software ” Theremino Geiger “.







Measurement of Background

The first measurement was that of the background radiation. Knowing that the plastic crystal is mainly sensitive to charged particles we expect to obtain a direct measurement of the cosmic ray flux on the detector surface :

The flow of particles that reach the detector (at sea level) should have the following value :

Scintillator Crystal Area = 32,5cm^2

32,5cm^2 x 0,01 particles/s cm^2 = 0,32 particles/s = 0,32cps

The result is shown below :

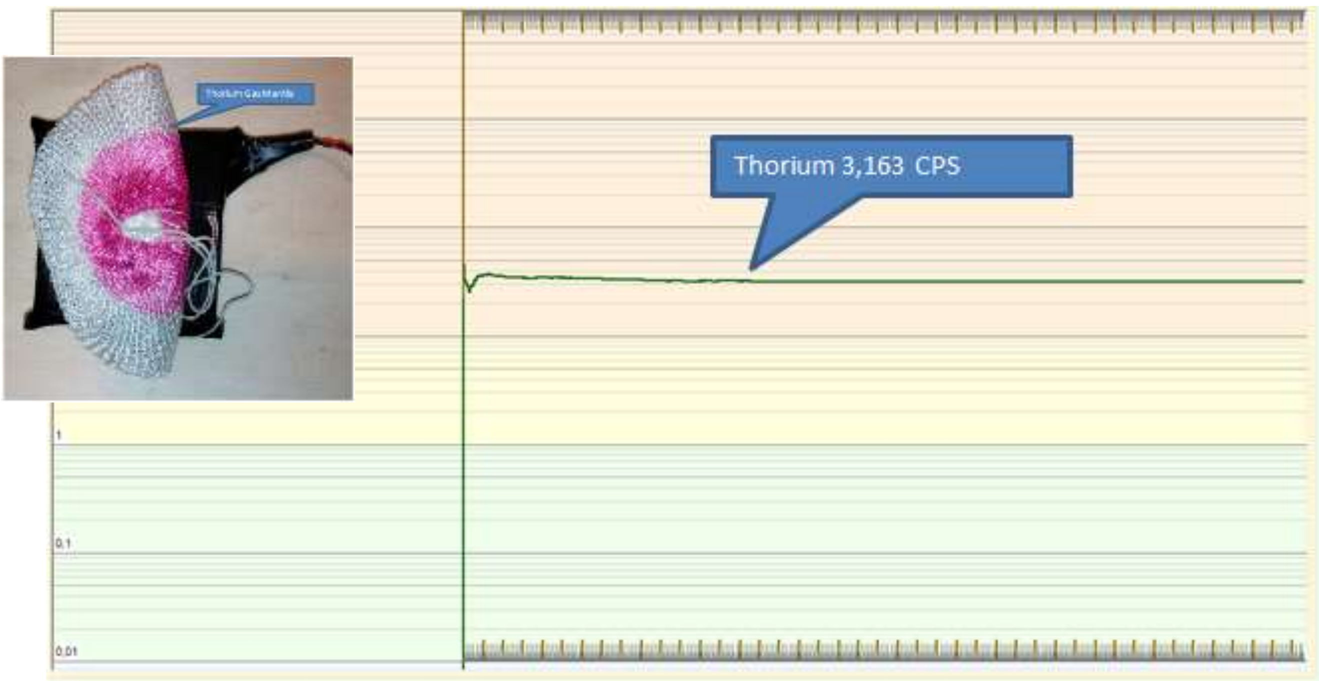
It could be seen that the obtained value is slightly greater than the theoretical value, this may be due both to the fact that the measurement was carried out at a height of 375slm, and then the flow of cosmic rays is greater than at sea level, and both to the fact that part of the events recorded by the detector may be due to the background gamma radiation.

Measurement of Isotopes

With the same setup : plastic scintillator, SiPM and counting box, counting measurements were made on some weakly radioactive samples. The measurements were made by putting the source in direct contact with the detector.

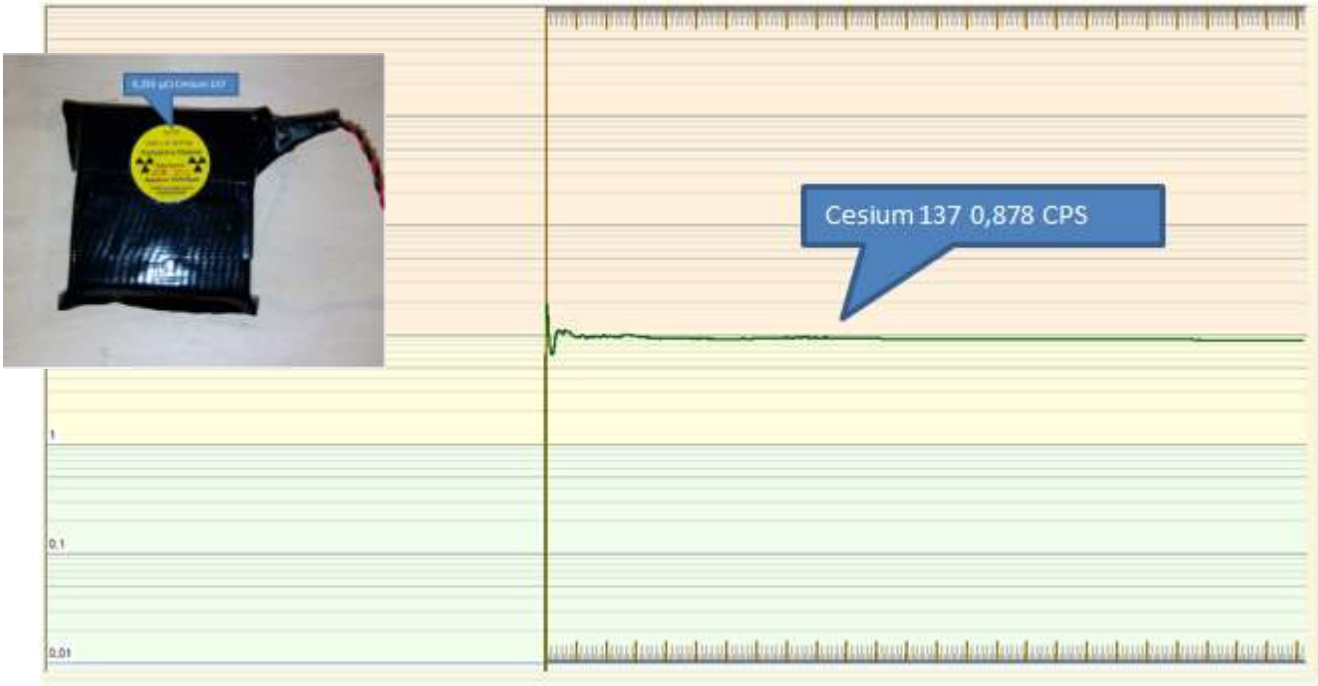
Thorium

As thorium sample a thoriated gas mantle has been used. The emission of radiation comprises a not negligible quantity of β radiation (electrons), easily detected by the sensor, indeed the result of the count is significantly higher than the value of the background.



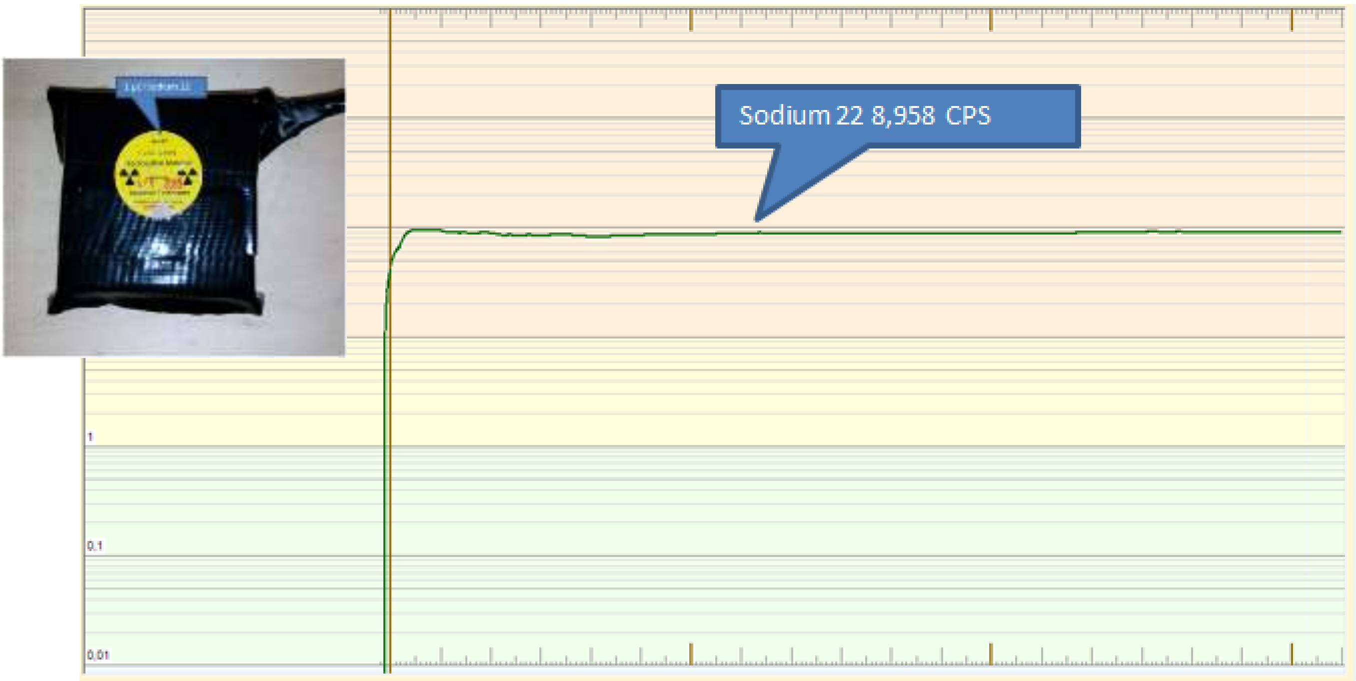
Cesium 137

A sample of 0,25 μCi of cesium has been used. The cesium emission includes a weak β radiation (electrons), which in any case are detected by the sensor, in fact the result of the count is slightly greater than the background value. **The main gamma emission of Cesium at 662keV is hardly detected**.



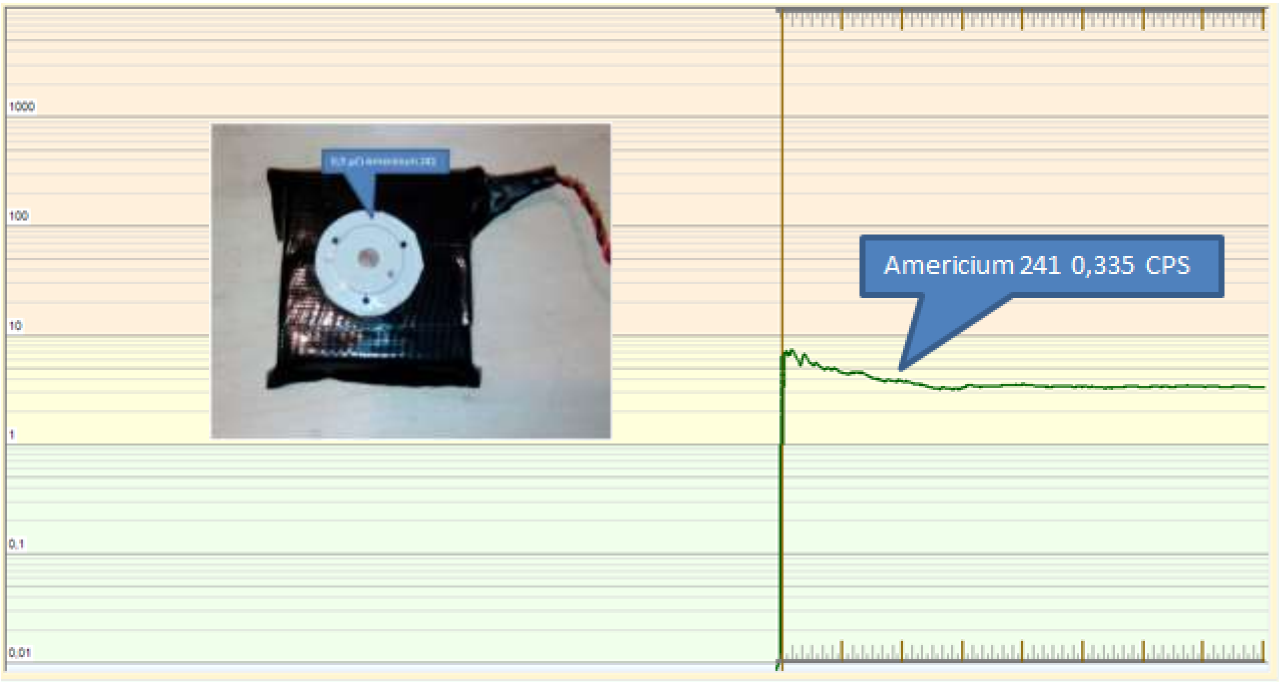
Sodium 22

A sample of 1 µCi of sodium has been used. The emission includes a considerable quantity of gamma radiation that are detected by the sensor, indeed the result of the count is much higher than the value of the background.



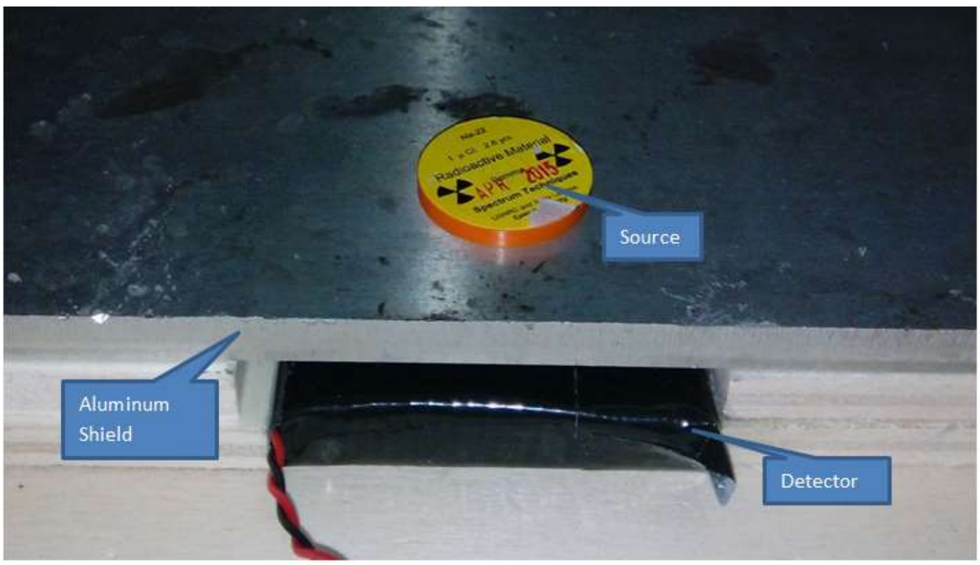
Americium 241

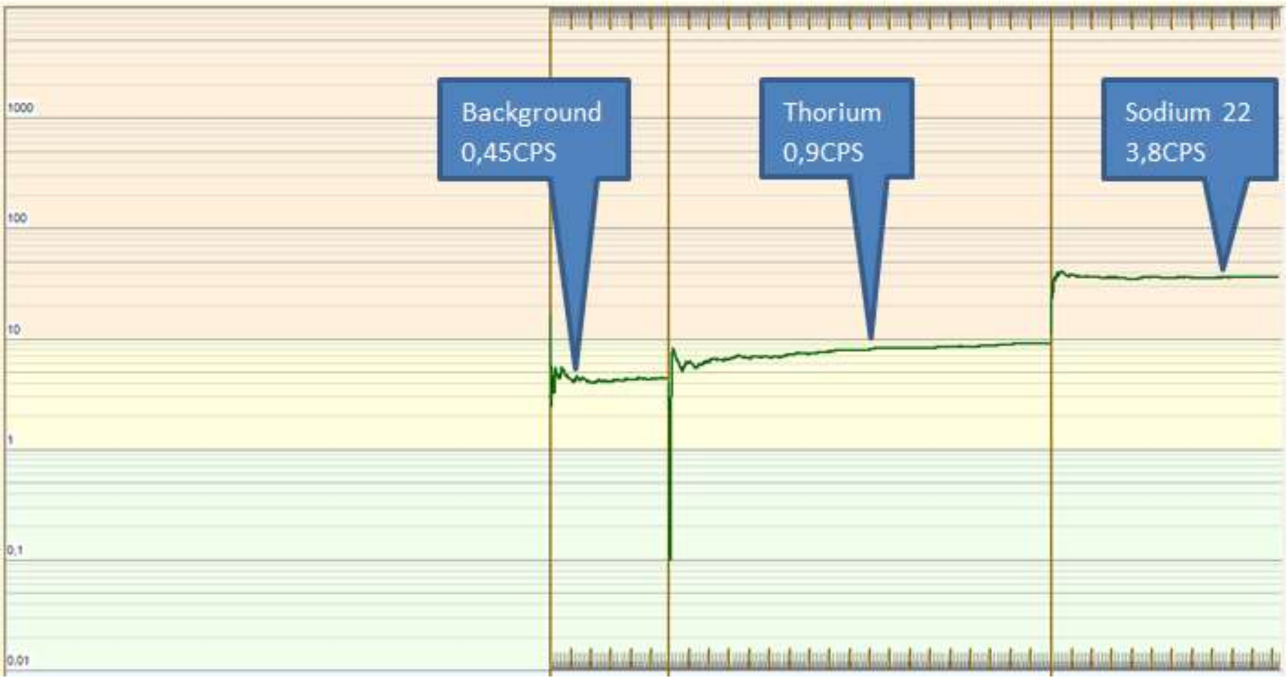
A sample of 0,9 µCi of Americium has been used. The emission includes a considerable amount of α radiation, which can not be detected by the sensor, indeed the counting result does not differ from the value of the background. **The main gamma emission of americium at 60keV is hardly detected**.



Assessment of sensitivity to Gamma Radiation

To assess the sensitivity of the detector to gamma radiation was made a measurement with the two sources of thorium and sodium 22 that emit a discrete quantity of gamma emissions, shielded by a slab of aluminum which should stop most of the beta radiation :

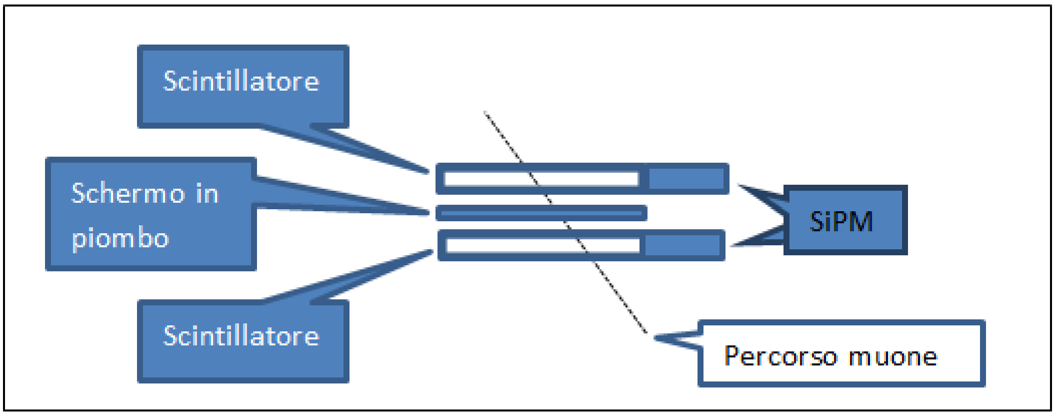




From the results of the measurements it is clear that the sensor responds to a limited extent with the aluminum shield, however, **it remains also a certain sensitivity to gamma radiation**, which are only weakly shielded from aluminum plate.

Time Coincidence

To increase the security that logged events are actually caused by cosmic rays we have chosen to use two identical detectors superimposed to each other and connected to a coincidence circuit.



As seen in the figure above the two plastic scintillator crystals were placed one above the other and separated by a lead screen to stop environmental radiation.

In the images below you can see the detectors in overlapping position for measurements in coincidence and in the side-by-side position, used to evaluate the random coincidence due to spurious events or background radiation.

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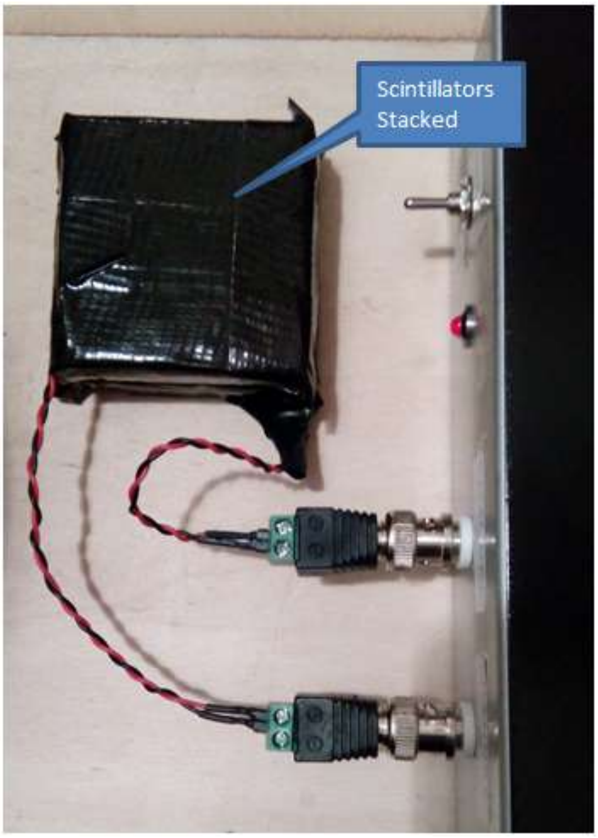
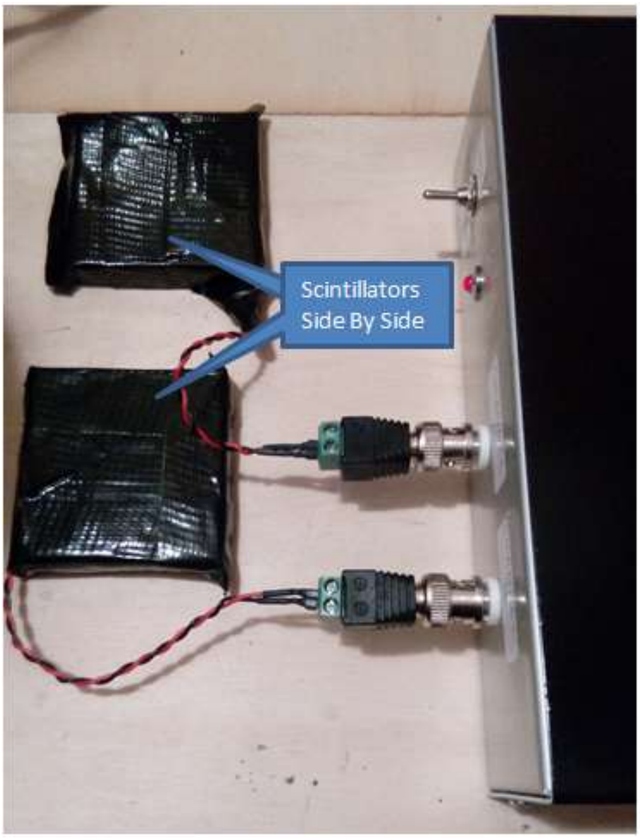
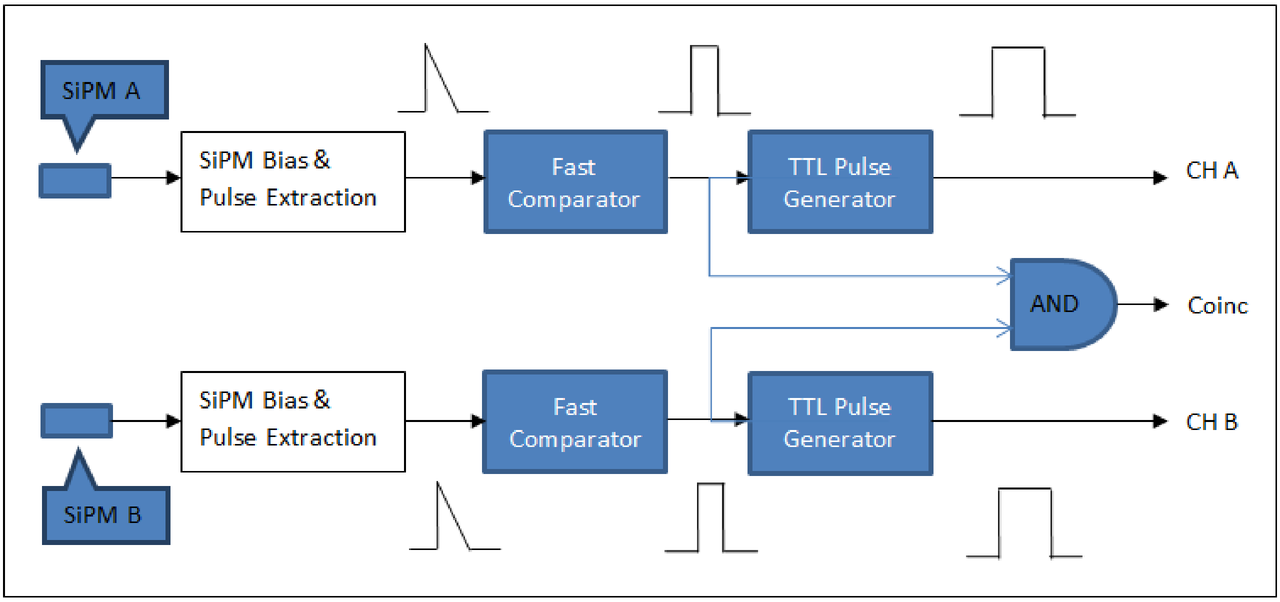




The pulses from SiPM are sent to an electronic device that performs the shaping of the pulses and produces the coincidence pulse with an AND logic gate :



Counting Results

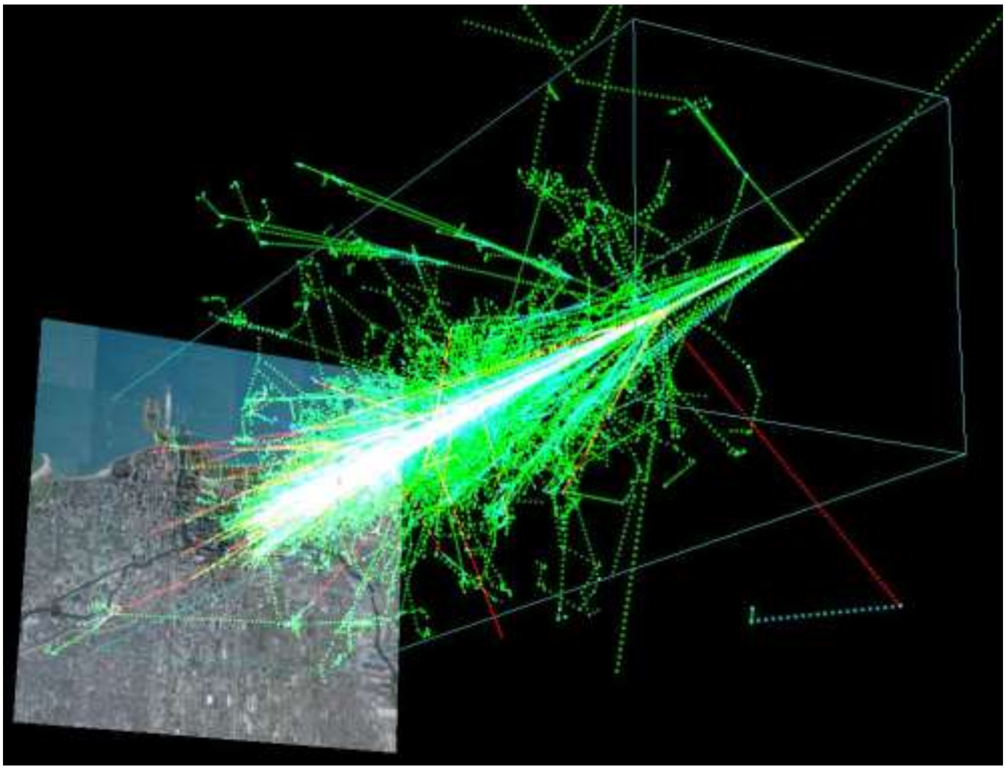
Positioning the scintillator crystals side by side, the result of the counting is practically zero, this is a sign of good temporal “resolution” of the coincidence circuit, in fact the pulses generated by the fast comparator, and used within the coincidence logic, have a duration of only about 200ns; the probability of false coincidences is therefore very low.

By positioning the crystal scintillators one above the other a count value close to the theoretical value is obtained, this value corresponds to the expected value for the cosmic ray flux on the detector surface.

The flow of particles that reach the detector (at sea level) should have the following value :

Scintillator crystal area = 32,5cm^2
32,5cm^2 x 0,01 particles/s cm^2 = 0,32 particles/s = 0,32cps

Cosmic Rays Electromagnetic Cascades



Introduction

The Earth is being continuously bombarded by high energy particles from deep space. The particles are mainly high energy protons together with a small component of helium nuclei, heavier nuclei and electrons. The energy range is enormous with some particles having energies of the order 10^{20} eV.

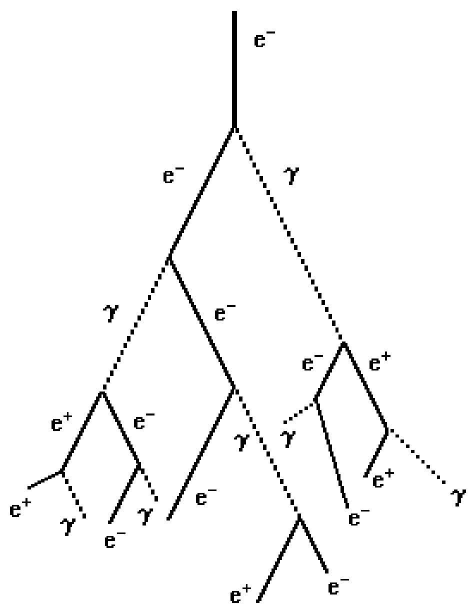
These primary cosmic rays hit the Earth at a rate of about one particle per square centimeter per second. They collide with atoms in the atmosphere and produce large showers of newly created secondary particles the progeny of which can be detected at ground level. The initial interactions in the upper atmosphere produce large numbers of charged and neutral pions. The charged pions decay into muons and muon neutrinos whereas the uncharged pions decay into **pairs of high energy photons which become the starting points of large cascades of electrons, positrons and gamma rays**. The resulting flux of particles at ground level consists mainly of these muons and electrons/positrons in the ratio of roughly 75 to 25 percent.

The muons lose their energy gradually by ionization of the material through which they pass. As they start with high energies they have the capacity to ionize many atoms before their energy is exhausted. Also, as they travel at nearly the speed of light, they tend not to ionize very efficiently and hence can travel through substantial lengths of matter, some meters of lead, before being stopped.

The process is a little different for the electrons. Theory shows that ionization of the medium is not the predominant energy loss mechanism for relativistic electrons, high energy electrons lose energy more efficiently through the emission of electromagnetic radiation as they are decelerated in the presence of matter. If ionization had been the main mechanism for slowing the electrons down then they might have had penetrative properties comparable to those of the muons, but the radioactive energy loss mechanism ensures that about 15cm of lead is sufficient to stop them.

The different energy loss mechanisms allow the sea level particle flux to be split into two main components. The penetrating muon part of the ground level flux is referred to as the 'hard' component and the easily absorbed electron part is called the 'soft' component.

Electromagnetic Cascades



The decay of a neutral pion into a pair of high energy gamma rays is the starting point of an avalanche of electrons, positrons and further gamma rays. This avalanche is known as an electromagnetic cascade. The process starts when one of the gamma rays passes close to the nucleus of an atom. Even though the gamma ray carries no electric charge its electromagnetic nature allows it to **interact with the strong electric field of the nucleus to cause the materialization of an electron-positron pair**. The energy required for pair creation is about 1 MeV, the gamma rays can have a thousand times that energy and hence the electron-positron pair produced can move on sharing nearly all the energy of the initiating gamma ray. If these fast moving electrons and positrons go on to pass close to other nuclei then they will suffer accelerations due to the positive charge of the protons. An accelerated charged particle will emit electromagnetic radiation. The intense accelerations can produce further gamma rays capable of producing more electron-positron pairs. The cycle of pair-production and gamma ray generation continues with the original gamma ray energy eventually manifesting itself as many particles. The process is shown schematically in the figure aside.

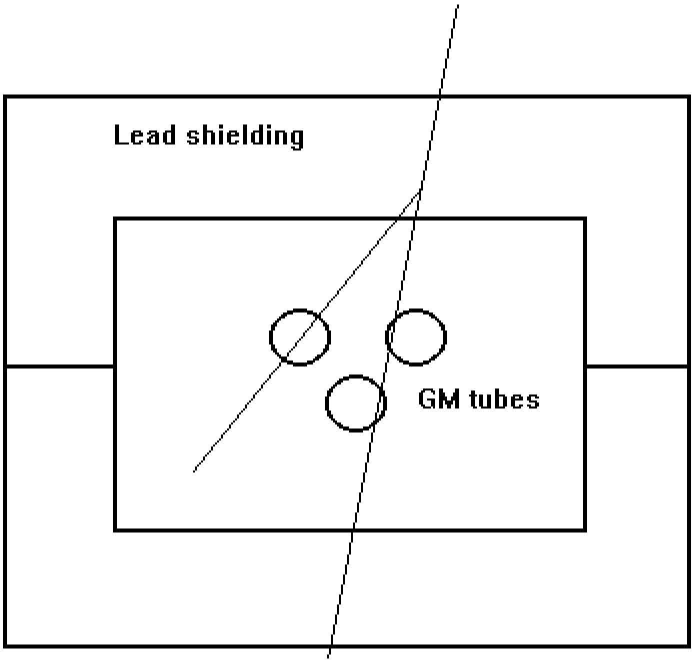
The cascade generation ceases when the shares of energy get sufficiently small such that the electrons are no longer capable of radiating efficiently; the relatively slow moving electrons are then brought to rest by ordinary ionization processes. The electron energy at which the main energy loss mechanism changes from radiation losses to ionization losses is known as the critical energy Ec. **The critical energy for electrons in lead is about 7.6 MeV**.

Whilst the electromagnetic cascade can grow over a large distance in air it is confined to much smaller regions in solids where the number of atoms per centimeters path length is greater. If the material is made up of atoms with a high atomic number then the greater nuclear charges can produce greater accelerations and so the cascade process can develop more readily than it would in a material with a lower atomic number.

Electromagnetic Cascades in Lead

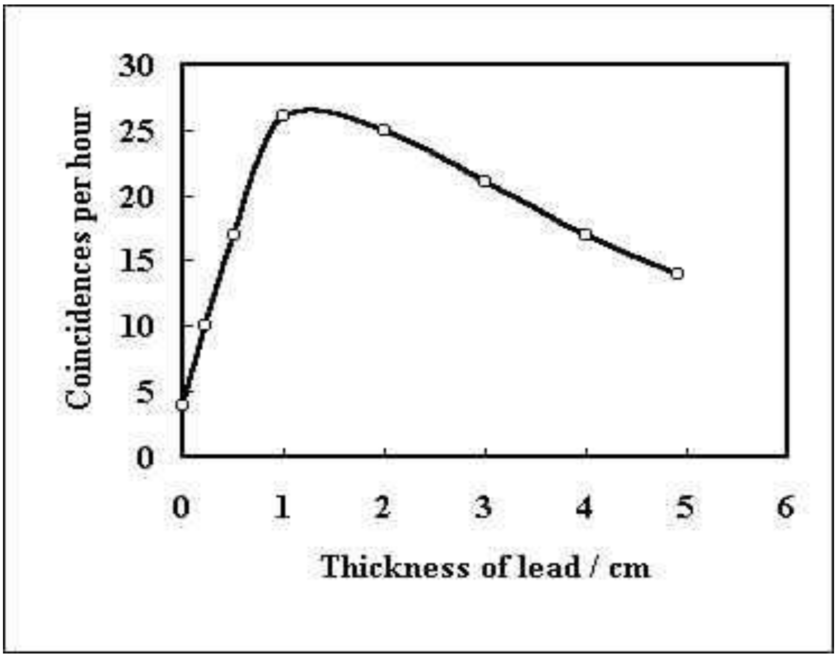
In his 1964 popular account of the historical development of the understanding of the nature of the cosmic radiation, Bruno Rossi describes the crucial experiments that led to today's picture. He recounts how, at the age of 24 in 1930, he built his own Geiger-Mueller counters and developed vacuum tube coincidence electronics to enable him to use groups of GM tubes in an investigation into the cosmic ray penetration of dense materials. **He found that a substantial proportion of the cosmic radiation detected at sea level could penetrate over 1m of lead**.

About the same time, investigators using cloud chambers reported observations of multiple tracks associated with the apparent generation of **secondary particles** close to the walls of the chamber. Rossi pursued this by using a coincidence arrangement of three GM tubes in a triangular array within a lead enclosure in order to record the generation of groups of particles. The arrangement is shown in the figure below.



A triangular arrangement was used to cut out the possibility of a single particle discharging all the counters at the same time. He was surprised to record a **high rate of coincidences**, as many as 35 per hour in some cases. When the upper part of the lead shielding was removed the coincidence rate fell to about 2 coincidences per hour. Even this lower coincidence rate was surprising since counter statistics associated with random coincidences predicted a much lower value. **The background coincidence rate can now be understood in terms of showers of particles produced in the air above the counters**.

The investigations were developed to see how the coincidence rate varied with thickness of lead placed above the counters. It was found that the rate increased steadily with thickness of lead, reaching a maximum between 1 and 2 cm then falling steadily to about half of the peak value as the lead thickness increased to about 5cm :



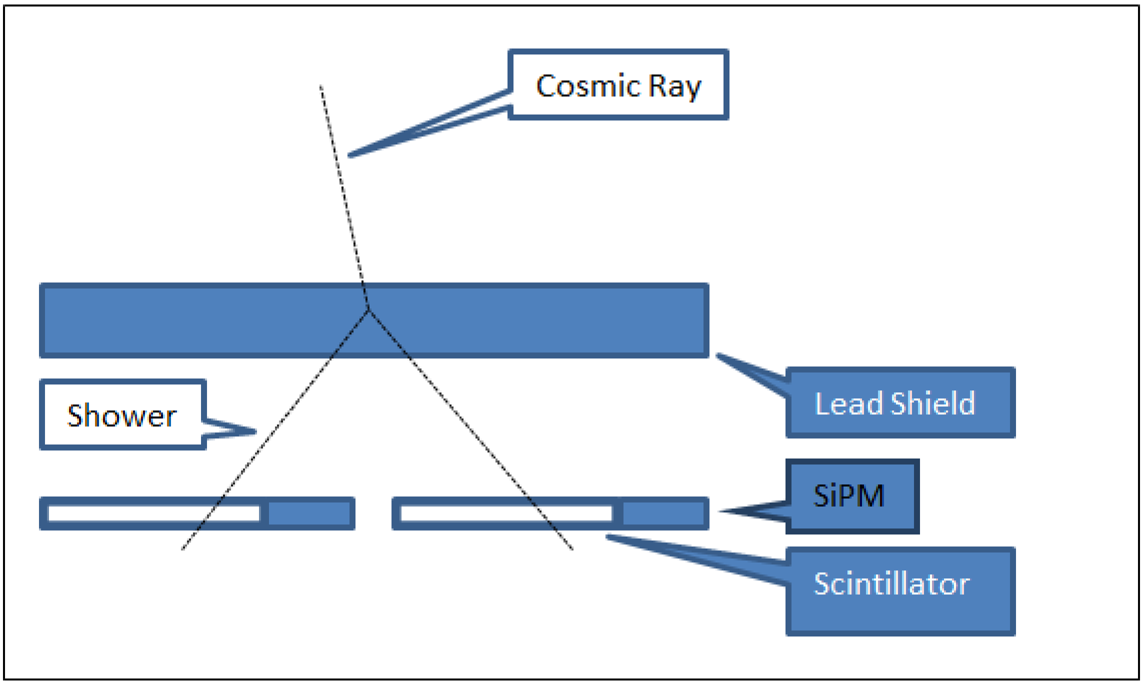
The rapid fall-off of the coincidence rate beyond the peak of the shower curve made it clear that the particles responsible for the production of the groups of particles were not the same as those capable of penetrating 1m of lead with ease.

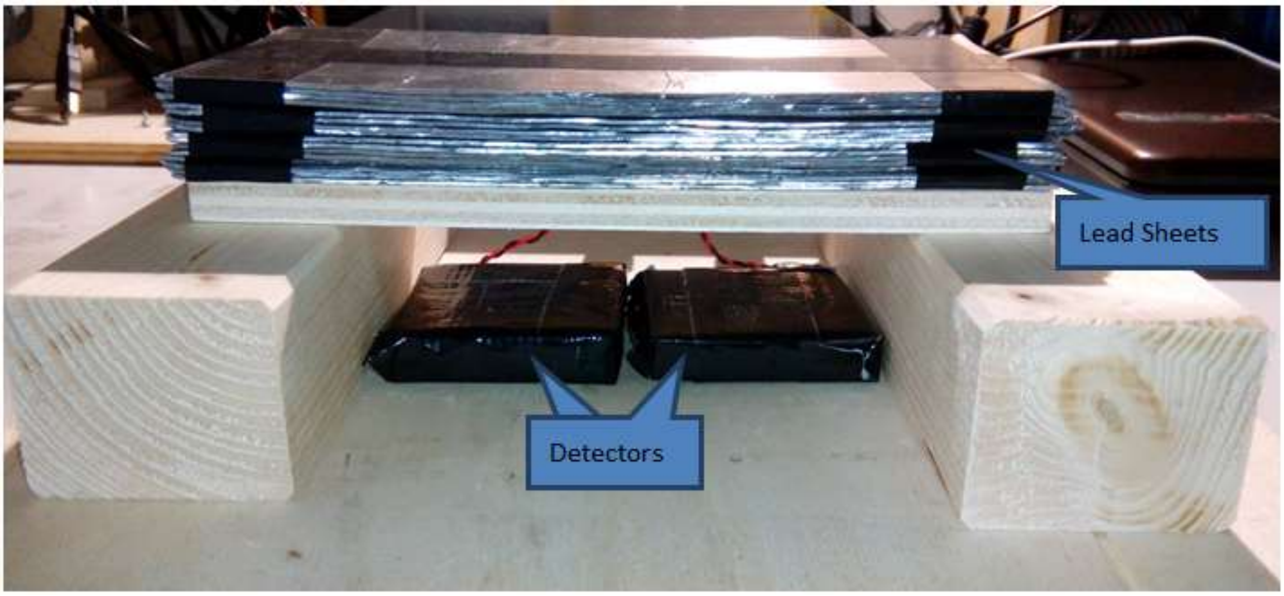
The explanation of the processes involved in electromagnetic cascades developed in the years that followed. Dirac had already predicted the existence of positrons and Carl Anderson produced cloud chamber evidence of positive electrons. In 1934, Hans Bethe and W. Heitler considered in detail what happened when a charged particle passed through the strong electric field of an atomic nucleus. They found that, at high energies, the particle is likely to release a large fraction of its energy as a photon. The picture of the deceleration induced emission of high energy gamma rays (called bremsstrahlung – or braking radiation) and the subsequent materialization of an electron-positron pair (pair production) began to develop. The theory enabled physicists to calculate the typical numbers of electrons and positrons likely to emerge below a given thickness of lead when a relativistic charged particle or a high energy gamma ray entered it from above.

The analysis of many sets of experimental data showed that the cascade theory adequately explained the features of the showers.

Reproducing Rossi's cascade experiment

Using two plastic scintillators coupled to silicon photomultiplier (SiPM) and the coincidence circuit we tried to reproduce the experiment of Rossi on electromagnetic cascades. The plastic scintillators are placed side by side, above is placed a lead screen which consists of a number of sheets with thickness of 1.2mm, the plates have been grouped in groups of 4 so as to have the lead shielding with thickness of 4.8mm. The scheme and images below describe this setup..

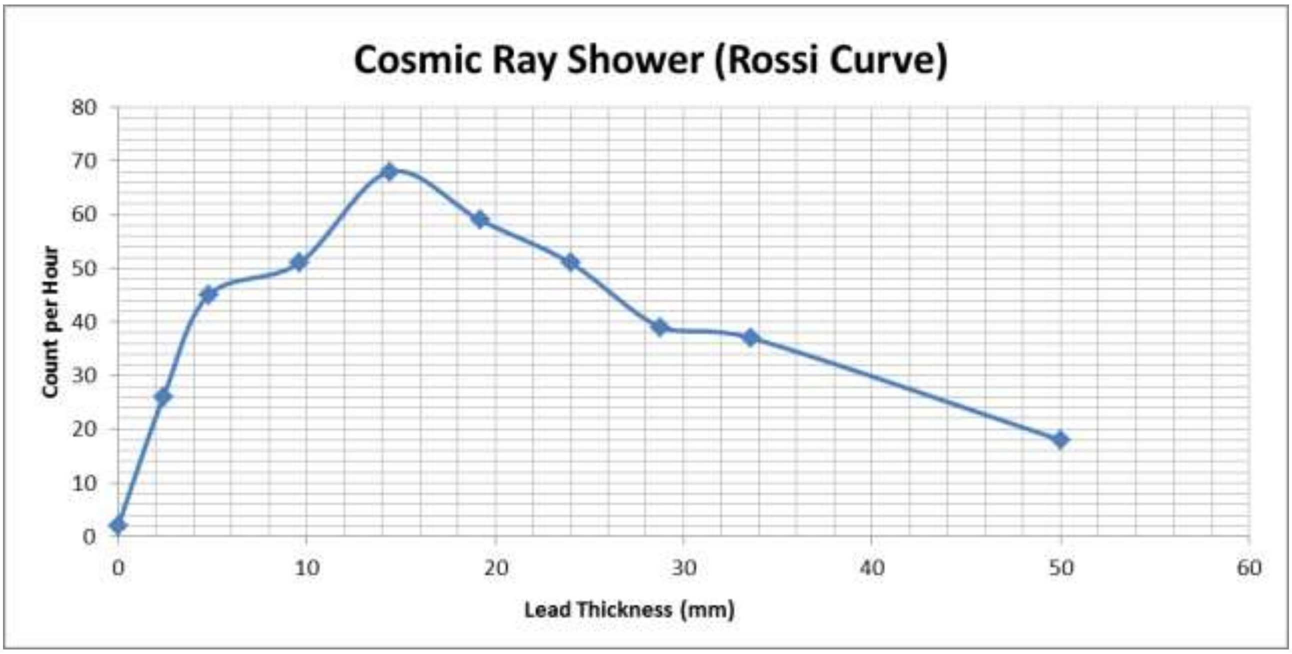




The pulses generated by the SiPM are sent to an electronic device that performs the shaping of the pulses and produces the coincidence pulse with an AND logic gate.

Results

The counting of the coincidence pulses has been done by varying the screen lead thickness from 0 to 50mm. The resulting curve is shown in the figure below :



As can be seen the agreement with Rossi curve is great and the maximum of the count is achieved for a thickness of about 15mm, the background value is low but not zero because of the cosmic showers generated into the atmosphere.

Using the theoretical model of this interaction (which is not described here) one can derive the average energy of the incident particles that give rise to electromagnetic cascade. From the experimental data obtained you get a value of about **70MeV**.