CosmicWatch: The Desktop Muon Detectors, exploring gamma-ray spectroscopy

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Cita 01.

Autor
Fuente

Wenn du es nicht einfach erklären kannst, hast du es nicht genug verstanden - Si no eres capaz de explicar algo claramente, es que aún no lo has entendido lo suficiente.

Albert Einstein

Declaración

Me permito afirmar que he realizado ésta tesis de manera autónoma y con la única ayuda de los medios permitidos y no diferentes a los mencionados el presente texto. Todos los pasajes que se han tomado de manera textual o figurativa de textos publicados y no publicados, los he reconocido en el presente trabajo. Ninguna parte del presente trabajo se ha empleado en ningún otro tipo de tesis.

Sede Bogotá., Fecha entrega

Andrés Felipe Vargas-Londoño

Acknowledgments

This goes to my family, my mom and my dad, who no matter how many mistakes I make, there is never a hint of judgement or disappointment. To every teacher who put his soul into letting me explore a corner of their bast knowledge. And to every friend who stood there when things did not seem to be going anywhere. But also specially to myself, for not letting me ever down.

Listado de símbolos y abreviaturas

Resumen

CosmicWatch: Los Detectores de Muones de Escritorio, explorando la espectroscopía gamma

El presente trabajo se concentra en el mejoramiento de CosmicWatch: Los Detectores de Muones de Escritorio, con el objetivo de evolucionar de un detector tipo contador Geiger a un espectrometro de gammas completamente funcional. Requiriendo por lo tanto buena resolución de enrgías y altas velocidades de sampleo, siendo estas las principales limitaciones de versiones anteriores de CosmicWatch. Usando un cristal centellador basado en Lutecio y dopado con Cerio (LYSO), se logró una resolución de $4.86\sqrt{E\ [\mathrm{MeV}]}$ al samplear datos con un osciloscopio Rohde&Schwarz RTO6.

Palabras clave: CosmicWatch, RaspberryPi Pico, Radiación gamma, Centelleo.

Abstract

CosmicWatch: The Desktop Muon Detectors, exploring gamma-ray spectroscopy

The present work focuses on the improvement of CosmicWatch: The Desktop Muon Detectors, with the goal to evolve from a Geiger-counter type of detector to a fully fnctional gamma-spectrometer. Therefore requiring good energy resolution and fast sample rates, which were the main limitations on previous CosmicWatch versions. Using a Cerium doped Lutetium-based scintillation crystal (LYSO), we have achieved an energy resolution of $4.86\sqrt{E\ [\mathrm{MeV}]}$ while sampling data with a Rohde&Schwarz RTO6 oscilloscope.

Keywords: CosmicWatch, RaspberryPi Pico, Gamma radiation, Scintillation.

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1 Introduction

CosmicWatch: The Desktop Muon Detectors [9], are a self-contained, low-cost, and easy-to-build particle detector for students, scientists, and cosmic-ray enthusiasts. It aims to make particle detection interactive and available to anyone interested in learning about the electronics and physics involved in this area of expertise. With this in mind, the detector design prioritizes the user experience across the board, from its construction to data acquisition and processing. It uses a silicon photomultiplier (SiPM) to collect light emitted by a plastic scintillator after a charged particle, like a cosmic-ray muon, deposits some of its energy in it. This project aims to further expand the capabilities of CosmicWatch by exploiting the already existing electronics and implementing the necessary features to transform the detector into a portable gamma-ray spectrometer

So far, previous iterations of CosmicWatch have worked as a Geiger counter, providing information about the number of particles detected, but ignoring energy deposition due to the poor resolution of the scintillating material used, generally plastic scintillators such as BC-404. The current speed of the electronics used is also a limiting factor, creating deadtime and therefore decreasing the sample rate. By switching to a Cerium doped Lutetium-based scintillation crystal (LYSO), testing new electronics and implementing better programming paradigms, this work thus aims to further explore and expand the capabilities of CosmicWatch, hoping to one day provide a self-contained, low-cost, and easy-to-build particle detector suited for gamma-ray spectroscopy.

2 Physical aspects

Atomic nuclei have multiple energy states, many of which are not stable, forcing them to release some of their energy in order to reach a stable state. One decay however does not always lead to a direct transition into a stable state, it may even require the atom to change into another depending on what way it has released its energy. On the other hand, radiation is not only produced when atoms decay, it is constantly raining down upon us from the cosmos, this kind of radiation can also be detected with a CosmicWatch, making it also necessary to explore. This chapter aims to provide an overview of some of the mechanisms through which nuclei reach stable states and what cosmic radiation is. Chapter 4 provides an overview of how this can be used to take interesting measurements with CosmicWatch.

2.1. Radioactivity

It is first necessary to understand the concept of activity. Not all atoms take the same time to decay, each atom has its own constant Γ which determines how likely it is to decay per unit of time. If one has an initial total of N_0 atoms, after a while it will be reduced due to the constant decay of atoms in the sample, this rate of change is given by the universal law of radioactive decay.

$$\frac{dN(t)}{dt} = -\Gamma N(t) \tag{2-1}$$

From this, it is easy to find that the number of remaining unstable atoms follows an exponential law

$$N(t) = N_0 e^{-\Gamma t} \tag{2-2}$$

The activity $A(t)$ of a radioactive source is given by how many decays occur per unit of time. This can be therefore obtained by multiplying the number of atoms $N(t)$ by the probability of decay per unit of time Γ.

$$A(t) = \Gamma N_0 e^{-\Gamma t} \tag{2-3}$$

The most common units for activity are the *curie* (Ci) and the *becquerel* (Bq), a becquerel represents one disintegration per second, while a curie represents 3.7×10^{10} disintegrations per second ($\approx$ the activity of one gram of ^{226}Ra). Under these definitions, the conversion between these units is given by the following relation:

$$1 \text{ Bq} = 2.703 \times 10^{-11} \text{ Ci} \tag{2-4}$$

The time constant Γ is often expressed in terms of the atom's lifetime τ under the relation $\Gamma = 1/\tau$. This means that τ is the time it takes to reduce a sample of N_0 by a factor of $1/e$, clearly $N(\tau) = N_0 e^{-\Gamma\tau} = N_0/e$. On the other hand there also exists a constant called half-life $T_{1/2}$, which represents the time it takes to reduce the sample by half, Sodium 22 for example has a half-life of 2.605 years. They can both be related by doing $T_{1/2} = \ln(2)\tau$.

2.1.1. Gamma emission

Unstable nuclei have multiple channels to release their energy through, the conditions that determine what channels an atom can use are not studied here, but rather the subsequent effects of such channels. An atom can decay by emitting gamma rays, alpha particles, neutrons, or protons, it can also undergo beta $\beta^{\pm}$ decay, Internal Conversion, and Electron Capture among others. This work will focus on beta decay and Electron Capture since these are the preferred channels of decay of the radioactive sources used to test CosmicWatch.

Beta decay

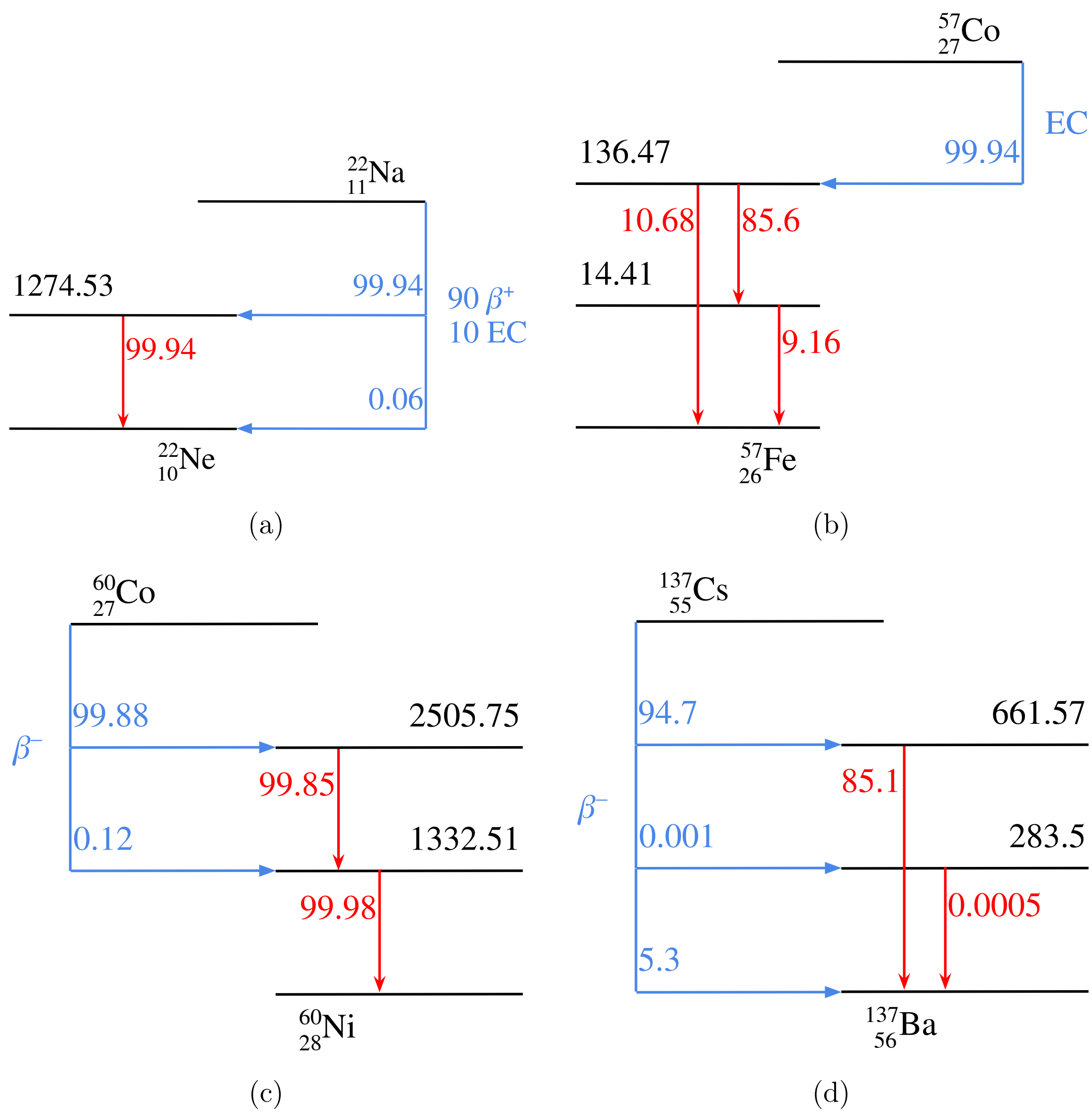


Fig **2-1**: Decay schemes for some isotopes used while testing the CosmicWatch. Only the main decay channels are included for clarity and simplicity.

There are two types of beta decay, they are represented by the following reaction schemes:

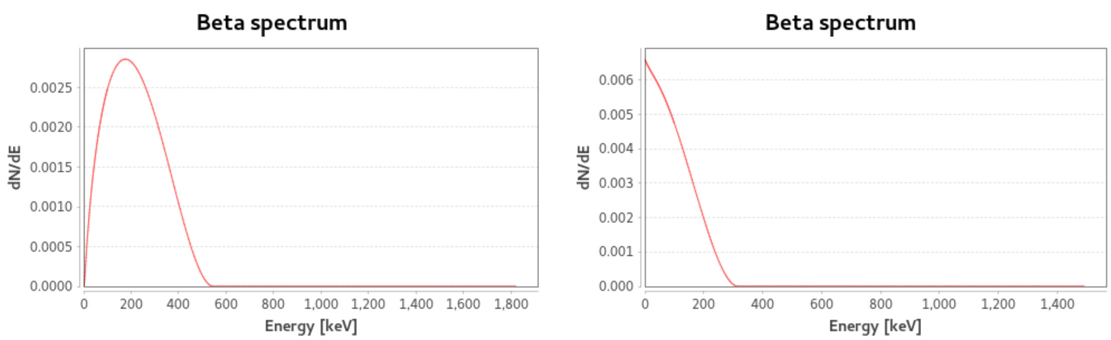
$$\beta^+ := \ {}^{A}_{Z}X \rightarrow \ {}^{A}_{Z-1}Y + e^+ + \nu \tag{2-5}$$

$$\beta^- := \ {}^{A}_{Z}X \rightarrow \ {}^{A}_{Z+1}Y + e^- + \bar{\nu} \tag{2-6}$$

Where the symbols follow the nuclear notation, X and Y represent the initial and final elements, A is the atomic number, Z the nuclear charge, $e^{\pm}$ are a positron or electron, and

$\nu/\bar{\nu}$ are a neutrino/antineutrino, Fig. **2-1** shows some examples of these processes. Note for instance the case of $^{22}_{11}$Na Fig. **2-1**(a), it undergoes β^+ 90 % of the time it decays, by the nuclear notation one can tell that the initial and final elements are Sodium and Neon respectively. In this process, a proton turns into a neutron, which is why the product element has $Z = 11 - 1 = 10$ while maintaining $A = 22$. It is important to also note that the total charge has to be conserved after the reaction occurs, which is why a positron e^+ is produced.

Alongside the positron/electron, a neutrino/antineutrino is ejected from the nucleus which, due to its extremely small interaction probability with matter, can not be detected. However, the negligible neutrino/antineutrino-matter interactions do not mean that their presence in the reaction does not have effects. The energy of the system also has to be conserved, since the particles $e^\pm$ and $\nu/\bar{\nu}$ are all ejected from the nucleus, higher or smaller portions of the total energy can be taken by the neutrino/antineutrino, which leaves multiple possible energy values for the positron/electron, resulting in continuous energy spectra.



(a) (b)

Fig **2-2**: positron/electron energy spectra for (a) ^{22}Na (β^+) and (b) ^{60}Co (β^-). Taken from [1].

2.1.2. Light-matter interactions

Compton scattering

Lineal attenuation coeficient

2.2. Cosmic Radiation

2.3. Particle interactions with matter

3 Detector description

3.1. History

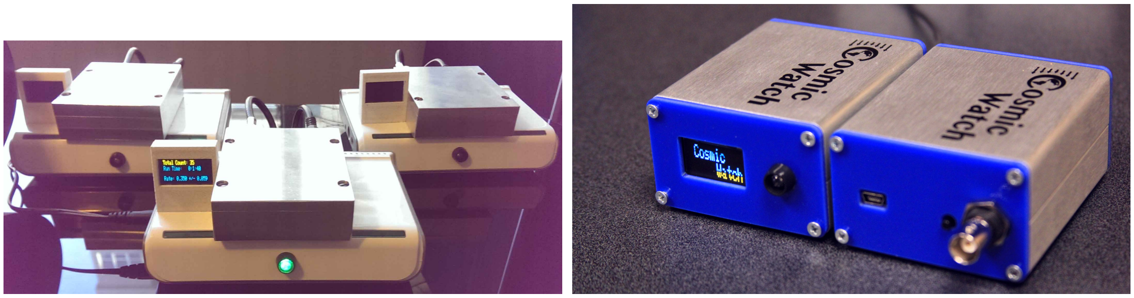
"The desktop muon detector was initially built as a Muon Tagging Optical Modules (MTOMs) for PINGU, the proposed low energy upgrade for IceCube experiment" [2]. Since the first iteration, CosmicWatch has had multiple versions, always aiming to reduce size and costs, simplify its construction, and provide better documentation for new CosmicWatch users. An in-depth review of the detector evolution can be found in [2] under "About the project/Project evolution".

The prototypes of CosmicWatch Fig. **3-1**(a) used liquid scintillator, this however proved to be inefficient, since it was prone to leaks. The second prototype used a $5 \times 5 \times 5$ cm^3 plastic scintillator in a light-tight reflective aluminum case Fig. **??**, this was however too slow, large, and expensive, making it not suitable for students.

(a) First prototype (b) Second prototype

Fig **3-1**: First versions of CosmicWatch, prototypes for PINGU, taken from [2].

Later iterations resemble the current goals of CosmicWatch, they are cheaper, smaller, and easier to build. Versions 1 and 2 (Fig. **3-2**(a)) introduced some user-friendly features, including battery/USB power with 0.3 W consumption, a software-adjustable trigger threshold, and cost about \$100. V2 in particular introduced the use of SD cards to save data and the capability to connect two CosmicWatches, making it possible to measure coincident events.



(a) Third prototype (b) CosmicWatch versions 1 and 2

Fig **3-2**: Newer versions of CosmicWatch, designs suitable for students, taken from [2].

The previous versions of CosmicWatch used an Arduino Nano to process the signal coming from the photomultiplier[1], which has only one core. This is a disadvantage when there is a high event rate since one can not sample data while saving previous events. The use of a Raspberry Pi Pico is one of the main improvements in upcoming versions of CosmicWatch, its two cores allow to sample data in one thread while the other handles serial communication to save previous events. This will reduce deadtime, making it suitable for high event rates, such as those found around active gamma sources.

3.2. Plastic vs. LYSO

Up until now, due to how affordable and malleable they can be, only plastic scintillators have been used, particularly Polyvinyltoluene-based scintillators such as BC-400 and BC404. Sadly, it is well known that their poor energy resolution and lack of linearity makes them useless for gamma spectroscopy, at least in small sizes as the ones used for CosmicWatch ($5 \times 5 \times 1$ cm^3). In addition to this, plastic scintillators have very low light yields 10000 photons/MeV [5], making it hard to detect low-energy events. Table **3-1** compares the general properties of some scintillating materials, better showcasing the advantages of LYSO in particular for gamma spectroscopy in the CosmicWatch context.

Tab **3-1**: General properties of some scintillating materials. Taken from [5, 6, 7, 8]. *Calculated from the attenuation coefficient at 662 keV shown in [8, p. 3]

Property	LYSO	BC-400	NaI(TI)	BGO
Density [g cm^{-3}]	7.1	1.032	3.67	7.1
Decay time [ns]	36	2.4	250	300
Light yield [ph/MeV]	33200	10000	38000	9000
Attenuation Length at 511 keV [cm]	1.2		3.3*	1.0

[1]See chapter 5 for an in-depth description of the inner workings of the detector electronics

Higher densities are good for energy deposition, catching particles and gammas more efficiently. Short decay times allow to make fast signal pulses. High light yields make it possible to detect low-energy events. Short attenuation lengths decrease the amount of material necessary to get energy depositions.

3.3. Power Consumption

3.4. KiCad

3.5. Accessories

3.6. 3D printed case

In order to hold the crystal in place on the SiPM PCB, it was necessary to design a 3D printed case -see Fig. **3-3** for an image of the 3D design on Inventor. With this we made sure that the crystal would not move relative to the SiPM, preventing scratches and providing a more stable optical coupling with the photomultiplier.

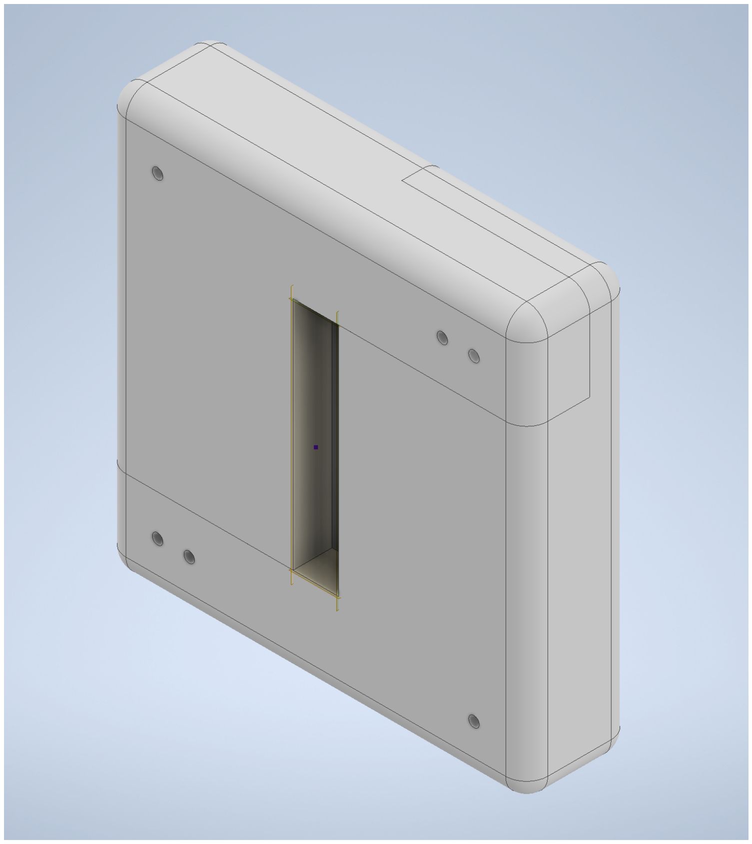


Fig **3-3**: 3D model of the LYSO case made on Inventor, the .cad files can be found on the repository CosmicWatch-gamma-spectroscopy-PCB.

The design keeps in mind that the crystal has to be wrapped in Teflon tape to increase reflectivity, which is why it comes in two pieces that come together around the crystal, lowering the risk of tears. Once the crystal is placed in the case it can be kept together using electrical tape.

Before using Teflon tape, the crystal was wrapped in tin foil, which made tears common (Fig. **3-4**) and greatly impacted the quality of the spectra that could be obtained with the detector.

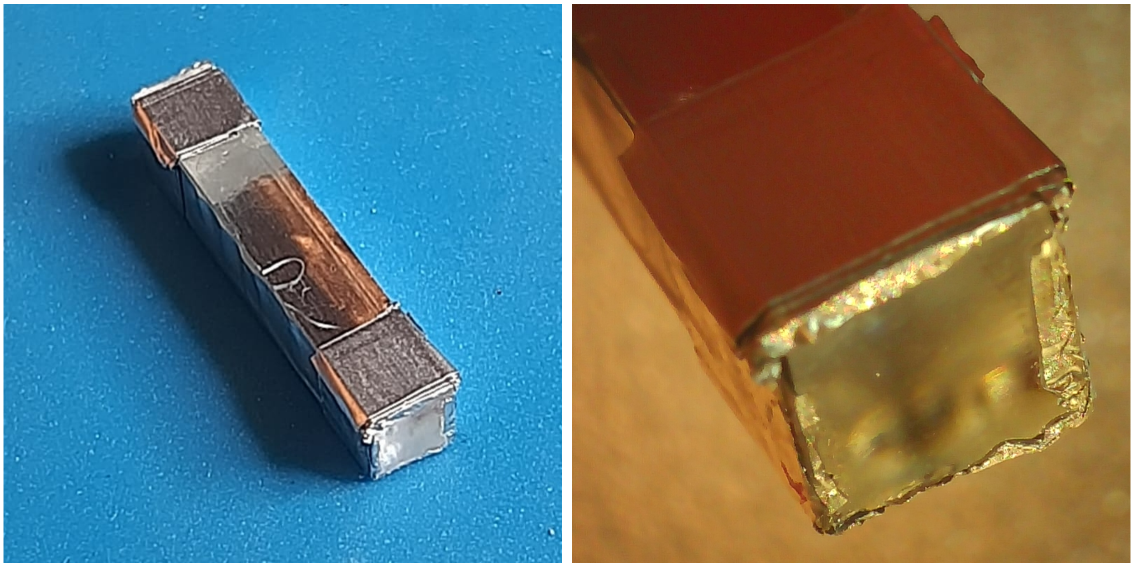


Fig **3-4**: Tin foil tear.

Teflon tape seems to solve the tearing problem. However, to reduce the risk of tearing the Teflon, multiple iterations of the case were designed (Fig. **3-5**)

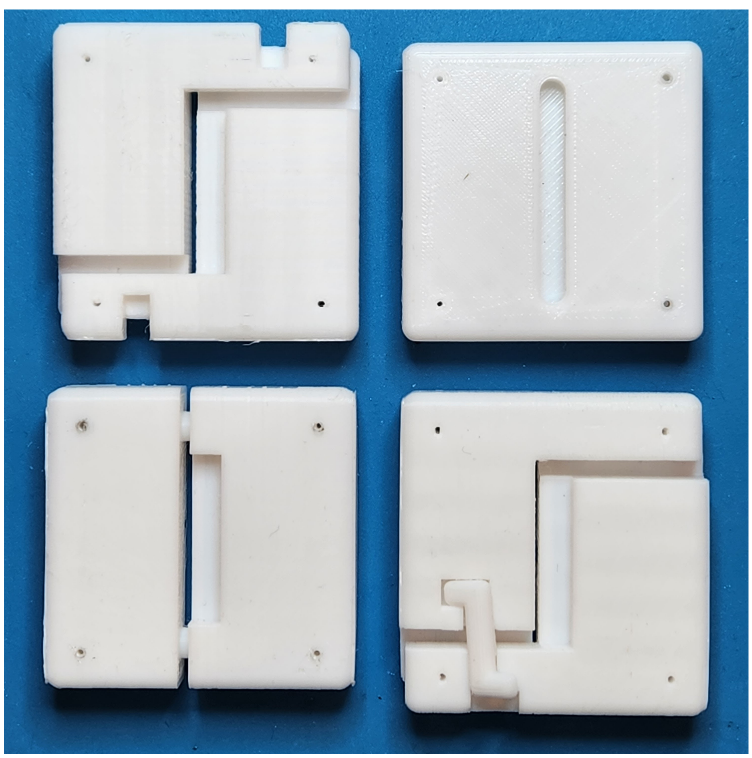


Fig **3-5**: 3D printed cases tested to reduce the risk of Teflon tears.

4 Detection methods

4.1. Scintillation

4.2. Single photon detectors

4.3. PMT's

4.4. SiPM advantages

5 Electronics

CosmicWatches have to be mainly low-cost and easy to build. In order to achieve this, the components selected for the construction have been carefully curated to make sure these restrictions were met. This however might be greatly responsible for some of the odd features found while testing the detector, like the lack of linearity and fluctuations in amplification and peak-detected values of seemingly equal input signals. The full KiCad project can be found in the GitHub repository: CosmicWatch-gamma-spectroscopy-PCB. The component numbers shown in this chapter are the ones that would have to be placed on the PCB in order to recreate the example schematics.

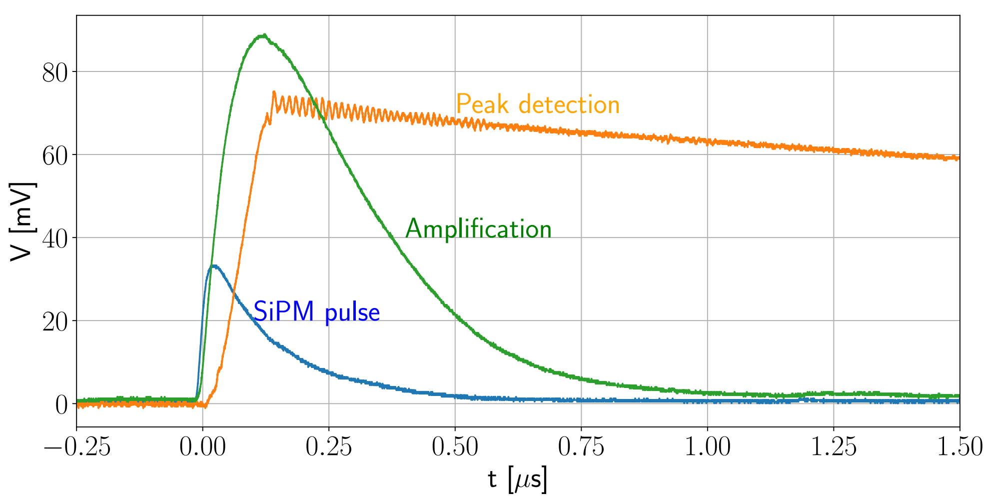


Fig **5-1**: Signal processing inside the detector.

5.1. Amplifier

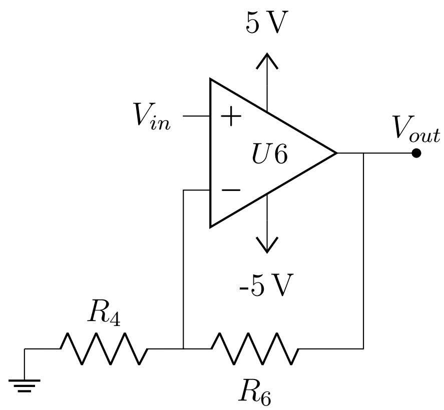


Fig **5-2**: Amplifier circuit schematic. An LT1807 op-amp is used for this and the peak detection stage.

The processing of a pulse coming out of the SiPM has to go through two main stages, amplification and peak detection, Fig. **5-1** showcases these stages. The brightest SiPM pulses seen so far do not exceed 200 mV, which covers a very small portion of the ADC range on the RP Pico (0-3.3 V [10, p. 18]). Amplification of the signal therefore allows for better resolution.

An op-amp on its own amplifies the voltage difference between the non-inverting (pin +) and inverting (pin −) inputs by its internal gain A_{int}, having then $V_{out} = A_{int}(V_+ - V_-)$. In this case, however, we are interested in controlling the gain of the circuit and therefore the amplification. In order to achieve this we introduce a feedback loop in the op-amp through $R4$ and $R6$, which controls how much of the output voltage is fed back into the op-amp. The theoretical amplification is therefore given by $V_{out} = (1 + R6/R4)V_{in}$. A simple schematic showcasing the component arrangement is shown in Fig. **5-2**.

5.2. Peak Detector

Since the LYSO crystal is so fast (36 ns of decay time [6]) the ADC sample rate and response time of the Pico both play an important role in the number of events that the detector will accurately acquire. It is therefore necessary to hold the voltage of the amplified pulse in order to increase the chances of reading the actual value of the incoming signal. This is the task of the peak detector, to widen the time window in which we can sample the ADC and get a correct reading.

The idea behind the peak detector is to store charge in a capacitor (C_{25}) through a diode (D_3), retaining the highest voltage the input signal has reached. A diode is placed before the capacitor so that once the signal's voltage goes below the peak voltage, the diode will be reverse biased, therefore preventing current from flowing while maintaining the voltage on the capacitor.

In order to measure the voltage in the capacitor, a discharging resistor has to be added (R_{15}/R_{19}). The time it takes the capacitor to discharge is given by $t = RC$. Although for example in the case of CosmicWatch-V2's peak detector, the values of R_{14} and R_{24} also play a role in the discharging time, which has proved not to be as trivial as calculating the equivalent resistance R_t of all three and simply take $t = R_tC$.

The schematic and PCB shown in the repository CosmicWatch-gamma-spectroscopy-PCB, include the connections and footprints necessary to place the components that make the designs illustrated in Subsections 5.2.1-4. Different results were found while testing these peak detector setups.

5.2.1. Basic Peak Detector

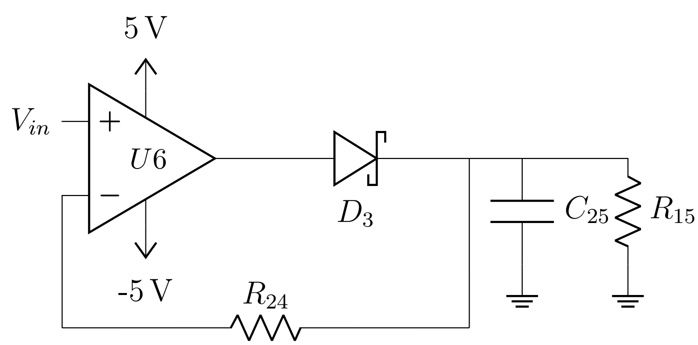


Fig **5-3**: Basic peak detector design.

Assuming ideal conditions, a diode is enough to retain the highest input voltage reached. Semiconductor diodes however don't behave ideally, they introduce a voltage drop that will keep the voltage stored in C_{25} at a lower potential than that of V_{in}. In order to prevent this, an op-amp (U_6)[1] is placed before the diode. In the configuration shown in Fig. **5-3**, the opamp will try to output the necessary current to equilibrate the inverting input voltage (pin $-$) to what it sees in the non-inverting input (pin $+$), to achieve this U_6 has to go one diode drop above V_{in}.

[1]Currently the only op-amp that has behaved reasonably well is the LT1807 by Analog Devices Inc. The LMH6658 by Texas Instruments seems to have trouble driving even small capacitors.

5.2.2. Preventing negative saturation

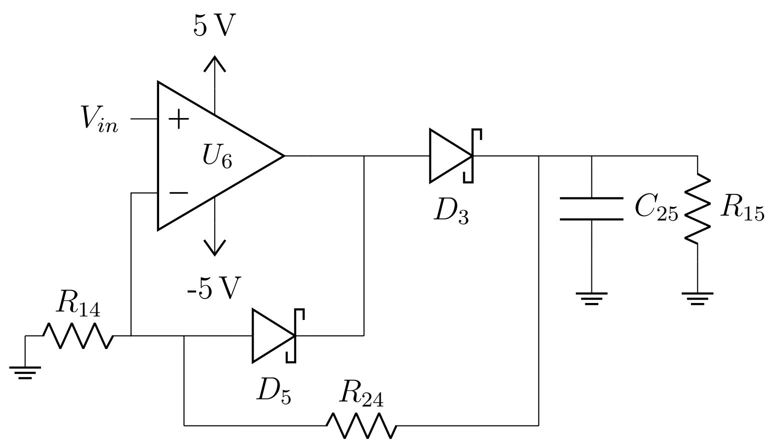


Fig **5-4**: Basic peak detector design, a second diode is added in order to prevent the op-amp from entering a negative saturation loop.

In the basic peak detector, once the signal voltage goes below the peak voltage, D_3 will be reverse biased and the inverting input of the opamp will see a higher voltage than the non-inverting input, this will force U_6 to go into negative saturation by driving the output voltage as low as it can in order to match both inputs. Once the signal gets close to the stored voltage in $C_2$5, the op-amp will have to get out of the negative saturation, this will take some time which depends on the slew rate of the opamp and therefore limits the operating frequency range of the circuit.

In order to avoid negative saturation D_5 is added, along with an outer feedback loop through R_{24}. In this case, once the input signal goes below the stored voltage, D_5 will be forward biased, allowing for a new feedback loop that decreases the op-amp's negative saturation time.

5.2.3. Basic Peak Detector + Buffer

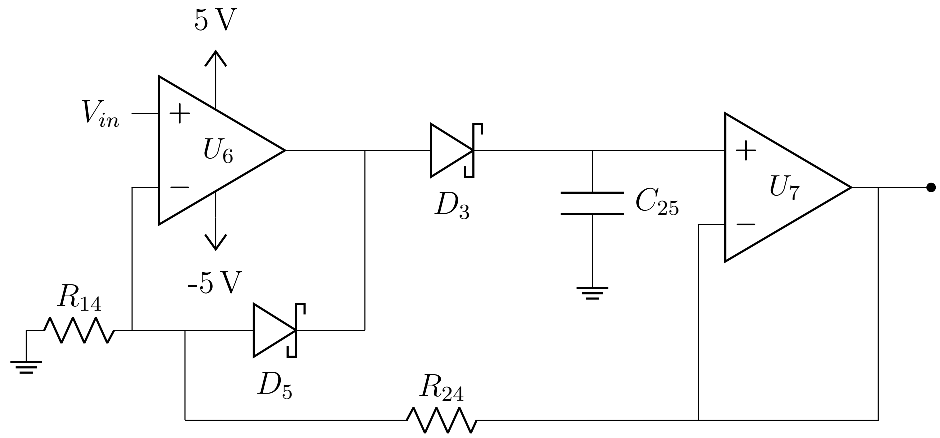


Fig **5-5**: Basic peak detector design, Adding a buffer to prevent discharging of the capacitor through the resistor and instead through any load in the circuit, in this case R_{29}.

This design follows the same principles as the one shown in the previous subsection. However, in this case, a buffer is added to introduce high impedance and prevent the capacitor from discharging through the resistor and instead through any load that may be applied after the circuit.

5.2.4. Nuclear Phoenix

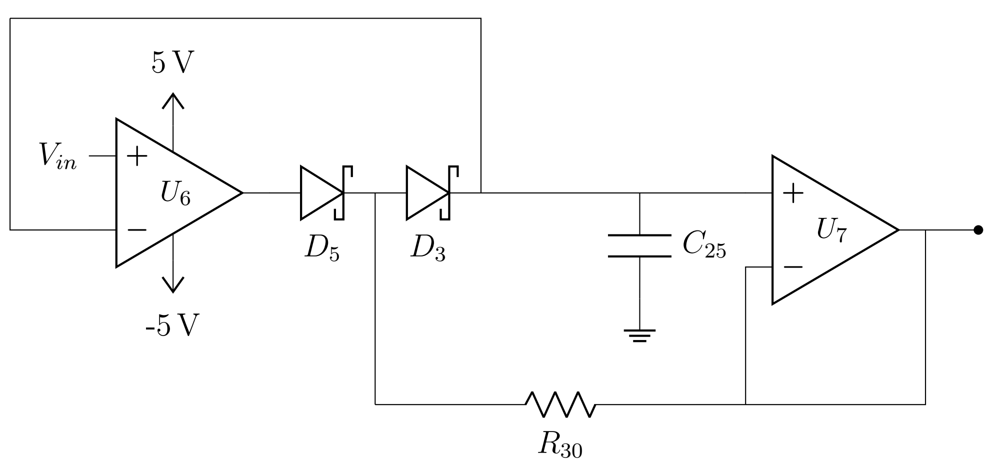


Fig **5-6**: Nuclear Phoenix peak-detector design. Taken from [3].

NuclearPhoenix is a physics student who has developed a gamma detector that also utilizes a Raspberry Pi Pico and a Silicon photomultiplier, his schematics also include a peak detection circuit which is shown in Fig. **5-6**, his project can be found in Open Gamma Detector. This design aims to prevent leakage current across D_3, this discharges the capacitor at a faster rate than intended once the peak voltage has been reached. In this case, R_30 is feeding back the peak voltage value to D_3, therefore creating a 0 V difference across the diode, preventing any leakage current from flowing out of C_{25} and into the output of the op-amp.

5.3. Trigger

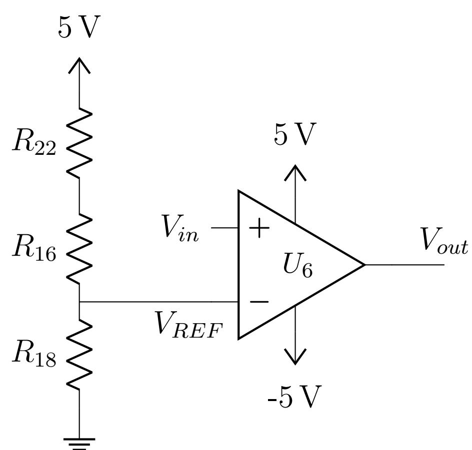


Fig **5-7**: Trigger circuit.

In this case, a voltage divider is used to force a positive saturation in the op-amp once the amplified signal reaches a threshold voltage, generating a "digital 1" that can be used to trigger the detector. The threshold, or V_{REF} as noted in Fig. **5-7**, is given by equation (5-1).

$$V_{REF} = \frac{R_{18}}{R_{22} + R_{16} + R_{18}} V_{cc} \tag{5-1}$$

5.4. Microcontroller

5.5. DC to DC booster

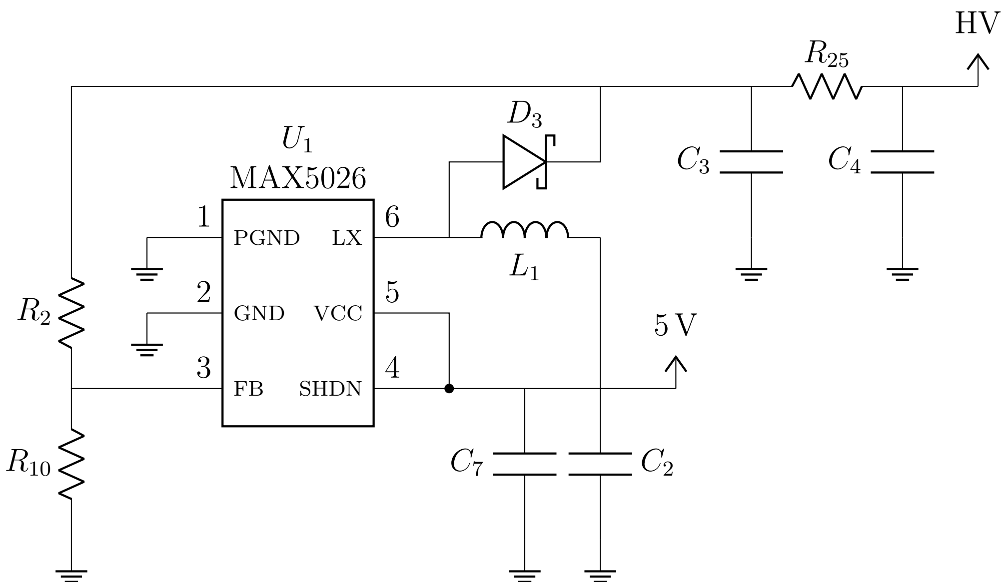


Fig **5-8**: DC to DC booster circuit. Careful considerations have to be made when placing the MAX5026 IC in order to reduce noise on the power line. It is advised to have a look at the datasheet in [4], section .$^{\text{A}}$pplications Information".

Acording to Onsemi [11], the operaing voltage of a MicroFJ-300XX-TSV SiPM is 25.2-30.7 V. It is then necessary to boost V_{cc} to the operating range of the SiPM, noted as HV in Fig. **5-8**. In order to achive this, a MAX5026 PWM Step-Up DC-DC Converter is used [4], which has a user-adjustable output voltage of up to 36 V using external feedback resistors.

In the circuit shown in Fig. **5-8**, R_{10} and R_2 determine the output voltage HV. According to [4], equation (5-2) allows to calculate the Value of R_{10} given a desired output voltage HV and a value of R_2 between 5 and 50 kΩ.

$$R_{10} = R_2 \left(\frac{\text{HV}}{V_{REF}} - 1 \right) \tag{5-2}$$

5.6. Single photons

6 Geant4 Simulation

6.1. What is Geant4?

6.2. Geometry

6.3. Muons going through the scintillator

6.4. Photons collected vs. produced

6.5. Optimum SiPM placement

6.6. Simulated Spectra

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7.1. Rohde&Schwarz RTO6 oscilloscope

7.2. CosmicWatch electronics

7.3. NIM

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8.1. Odd features in Cesium spectra

8.2. Adding LYSO radioactivity to Geant4

9 Conclusion

A RaspberryPi Pico code

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