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# SiPM

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Silicon Photomultipliers for  
radiation detection

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Theremino System  
Rev.3

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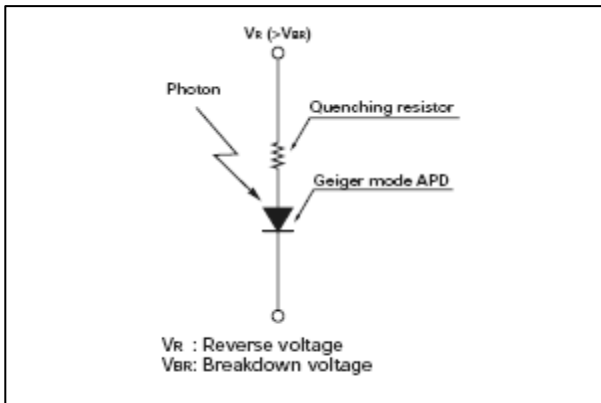
# SiPM



The silicon photomultiplier is a radiation detector with extremely high sensitivity, high efficiency, and very low time jitter. It is based on reversed biased p/n diodes, it can directly detect light from near ultra violet to near infrared, and it is employed in all those applications where low light/radiation level must be measured and quantified with high precision.

A SiPM consists of a matrix of small-sized sensitive elements called micro-cells (or pixels) all connected in parallel. Each micro-cell is a Geiger-Mode avalanche photodiode (GM-APD) working beyond the breakdown voltage ( $V_{bd}$ ) and it integrates a resistor for passive quenching.

A Geiger-Mode avalanche photo-diode is an avalanche diode biased beyond the breakdown voltage. In this way in the depleted area, there is a strong electric field enough to give a single electron the energy enough to trigger the ionization process by means of multiple collisions in an avalanche process.



it is clear that a photodiode in which the arrival of a photon has triggered the avalanche process, has no opportunity to appreciate the arrival of a second photon. It is necessary therefore a process that stops the avalanche, lowering the electric field at the ends of the depletion region to a value such as not to allow more multiplication by impact of the electrons. The reverse bias voltage returns below the value of breakdown for a certain period, said time of "hold-off". During this time interval, the device cannot detect the arrival of photons. To improve the efficiency of the photodiode it is necessary that this

blind time is as small as possible. This involves the use of a quenching circuit. The simplest quenching circuit consists of a resistor in series at the junction of the photodiode.

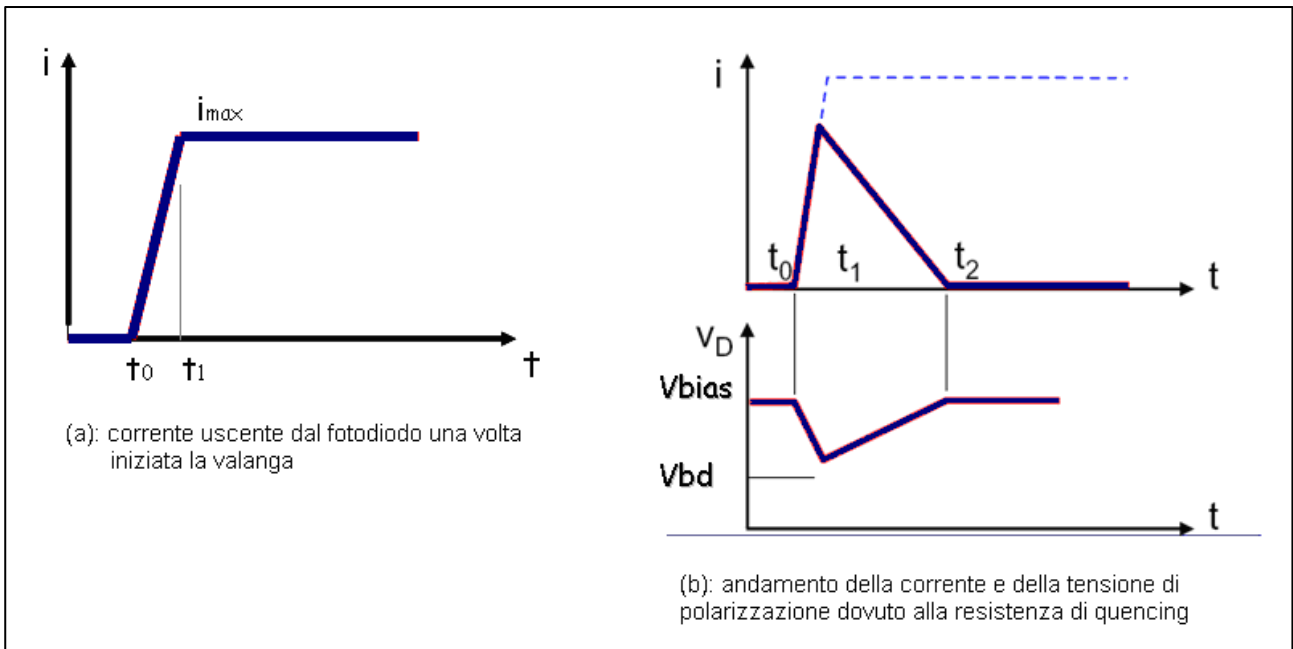
Commonly, the active area of the SiPM is of a few square millimeters. Depending on the model, the number of pixels can vary between a hundred and a few thousand and each of them is constituted by a square cell of side lies between 25  $\mu\text{m}$  and 100  $\mu\text{m}$ . The various pixels are separated from each other by a thin layer of insulating material. Considering that on average a cell is struck by a single photon, it is possible to derive the number of incident photons by the number of activated cells.

The SiPM have advantages such as low voltage operation, insensitivity to magnetic fields and a very high gain:  $G = 100,000$  to  $1,000,000$ .

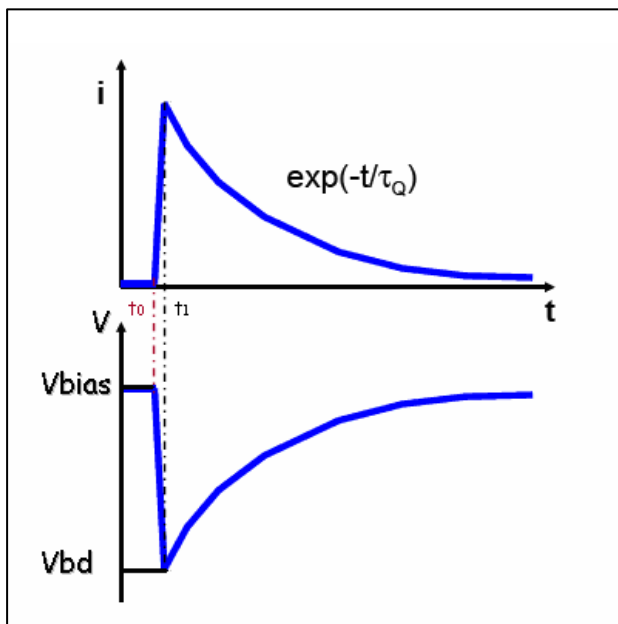


## Main features of SiPM AdvanSiD NUV 4x4

- 4x4 mm<sup>2</sup> detection area
- 40  $\mu\text{m}$  micro-cells, 60% fill-factor
- Low dark count rate
- NUV-SiPMs: 420 nm peak sensitivity
- Gain temperature stability < 1 %/°C
- MR compatible



Trend of the current and bias voltage as a function of the resistance of quenching



Trend of the current and voltage for a pulse produced by a SiPM. The rising edge is very fast, on the order of 10ns. The falling edge depends on the capacity of the junction and the resistance of quenching, and that is in the order of 100ns.

The SiPM has to be biased with a voltage  $V_{bias}$  greater than the voltage  $V_{bd}$  (Breakdown voltage). The value of the "overvoltage" ranges from 2 to 4 V. The  $V_{bd}$  has a value of about 28V, it follows that the bias voltage has a value ranging from 28V to 32V.

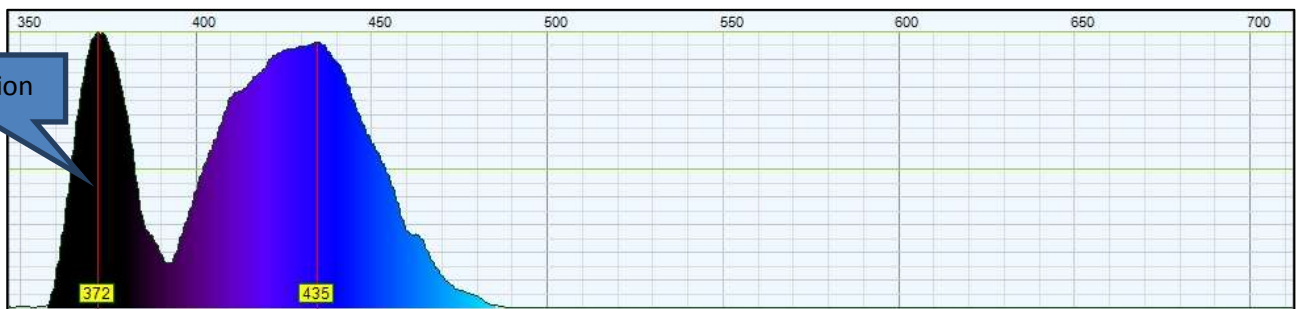
- $V_{bd} = 28V$**
- $V_{ov} = 2-4V$**
- $V_{bias} = 30-32V$**

The SiPM have a significant noise, called "dark current". The phenomenon of dark current is explained by the spontaneous generation, by thermal effect, of electron-hole pairs in the depleted region. This is due to the presence of centers of generation-recombination that have an energy level place approximately in the middle gap between the valence band and the conduction band. The presence of recombination centers arises from imperfections in the crystal lattice that introduce energy levels within the gap.

## LYSO Scintillation Crystal



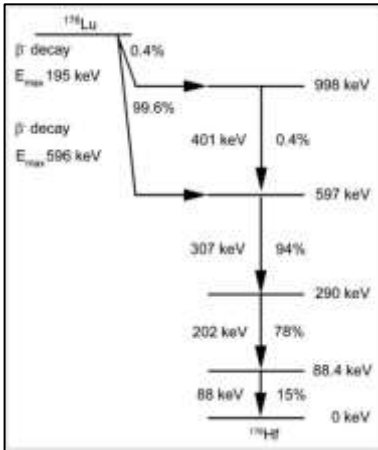
Lutetium-yttrium oxyorthosilicate, also known as LYSO, is an inorganic chemical compound with main use as a scintillator crystal. Its chemical formula is  $\text{Lu}_2(1-x)\text{Y}_2\text{xSiO}_5$ . It is commonly used to build electromagnetic calorimeters in particle physics. LYSO crystals have the advantages of high light output and density, quick decay time, excellent energy resolution.



Fluorescence spectrum of a scintillator LYSO crystal excited by UV emission from a “wood” lamp. Emission peak at about 430nm

### Physical Properties Of LYSO crystal

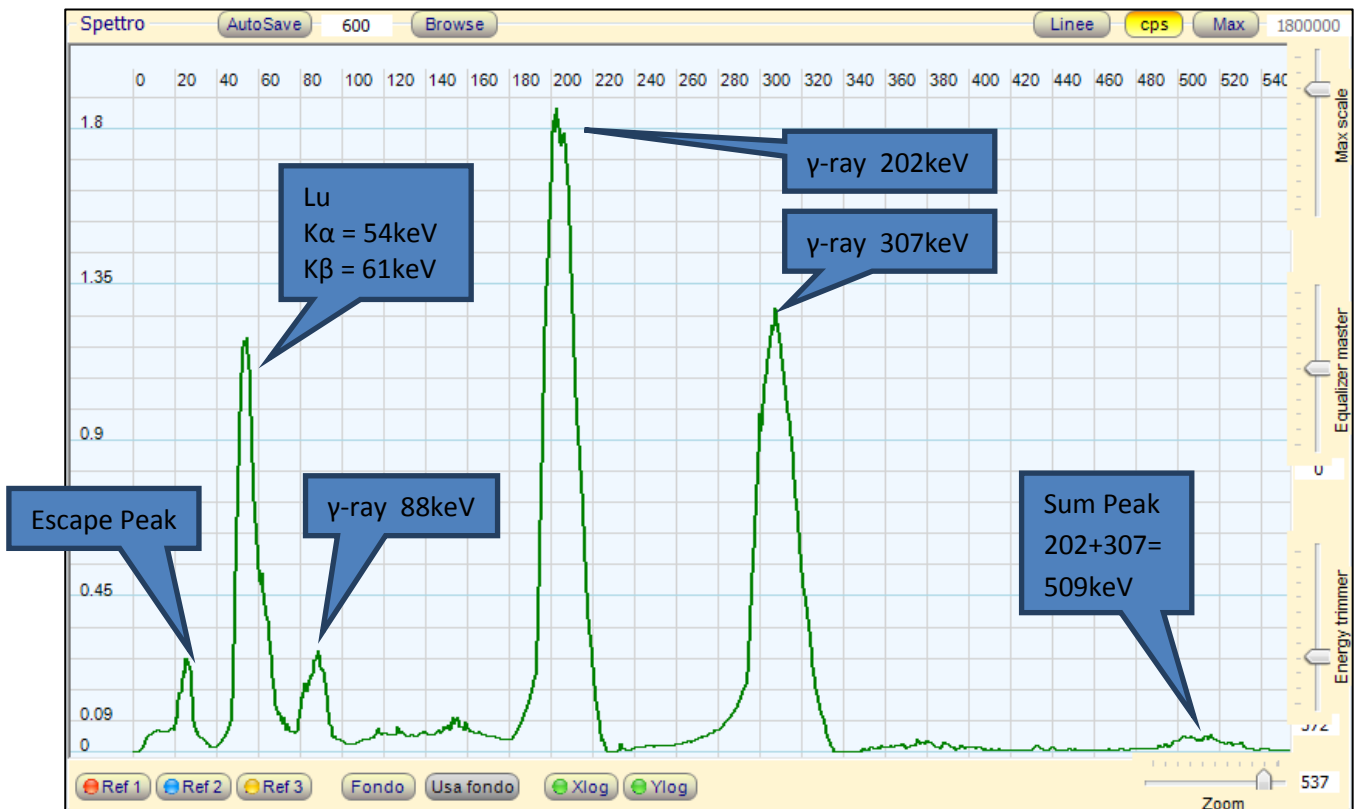
Density (g/cm <sup>3</sup> )	7.4
Effective Atomic Number	66
Radiation Length (cm)	1.10
Decay Constant (ns)	40-44
Peak Emission (nm)	428
Light Yield (Relative BGO=100%)	190
Index of Refraction	1.82
Peak excitation (nm)	375
Radiation Hardness (rad)	>10 <sup>6</sup>
Melting Point (°C)	2050
Hardness (Mohs)	5.8
Cleavage	None
Hygroscopicity	No



LYSO crystal contains the element **lutetium** which is composed by two isotopes, but only one is stable,  $^{175}\text{Lu}$  (natural percentage 97,41%) while the other,  $^{176}\text{Lu}$  is a beta emitter and it decays with half-life of  $3,78 \times 10^{10}$  years (2,59% natural percentage).

In the image is shown the beta decay chain of lutetium  $^{176}\text{Lu}$ .

Due to the content of Lutetium, the crystal LYSO appears to be weakly radioactive.

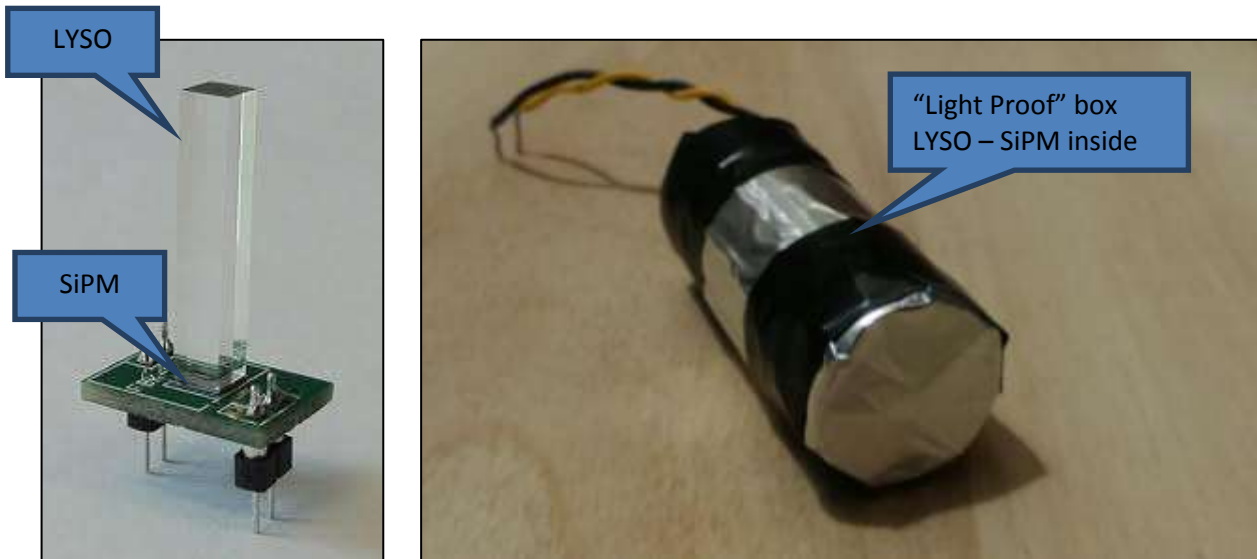


**Gamma emission spectrum of a LYSO scintillator crystal**

**Scintillation Probe – NaI(Tl) 25.4x25.4mm crystal -PMT R6095 Hamamatsu - Lead Shielded Measure**

In the gamma spectrum are evident the photo peaks at 88keV, at 202keV and at 307keV. In the spectrum are also visible X emissions from Lutetium and a sum peak at 509keV. This set of gamma emissions, which extend from 50keV to 500keV, produce a non-negligible background that it is not possible to shield and therefore make the LYSO crystal less suitable for spectrometry applications of weakly radioactive sources.

## Gamma Detector with LYSO crystal



The crystal LYSO and the SiPM are coupled as shown in the first image to the left, using an “optical glue” to stick the crystal to the surface of the sensor. In the picture you cannot see, but the crystal LYSO was wrapped with white Teflon tape (see picture on the previous pages) in order to increase the reflectivity and thus efficiency.

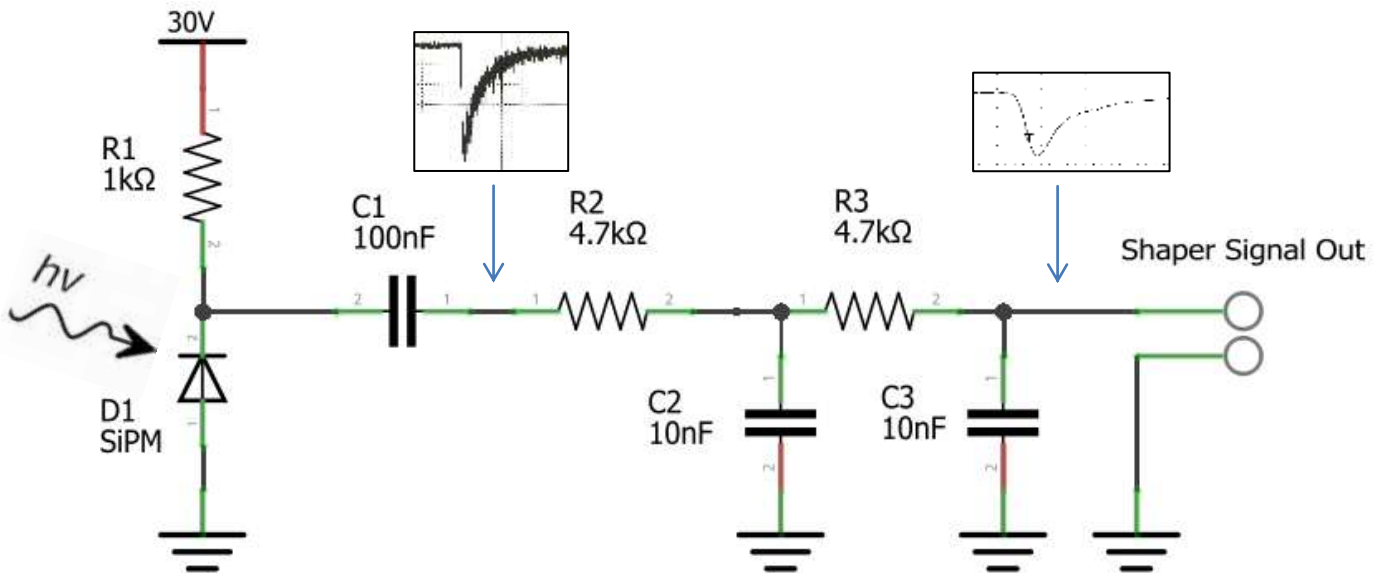
SiPM and LYSO were then inserted into a plastic tube covered with tape and aluminum tape, so as to ensure the seal to light.

Inside the plastic tube some foam has been inserted in order to keep the crystal in position on the front window and protect the sensor from accidental impact.

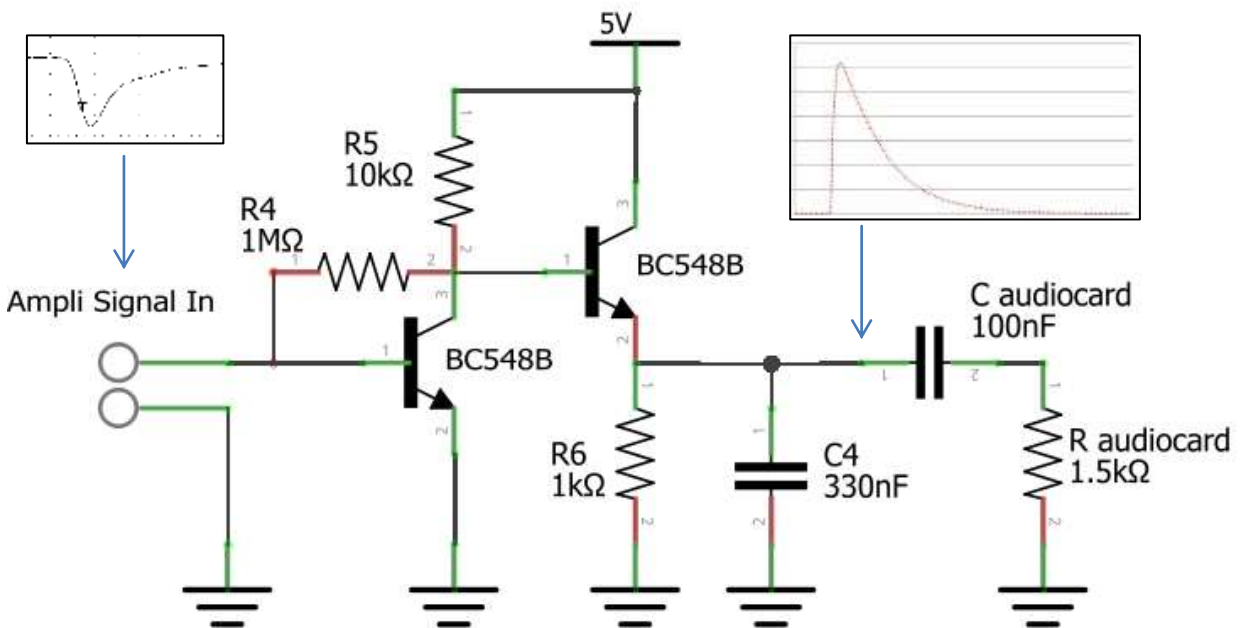
## SiPM Adapter

The signal produced by SiPM is very short and small scale (50-100mV). To be acquired by the sound card of Theremino MCA it must be properly shaped and subsequently amplified.

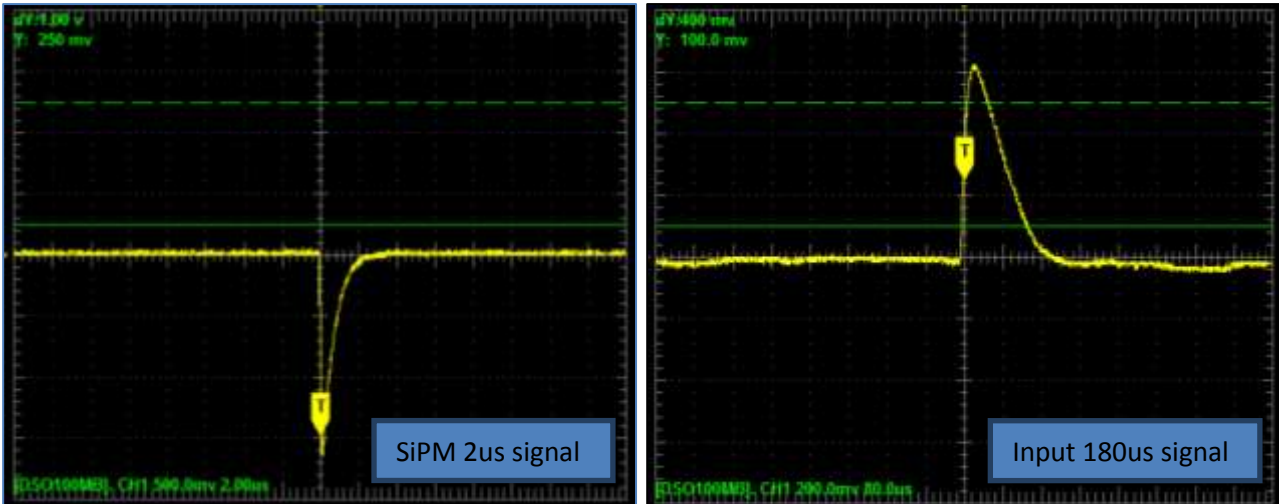
The first stage of the SiPM adapter is constituted by the bias and extraction circuit of the pulse. The load resistance R1 is set to Vbias, while the anode of the SiPM is connected to ground, this allows to obtain negative pulses, so that, after the reversal produced by the amplification stage, they turn positive to be sent to the audio card.



The two low-pass cells R2C2 and R3C3 are intended to lengthen pulse until 100-200usec and round off the tip so that during the subsequent sampling of the ADC of the sound card is easier to determine the peak value of the pulse . However, after the "shaper", the pulse has very low amplitude thus an amplifier stage is needed.







### Output pulses from SiPM and after the amplification stage

The amplitude value and the duration of the output signal depend on several factors:

- **Vbias** : increasing Vbias (28-32V) also increases the amplitude of the output signal. From tests carried out it has been seen that, for a value of around 30V the best results in terms of energy resolution are obtained.
- **R1** : this resistor converts the current pulse in a voltage pulse. Setting it too high could drive the amplification chain in saturation. Low values (50ohm) allow us to obtain very short pulse durations. In our case it is convenient to raise R1 just to stretch the pulse.
- **C2, C3** : increasing the value of these capacitors the amplitude of the signal falls and the duration increases.
- **R5** : the value of this resistor determines the gain of the amplification stage.

The values of the components present in the schemes allow to have an energy range more or less corresponding to real values.

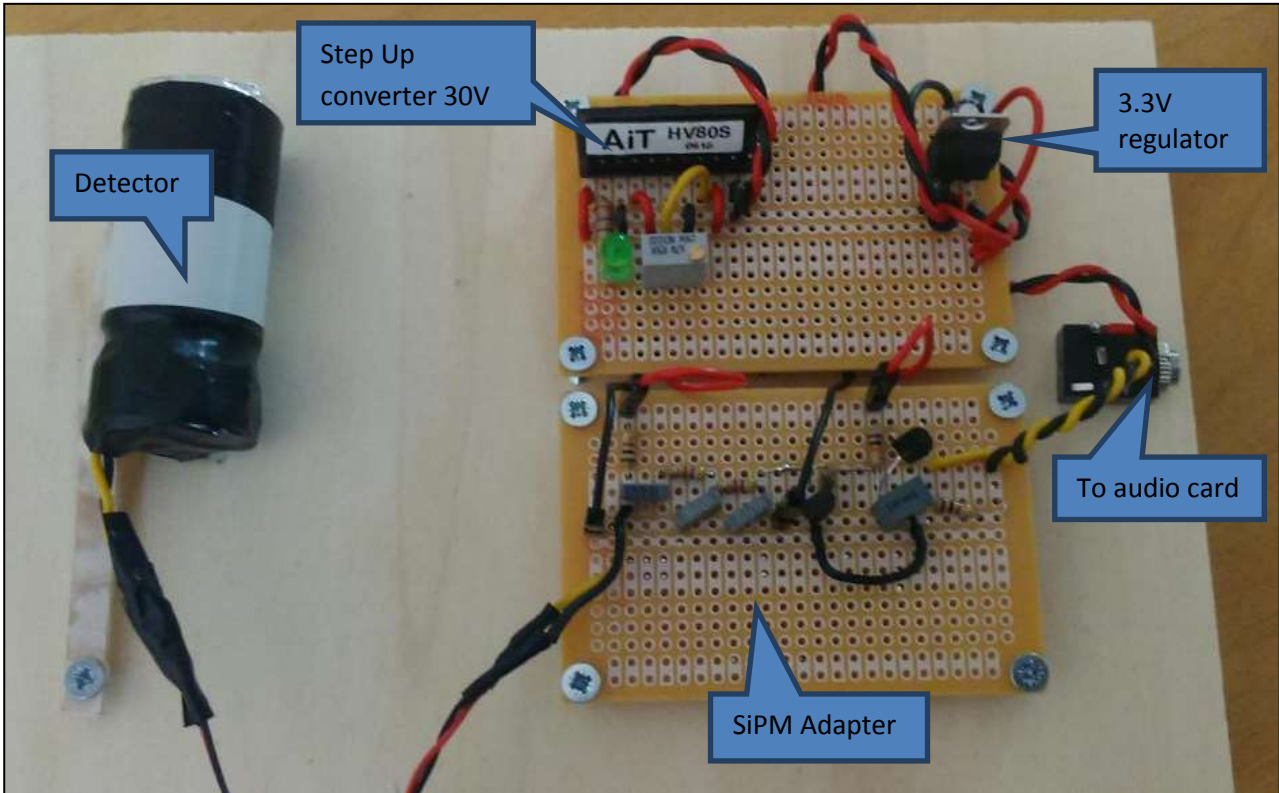
For calibration, you may want to vary the voltage Vbias within the range 29-31V, while fine tuning is done within the application Theremino MCA.

Particular care should be made in the control of noise / ripple present in the power voltage of the shaper (30V) and the amplifier (5V). For good results the final noise should not be higher than 1mv.

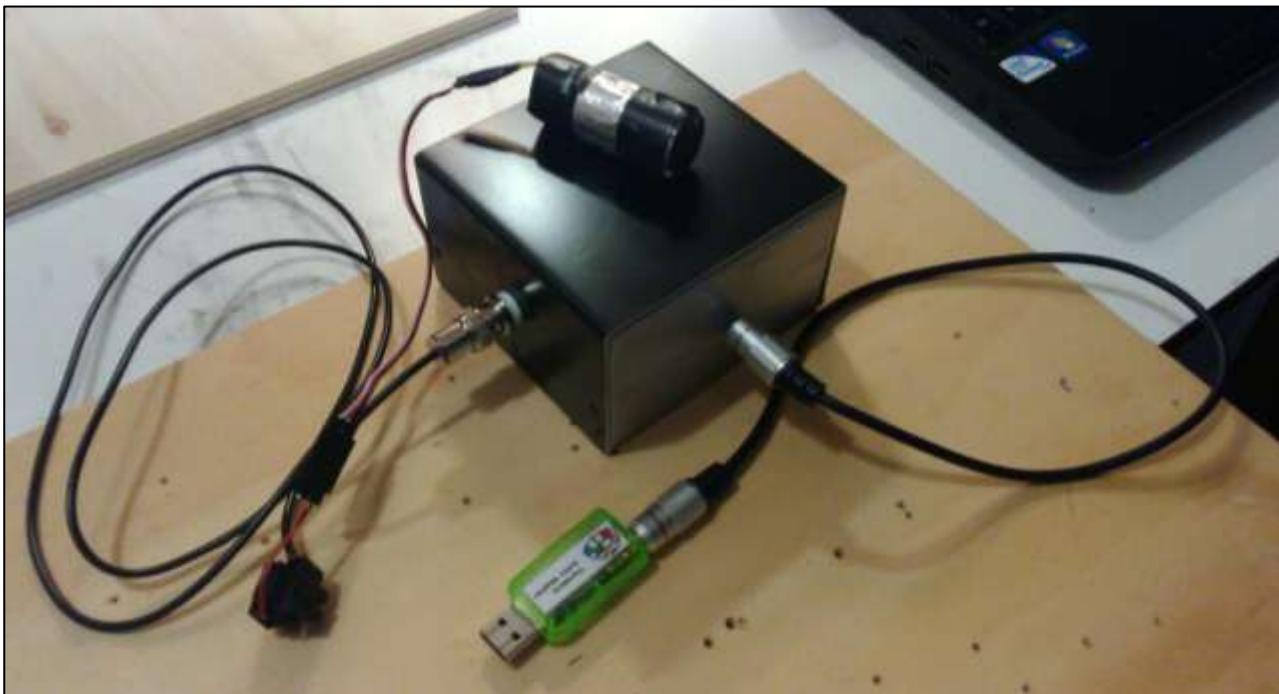
Batteries could also be used to get the required voltages.



**“Low noise” 30V power supply**



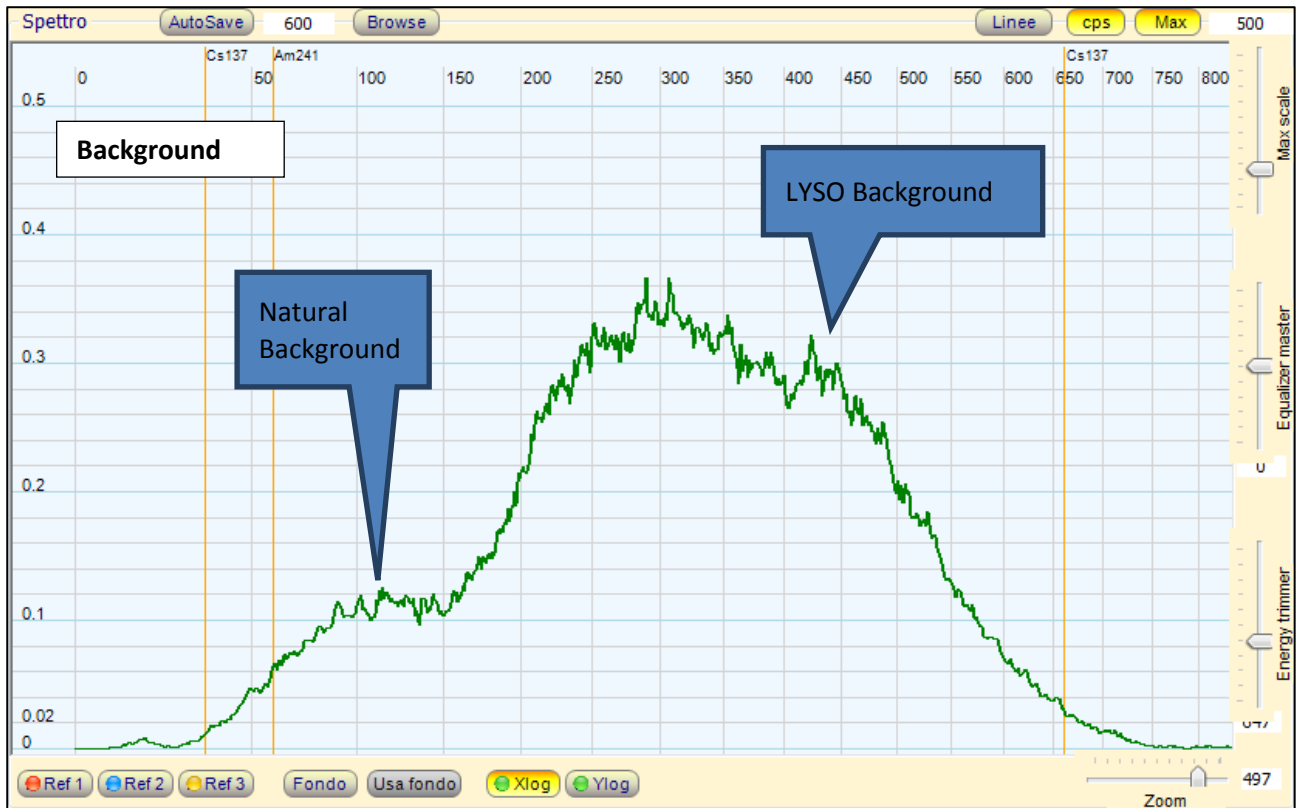
Gamma spectrometer with SiPM LYSO detector, SiPM Adapter and power supply



SiPM prototype Gamma Spectrometer with USB audio card

# Gamma Spectra with LYSO

## Background

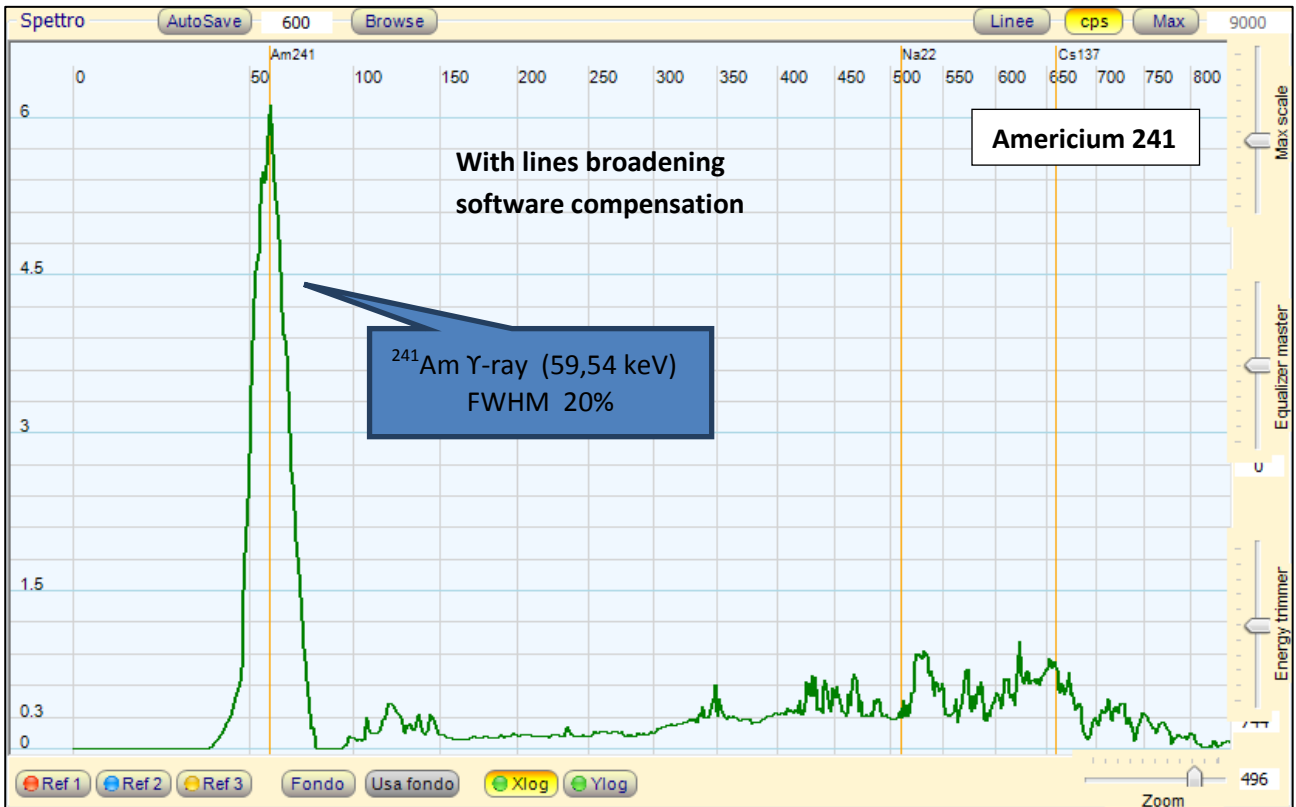
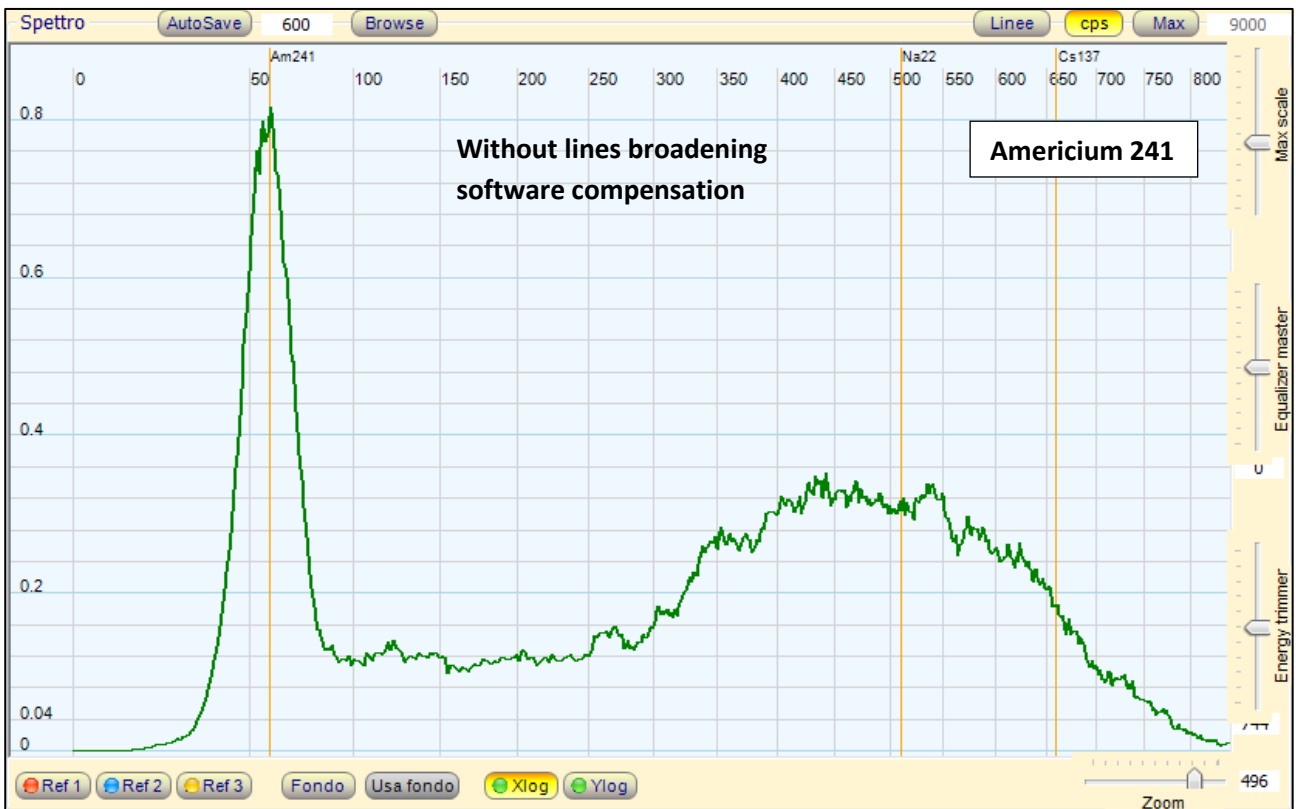


## Background Gamma Spectrum – SiPM and LYSO

The spectrum of background includes natural background radiation and the contribution of the natural radioactivity of the crystal LYSO due to content in Lutetium.

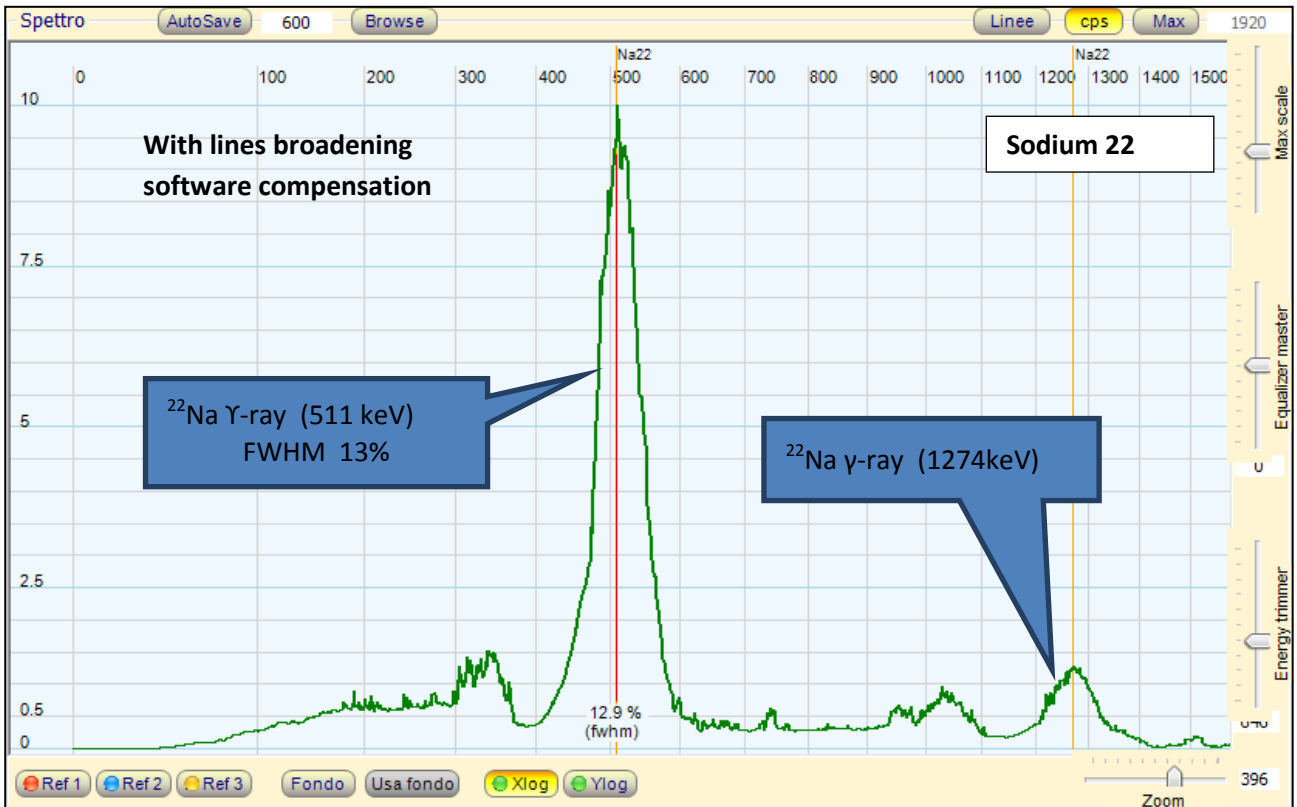
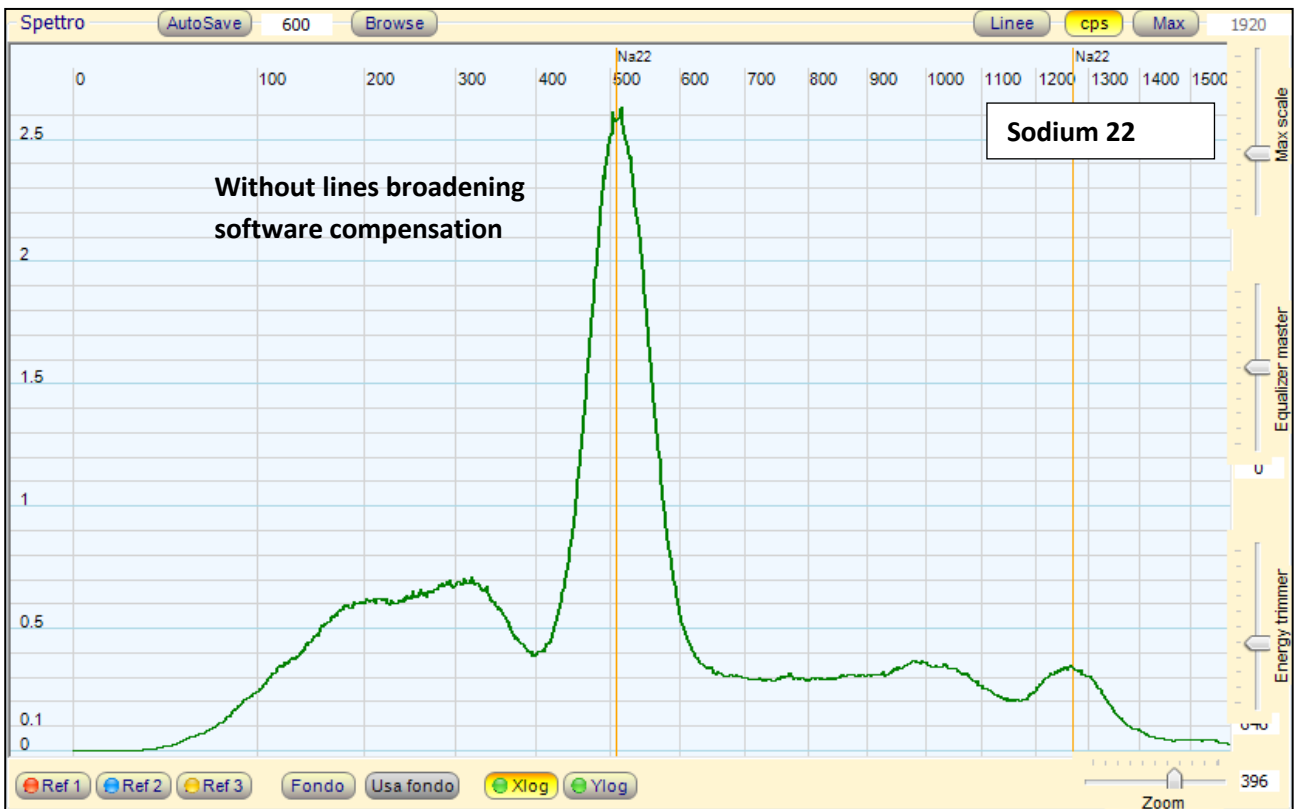
The part of the background radiation has its maximum in the range between 100 and 150keV, while the part due to the crystal LYSO is mainly comprised between 200 and 500 keV.

# Americium 241



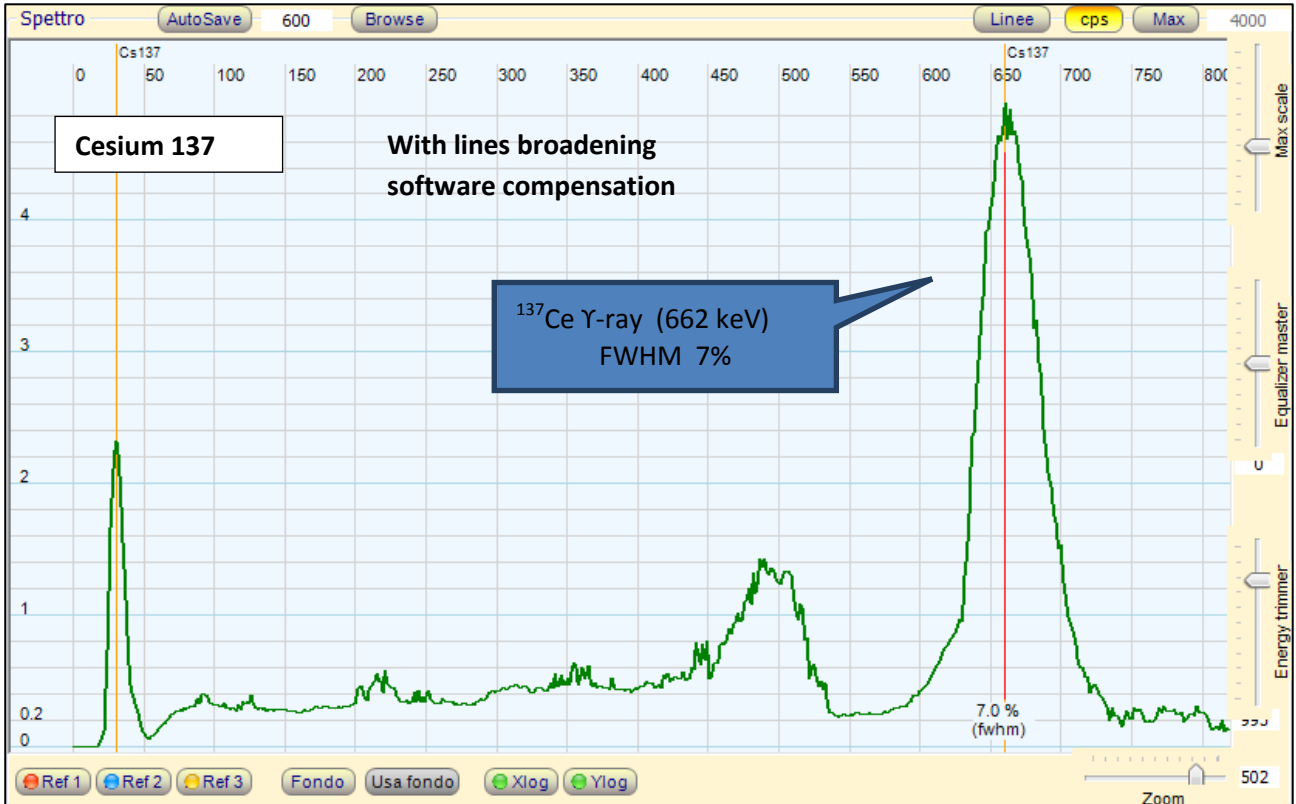
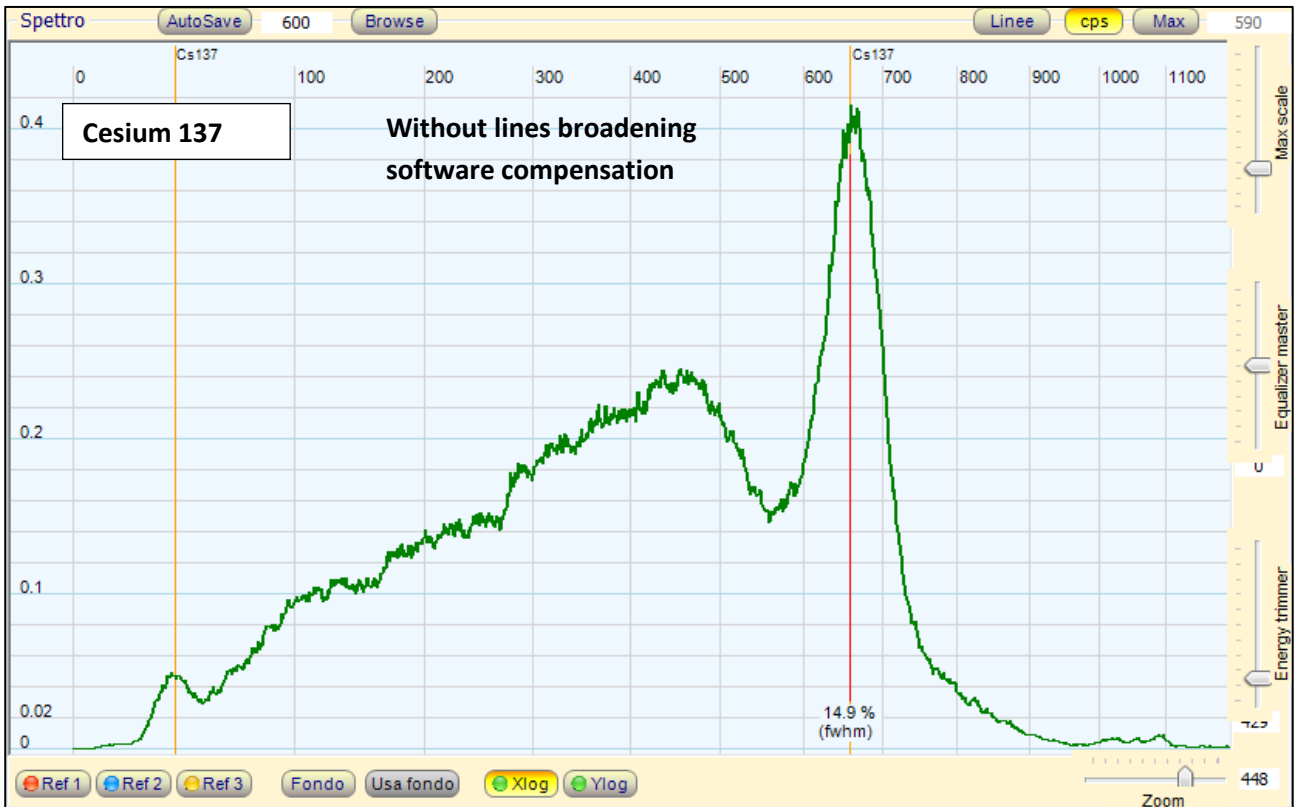
0.9uCi  $^{241}\text{Am}$  – Americium Gamma Spectrum – SiPM and LYSO

# Sodium 22



1uC  $^{22}\text{Na}$  Gamma Spectrum – SiPM and LYSO

# Cesium 137

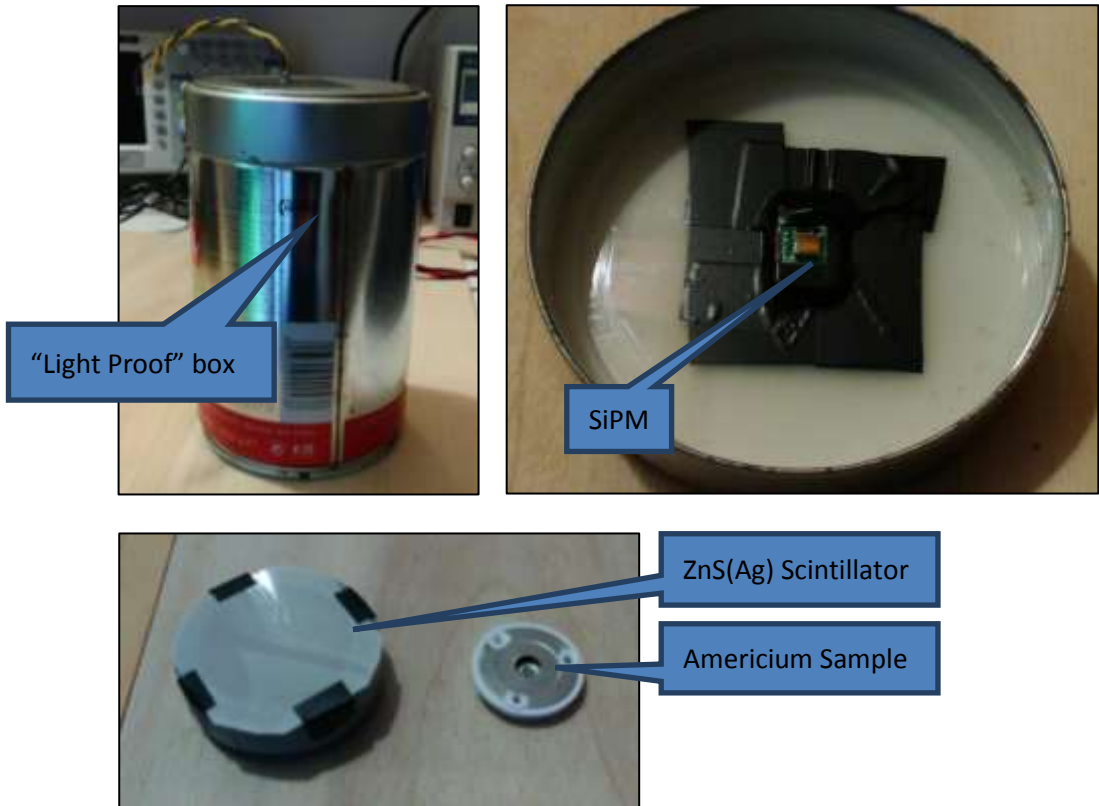


0.25 $\mu\text{C}$   $^{137}\text{Ce}$  – Cesium Gamma Spectrum – SiPM and LYSO

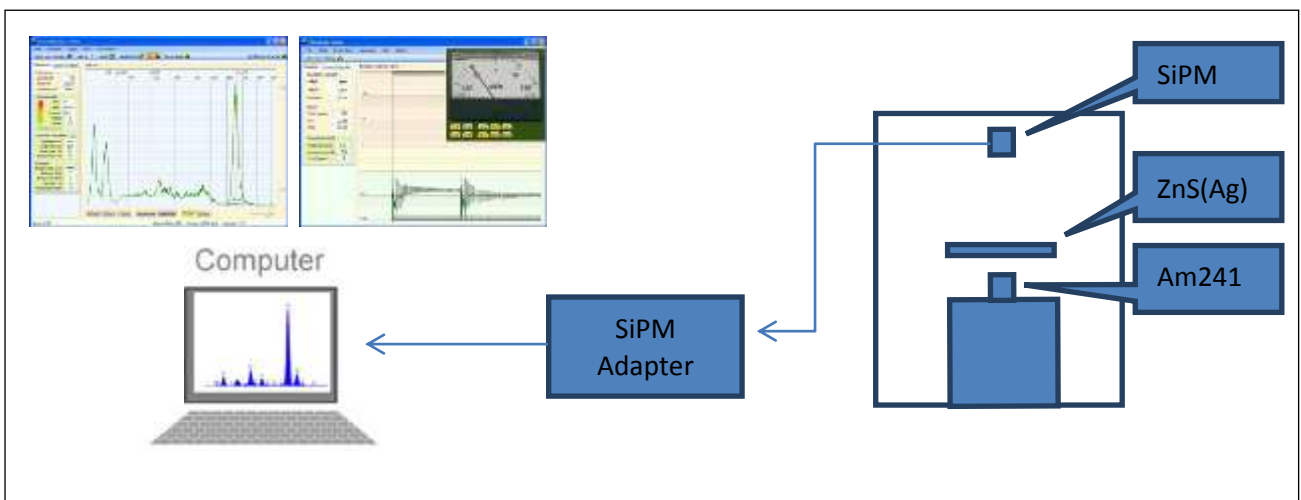


# Alpha Scintillation Detector

Americium <sup>241</sup>Am with ZnS(Ag) Scintillation screen



As another example of application of the SiPM, a simple alpha scintillation probe has been realized. The probe is based on a screen of ZnS (Ag). As alpha source the classic source of 0,9uCurie <sup>241</sup>Am has been utilized. Alpha source and scintillator screen were placed inside a cylinder of aluminum airtight and light-tight, the silicon photomultiplier was fixed on the cap of the cylinder. The SiPM has been connected to the SiPM adapter, already described in a previous paragraph, the signal is acquired by the adapter and sent to the sound card. The program Theremino MCA / Theremino Geiger make the counting.



The signal that is acquired by the sound card and sent to Theremino MCA is very low in amplitude, slightly above the noise level, however, it is enough to be recognized by Theremino MCA and counted by Theremino Geiger.

To maximize the signal, the alpha source, the screen ZnS (Ag) should be placed as close as possible and in correct axis.

The bias voltage of the SiPM is then adjusted in the range 28V-32V in order to maximize the signal / noise ratio and the counting rate.

The counting result is shown in the Theremino Geiger screenshot below, with a value of about **700 CPM**.





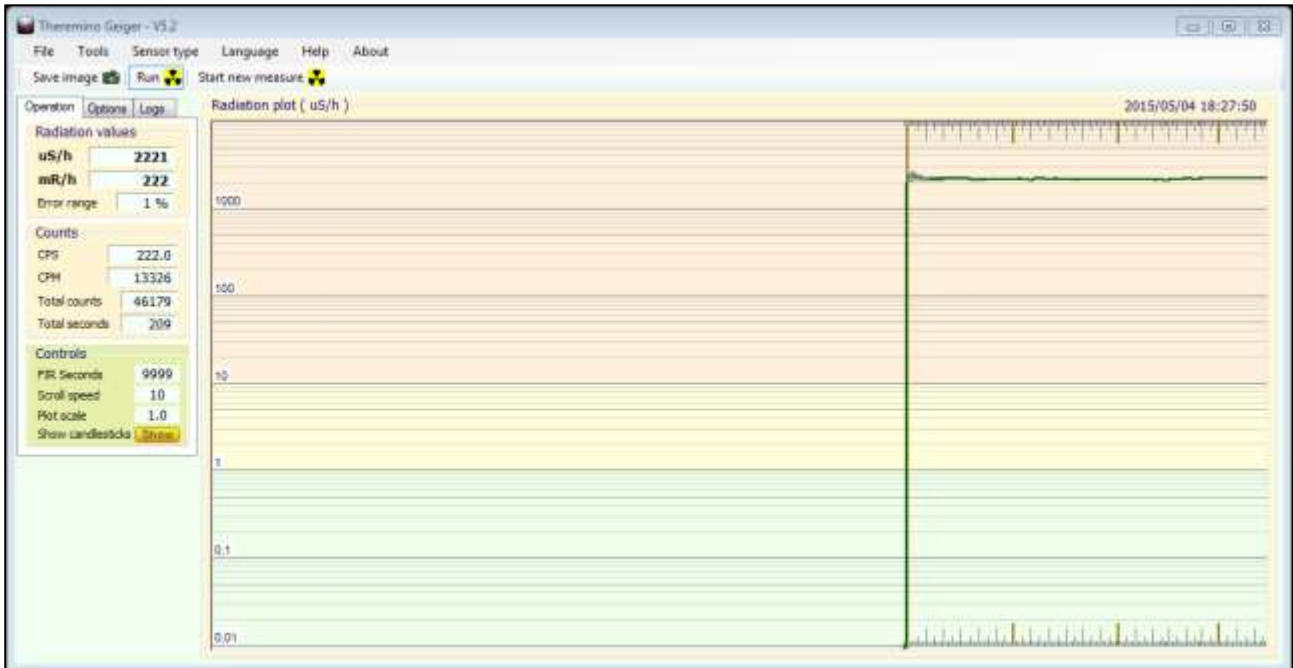
## Radium $^{226}\text{Ra}$ - luminous paint



The watch hands have on the surface a luminescent paint based on radium and zinc sulphide which acts as a scintillator.

The alpha scintillation probe based on the SiPM can be used to perform the counting of the scintillation events that occur on the surface of the watch hands. The container with the watch hands is placed inside the casing, close to the SiPM sensor.

The counting result is shown in the Theremino Geiger screenshot below, with a value of about **13000 CPM**.



## SiPM LYSO Gamma Detector

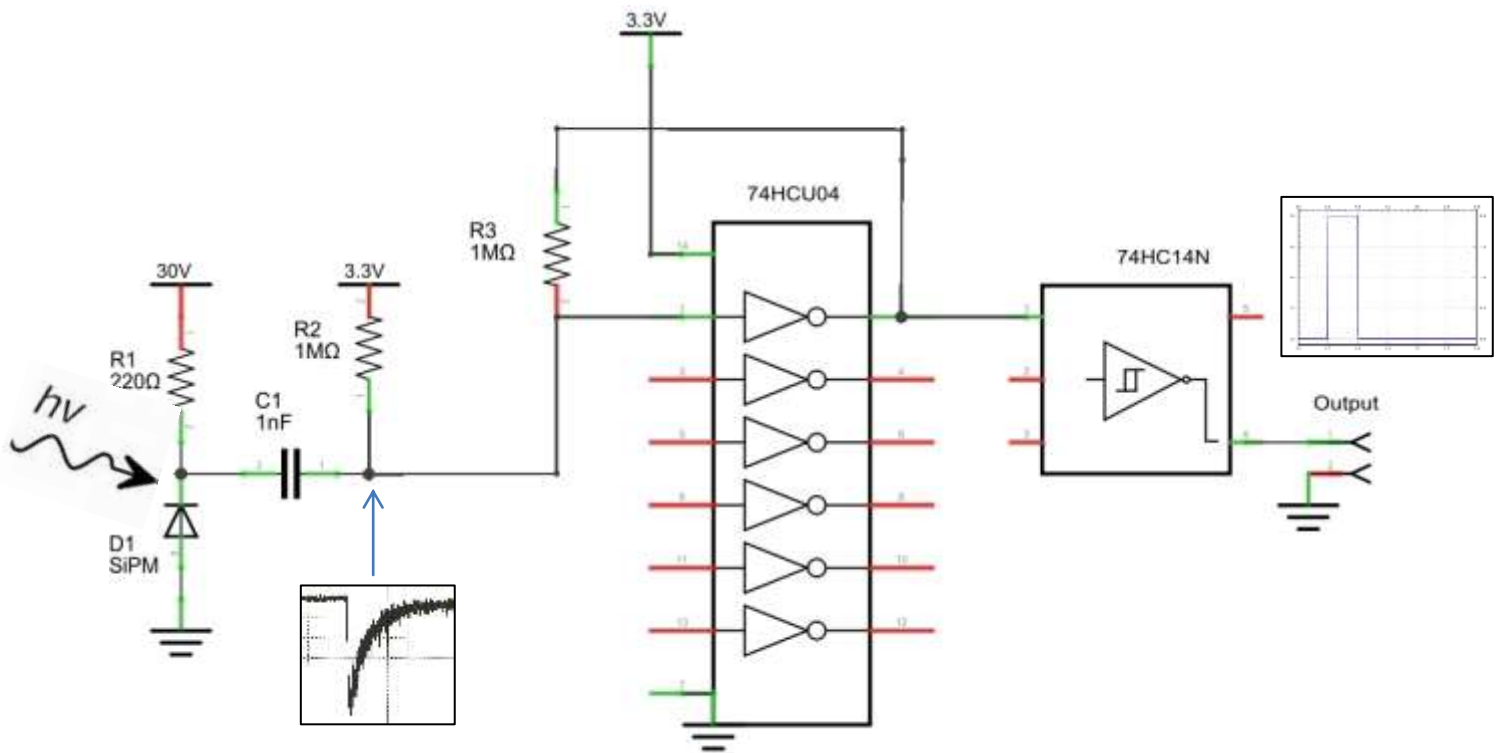
In order to use SiPM + LYSO as gamma detector it is better to keep the pulse signal as short as possible. One resistor of 47ohm and a capacitor to extract the signal of 1nF are a good compromise which allow to obtain pulses of about 200mV and about 200ns long.

These pulses are amplified with a not-buffered CMOS inverter with 100kohm resistor as a feedback. The amplified signal are squared by other two inverter CMOS which act as triggers.

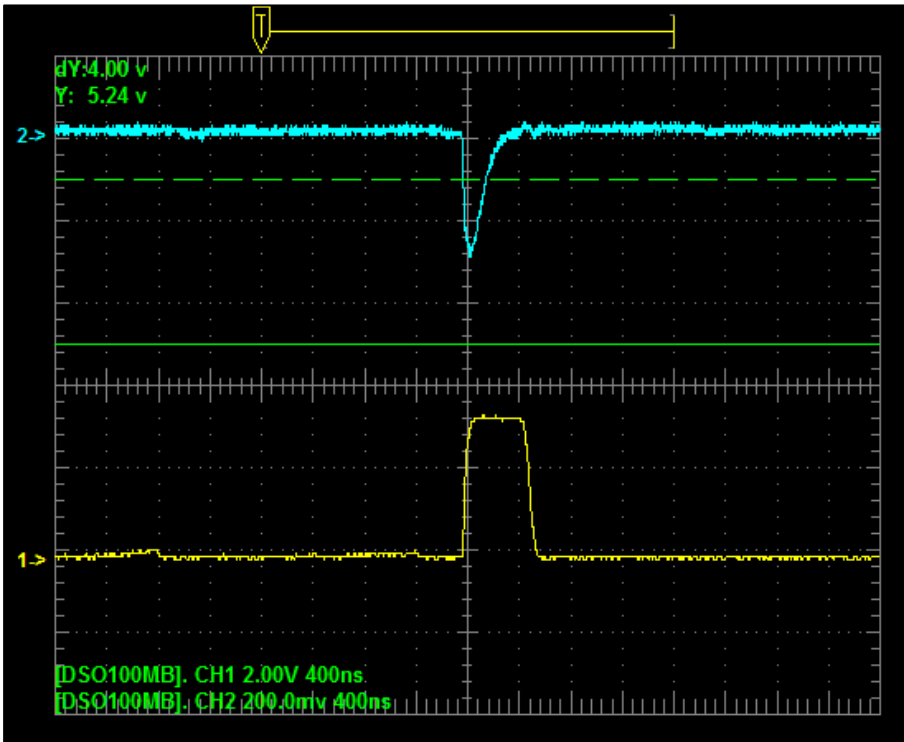
A positive CMOS signal of 3,3V and duration of about 400ns is obtained.

The CMOS inverters have been chosen because of their high speed compared to standard Op Amp and because they do not need special double voltage power supply

A couple of detectors can be managed with this circuit.

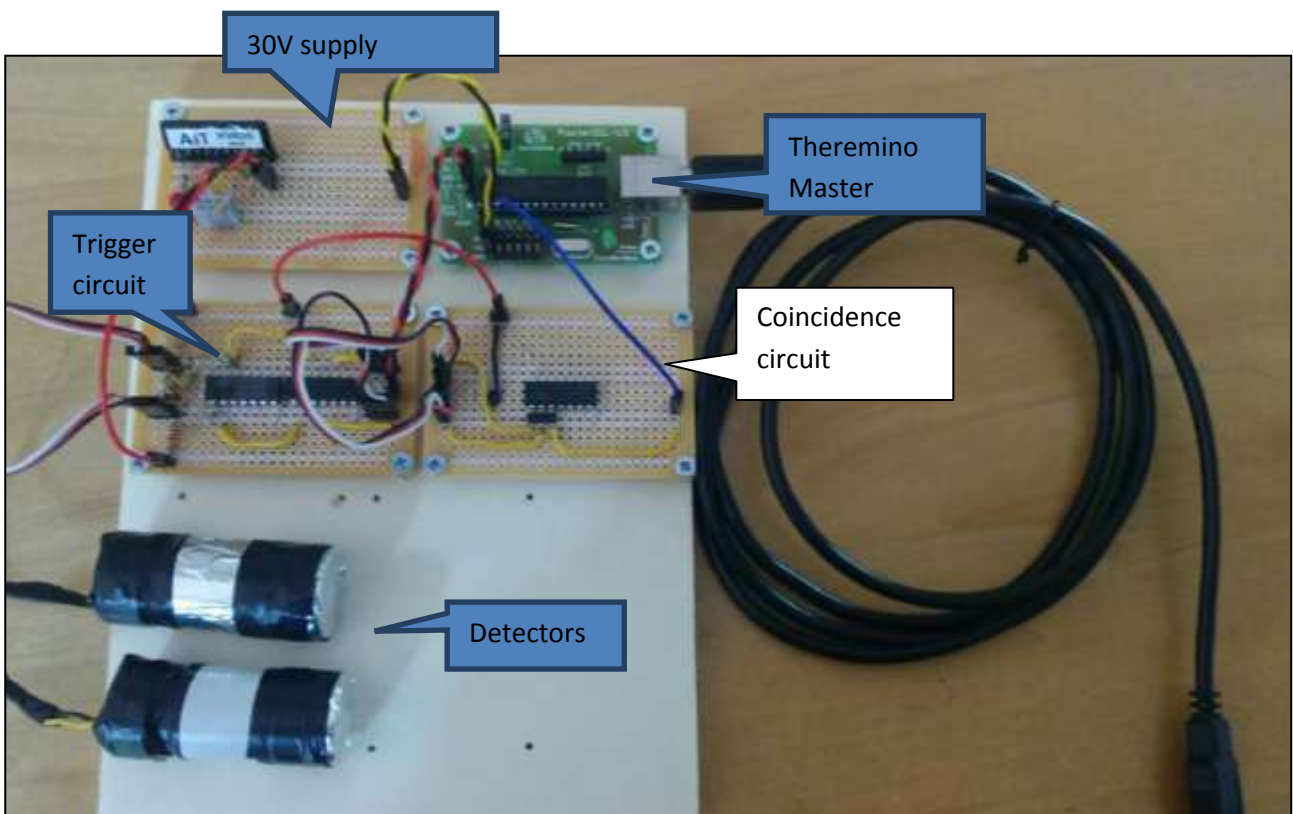


The output pulses are sent to a Theremino Master Module, the PIN has to be configured as “Fast Counter” in order to perform the counting operations.



The upper line shows a SiPM pulse of about 200ns.

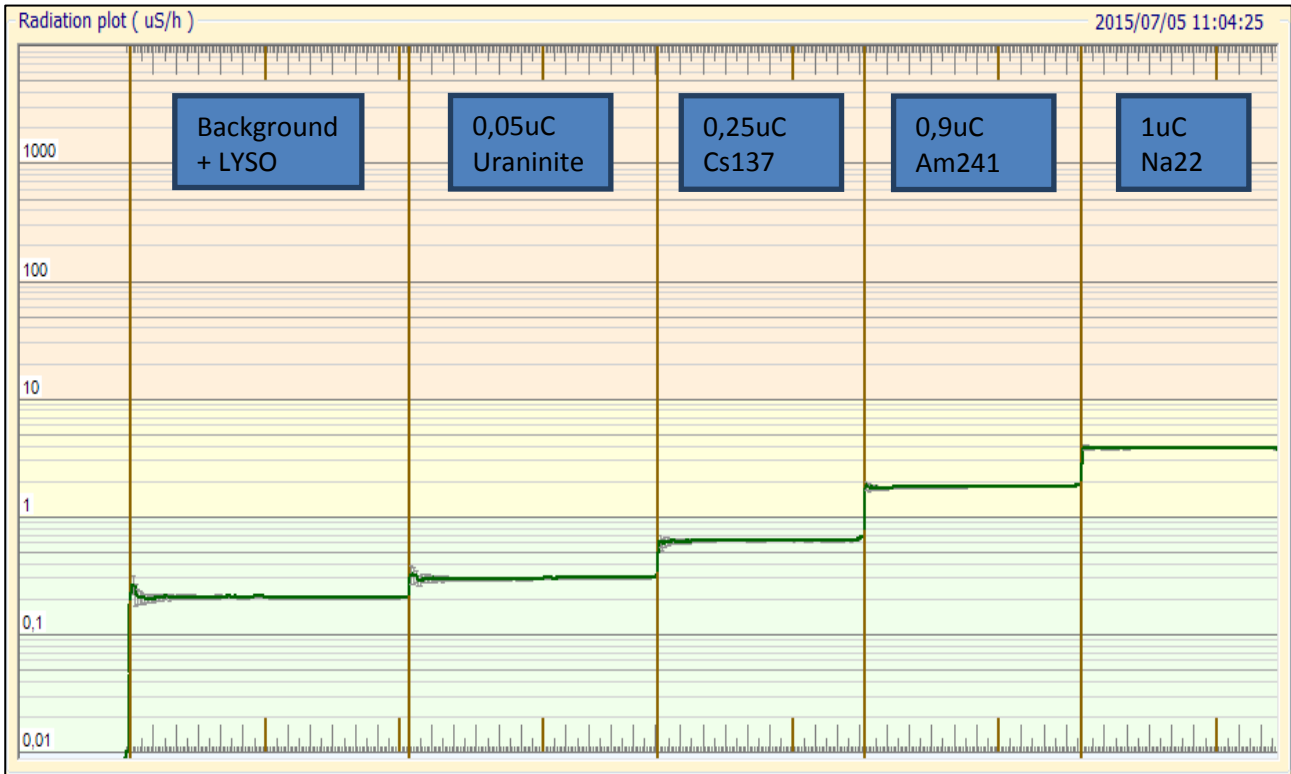
The lower line shows a 3,3V pulse of about 400ns generated from inverter chain.



Gamma Detector with two SiPM / LYSO sensors, the 30V power supply, the PCB with sensors connection and the amplification and trigger circuit. On the right there is the Theremino Master Module to which are sent the pulses for counting.

Theremino Geiger has to be calibrated with sensitivity and background level of SiPM / LYSO based detector. After calibration good results can be obtained with this detector. Due to the scintillation crystal the sensitivity of the detector is very high. A little defect is the high count value that is recorded idle, approximately 100CPS, this is due to the radioactivity of crystal LYSO due to content in lutetium.

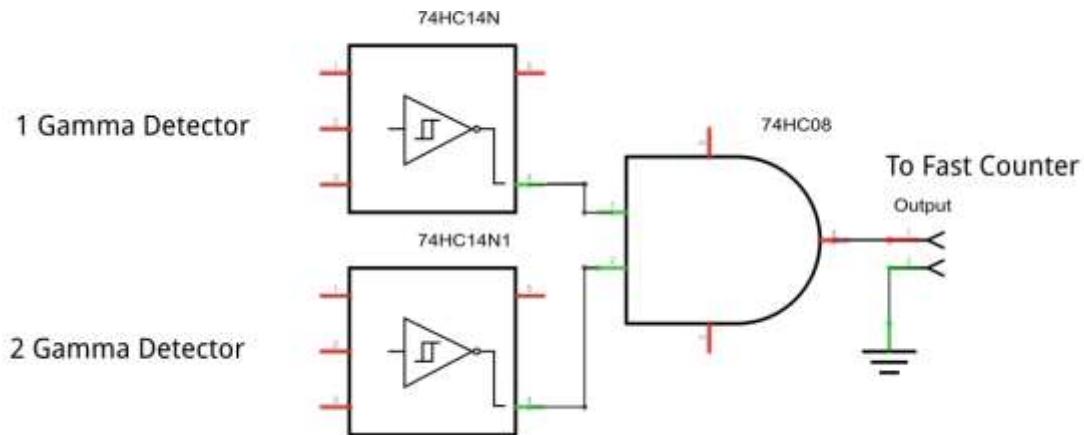
In the chart below are shown the measures of some radioactive sources.



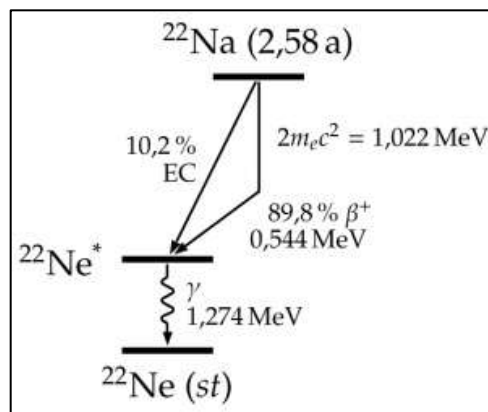
Radioactivity measures performed with Theremino Geiger and SiPM gamma detector

## Coincidence Measurements

The excellent timing properties of SiPM are exploited to make precise measurements of events of coincidence. The tests were made using two SiPM gamma detector ( see previous section) , whose logic outputs are sent to an AND logic . In this way it is obtained an output pulse only when the two detectors produce a pulse at the same time.

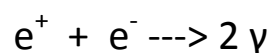


As source a tablet of 1  $\mu\text{C}$   $^{22}\text{Na}$  has been used. It has an emission  $\gamma$  -  $\gamma$  due to annihilation of positrons emitted in  $\beta$  decay. The two gamma photons of 511keV are emitted in diametrically opposite directions due to the principle of conservation of momentum.

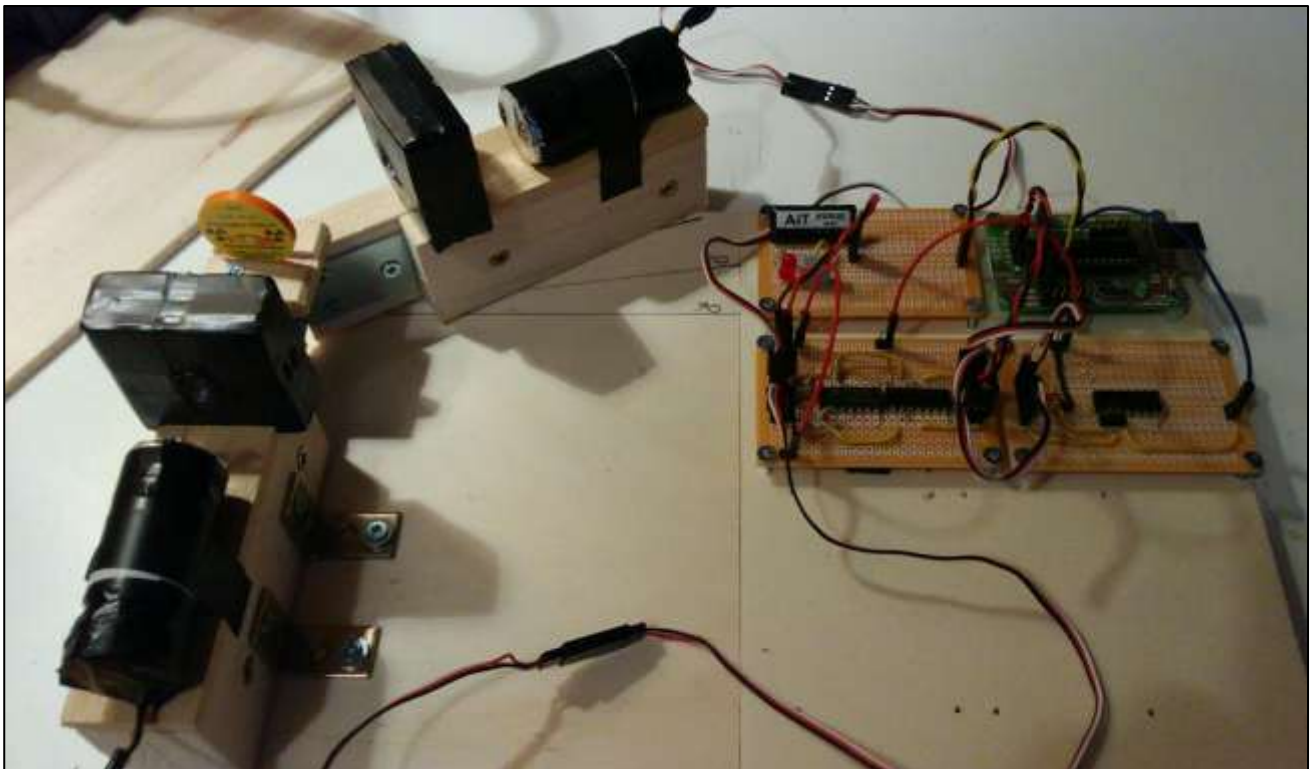
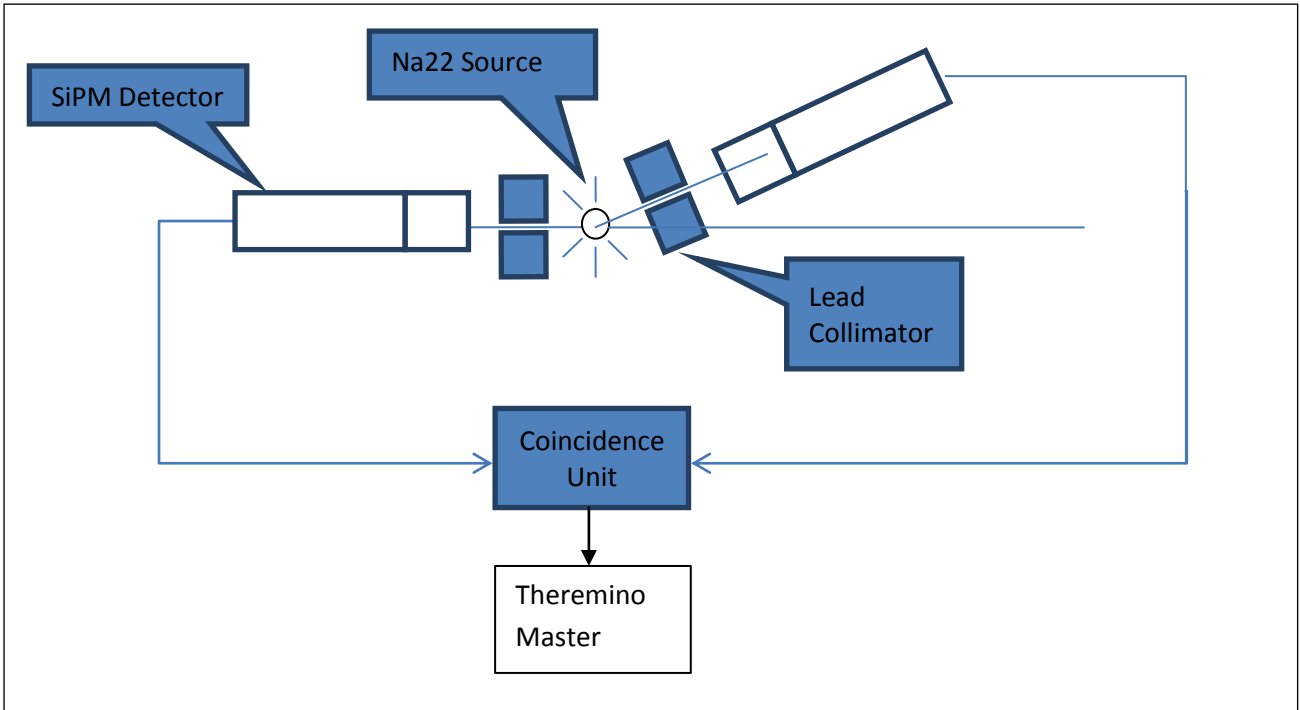


1  $\mu\text{C}$  isotope  $^{22}\text{Na}$  and decay chain

The isotope Na 22 decays (in 99.95% of cases) with a half-life of 2.6 years, by positron emission or electron capture to the first excited state of  $^{22}\text{Ne}$  1,274 MeV (which then relaxes by emitting gamma photon). The positrons emitted by the source annihilate inside the material that acts as a support to the source, producing two gamma photons of energy 0.511 MeV each, according to the process :

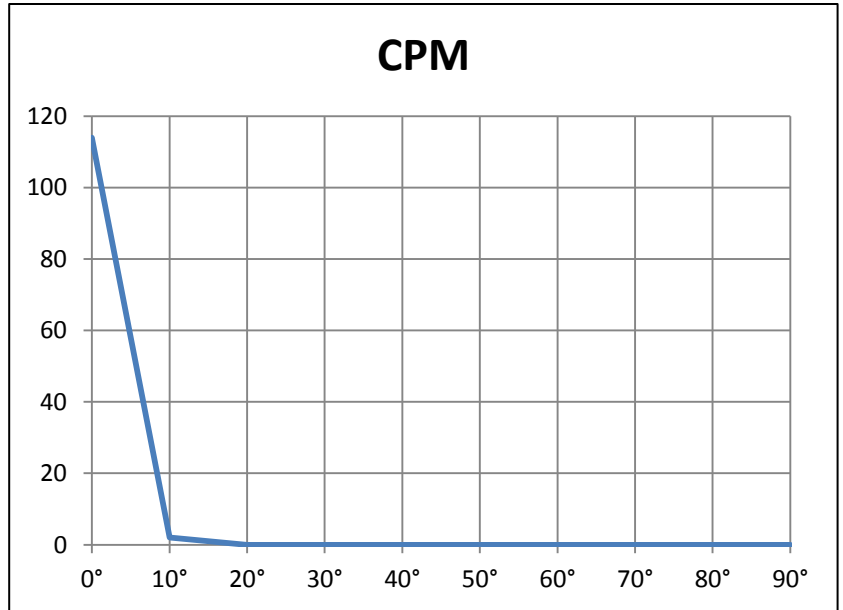


The two gamma photons to 0.511 MeV are issued at 180 degrees from each other. This allows measurements of correlation and coincidence.



Experimental setup

$\theta$	CPM
0°	114
10°	2
20°	0.5
30°	0.5
40°	0.5
50°	0.5
60°	0.5
70°	0.5
80°	0.5
90°	0.5



The table shows the results of measurements ( ratemeter ) to vary the angle of inclination of the two SiPM gamma detector. The measurements were made on an integration time of 200s .

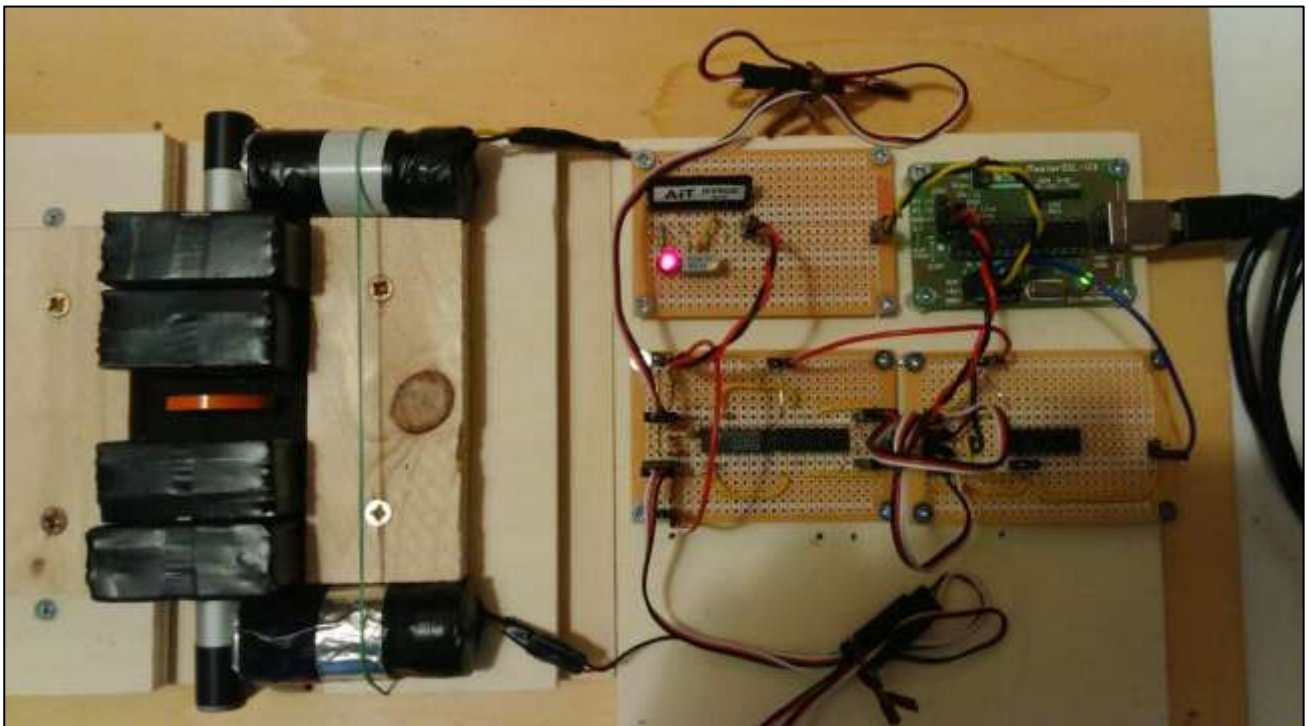
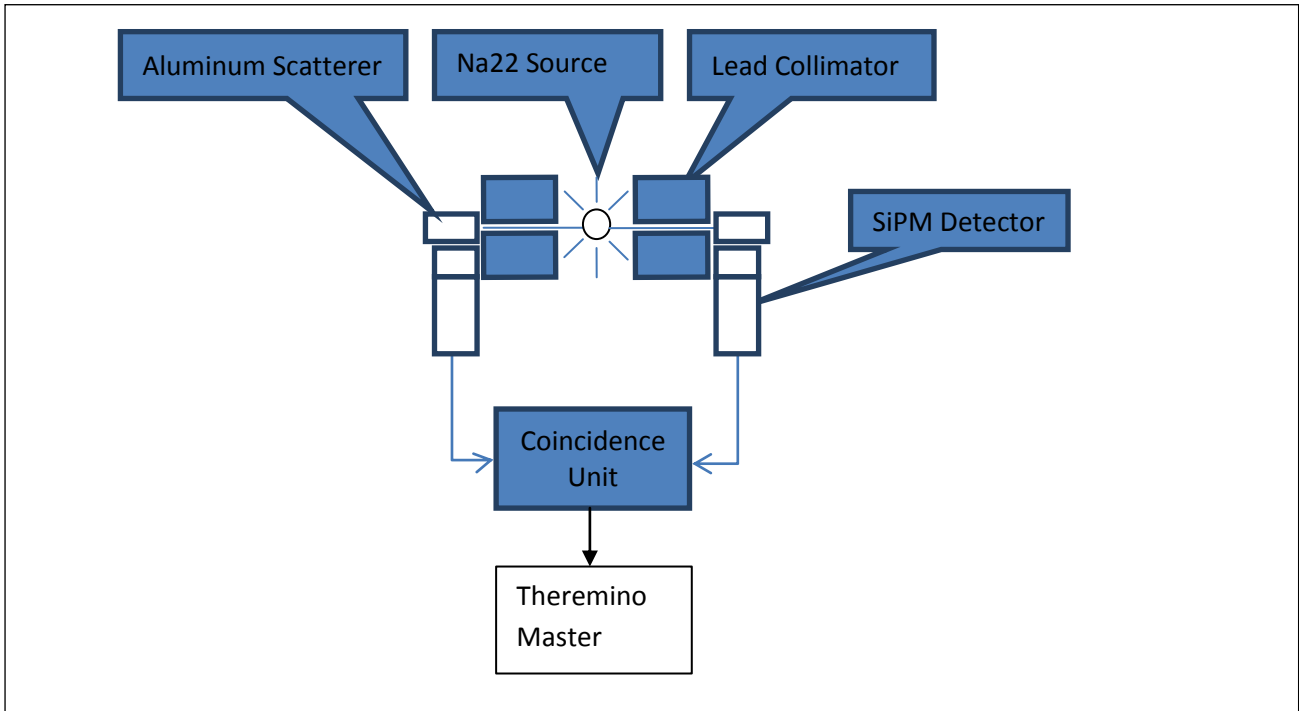
The value of 0.5CPM is the value of the background that is measured "idle" and it is due to spurious events and random coincidences that occur in the detector, especially because of the residual radioactivity present in the crystal LYSO.

As you can see the peak is achieved when the two detectors are aligned.



## Angular Correlation in Na22 Y-Y emission

The two SiPM detectors, used in coincidence mode, have been used to make some qualitative measures on the angular correlation of gamma photons emitted in the annihilation of positrons emitted in the  $\beta$  decay of the isotope Na22.



**Experimental setup**

1 $\mu$ C Na22 source – 12mm Al compton scatterer – 40mm wide lead collimators with 10mm hole



The measurements were made by placing the detector in the following two positions :

- Parallel detectors
- Orthogonal detectors



Parallel



Orthogonal

Type of Measure (Measure time 9999s)	CPM
Background without Na22 source	0.50
Background with Na22 source without compton scatterer	1.30
Parallel detectors	1.68
Orthogonal detectors	1.90

Subtracting the background value which is measured without Compton scatterer you get the following values :

Detector  $\parallel$  = 0.38 CPM

Detector  $\perp$  = 0.60 CPM

These values are compatible with the theoretical predictions (and experimental verifications made , for example, in the Wu - Shalnov experiment) that establish a counting rate higher in the case in which the detectors are orthogonal .

This is considered a confirmation that the gamma photons emitted are polarized in planes offset by 90 °.

This result is compatible with the hypothesis that the two gamma photons are entangled .

## Disclaimer and Safety Warning

- **Before using any radioactive sources:** local, national, and international regulations may restrict the purchase, storage, transport, use or disposal of radioactive sources. Please consult your local regulations to ensure your compliance before you manage any radioactive sources.
- **Never** tamper with an ionization smoke detector or attempt to remove the radioactive source. **Do not dismantle** smoke detector. **Do not remove** the radioactive material from any object.
- The experiments shown in this document are intended for **educational purposes** and for **testing** the measuring instruments and **should never be replicated without** proper knowledge and without the compliance with regulations.

### Precautions with Radioactive Sources

**Time:** The simplest way to reduce exposure is to keep the time spent around a radioactive source to a minimum. If time is cut in half, so is the exposure, with all the other factors remaining constant.

**Distance:** Distance is another effective means to reduce radiation exposure. A formula known as the “inverse square law” relates the exposure rate to distance. Doubling the distance from a radioactive source reduces the exposure to one-fourth its original value. If the distance is tripled, the exposure is reduced by a factor of nine.

**Shielding:** Shielding is any material used to reduce the radiation reaching the user from a radioactive source. While a single sheet of paper may stop some types of radiation such as alpha particles, other radiation such as neutrons and photons require much more shielding. Dense materials, such as lead or steel, are used to shield photons. Materials containing large amounts of hydrogen, such as polyethylene, are used to shield neutrons.

**Never wear** the same rubber gloves while operating your counting instrument, as any contamination on the glove could be transferred to the instrument.

**No food or drink** is ever to be permitted in a radioactive laboratory.

Another good habit to acquire is **never allowing the hands to touch** any other part of the body, or another individual, while working with liquid sources.

### Acknowledgments

We are thankful to **AdvanSiD**, particularly to Claudio and Alessandro, for providing the SiPM modules used in tests.