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

Texto del resumen.

Palabras clave: Use palabras clave que estén en Theasaurus

Abstract

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

Abstract text.

Keywords: Use keywords available in Theasaurus

Table of contents

List of Figures

List of Tables

Chapter 1

Introduction

CosmicWatch: The Desktop Muon Detectors [2], 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

Using a Cerium doped Lutetium-based scintillation crystal (LYSO), we have achieved an energy resolution of $4{,}86\sqrt{E\ [\mathrm{MeV}]}$ while testing in a Rohde&Schwarz RTO6 oscilloscope to sample the data.

The human body is known to have many limitations, our senses are often not the best tools to delve into the intricacies of nature. For many years scientists have taken advantage of the sensitivity of materials to further expand our capabilities to explore the world around us, bringing to our reach worlds once invisible. Scintillating crystals for example have allowed us to develop a type of detector able to distinguish the energy deposition in it, making elusive particles trackable, no longer letting them escape our curiosity. The wonders of these types of detectors are sadly not easily available to everyone, scintillating and solid-state detectors are often out of the economic capacities of most. CosmicWatch Desktop Muon Detectors are therefore an extremely powerful tool to bring particle detection closer to the public, students, and young scientists like myself. 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.

Chapter 2

Physical aspects

2.1. Radioactivity

2.2. Cosmic Radiation

2.3. Particle interactions with matter

Chapter 3

Detector description

3.1. History

3.2. Plastic vs. LYSO

3.3. Power Consumption

3.4. KiCad

3.5. Accessories

3.6. 3D printed case

In order to make the crystal easier to mount on the SiPM PCB it was necessary to design a 3D printed case. With this we made sure that the crystal would not move with respect to the SiPM, preventing scratches and providing a more stable optical coupling with the photomultiplier.

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 by means of electrical tape.

Chapter 4

Detection methods

4.1. Scintillation

4.2. Single photon detectors

4.3. PMT's

4.4. SiPM advantages

Chapter 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. The full KiCad project can be found in the GitHub repository: CosmicWatch-gamma-spectroscopy-PCB. The component numbers shown in this section are the ones that would have to be placed on the PCB in order to recreate the example schematics.

5.1. Amplifier

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. **5-1**.

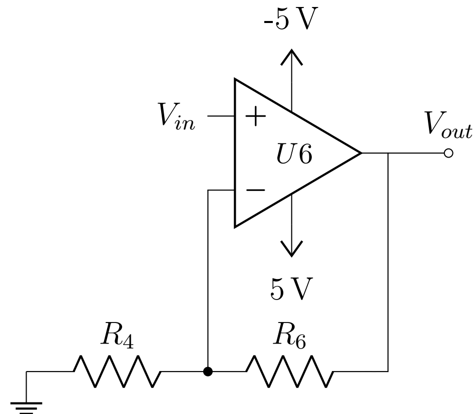

Figura **5-1**: Amplifier circuit schematic. An LT1807 op-amp is used for this and the peak detection stage.

5.2. Peak Detector

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 reaches. 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

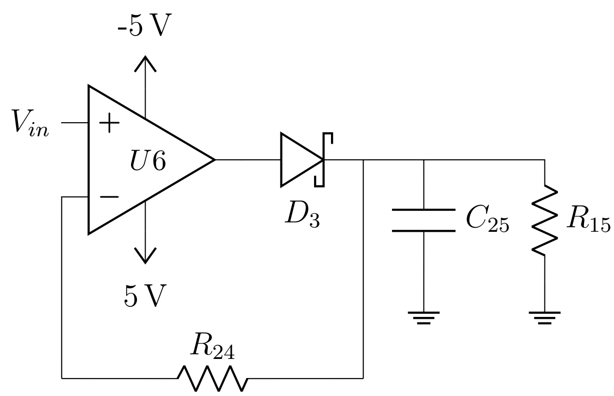

Figura **5-2**: Basic peak detector design.

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. **5-2**, 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

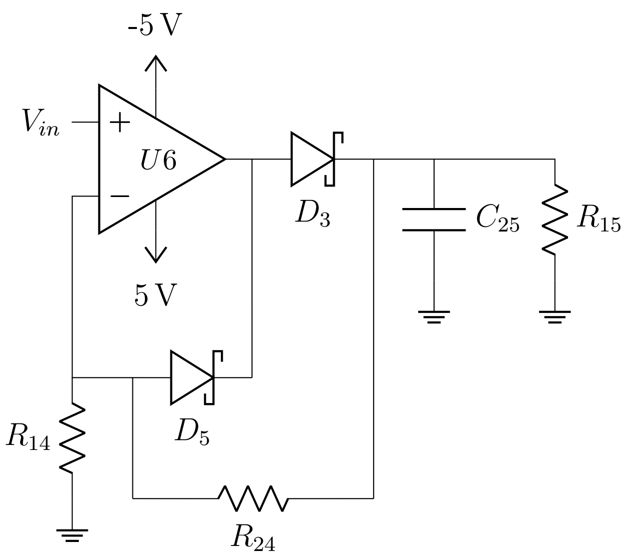

Figura **5-3**: Basic peak detector design, a second diode is added in order to prevent the op-amp from entering a negative saturation loop.

5.2.3. Basic Peak Detector + Buffer

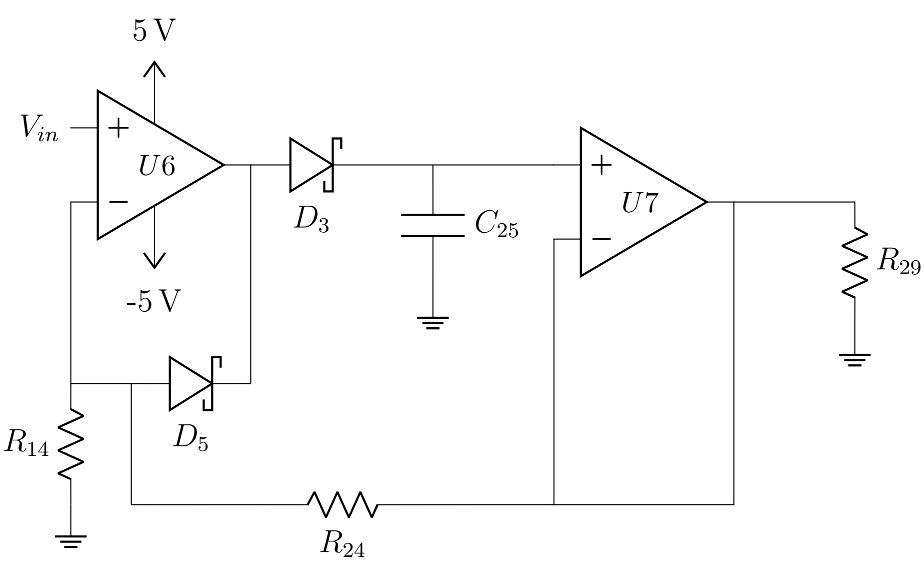

Figura **5-4**: Basic peak detector design, Adding a buffer to prevent discharging of the capacitor through the resistor and instead through any load in the circuit, in this case R_29.

5.2.4. Nuclear Phoenix

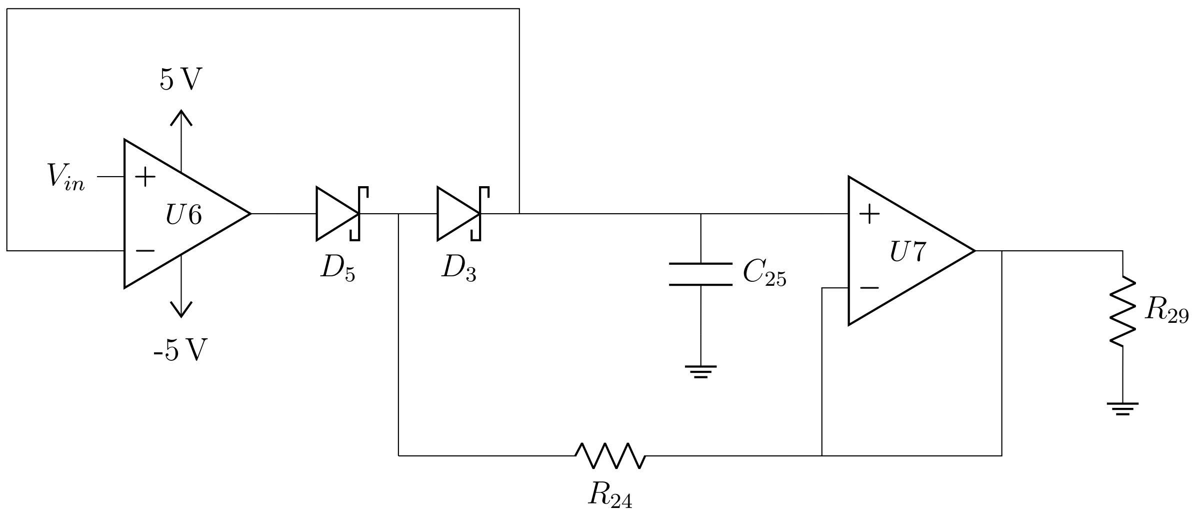

Figura **5-5**: Nuclear Phoenix peak-detector desing. Taken from [1].

5.3. Trigger

5.4. Microcontroller

5.5. DC to DC booster

5.6. Single photons

Chapter 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

Chapter 7

Measurements

7.1. Rohde&Schwarz RTO6 oscilloscope

7.2. CosmicWatch electronics

7.3. NIM

Chapter 8

Ongoing work and future directions

8.1. Odd features in Cesium spectra

8.2. Adding LYSO radioactivity to Geant4

Chapter 9

Conclusion

Appendix A

RaspberryPi Pico code

Bibliography

[1] Nuclear Phoenix. Open-gamma-detector, 2024.

[2] Spencer N. Axani. The physics behind the cosmicwatch desktop muon detectors, 2019.