



Educational Handbook

Nuclear and Particle Physics Experiments

2027





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From R&D to the registration of the incoming purchase orders, through:

- Resource Planning
- Scheduling
- Production

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CAEN Educational Handbook

Nuclear and Particle Physics Experiments



<https://edu.caen.it>



CAEN draws upon over 45 years of collaboration with the High Energy & Nuclear Physics community to enhance

university educational laboratories. This includes providing advanced instrumentation developed for major experiments worldwide and leveraging teaching experience at esteemed institutions like the University of Insubria (Como, Italy), University of Ferrara (Italy), and Aveiro University (Portugal), as well as partnerships with prestigious academic programs such as the Erasmus Mundus in Nuclear Physics and LA CoNGA Physics.

In addition to offering detailed Educational Notes showcasing a variety of experiments based on the latest technologies and instrumentations, CAEN also provides dedicated training sessions. These sessions, led by expert staff, are tailored to meet specific customer needs. The goal is to inspire students and facilitate their understanding of diverse physics phenomena through state-of-the-art technologies, instruments, and methodologies.

In collaboration with:

University of Insubria, Italy
University of Aveiro, Portugal
Nuclear Instruments srl, Italy,

University of Ferrara, Italy
Erasmus Mundus
LA CoNGA Physics





CAEN Electronic Instrumentation

Tools for Discovery



CAEN SpA is a worldwide leading company provider of a comprehensive range of high/low voltage power systems and data acquisition/front-end modules compliant with IEEE standards for nuclear and particle physics.

Extensive research and development capabilities allowed CAEN SpA to play an important long-term role in this field. Thanks to years of close collaborations with the most important Research Centres of the world, CAEN strives to deliver innovative products and services worldwide.

CAEN portfolio includes over a thousand products and solutions for nuclear measurements, whose quality is monitored throughout the entire production cycle and guaranteed by UNI EN ISO 9001:2015 standard. Its products appeal to a wide range of customers including engineers, scientists and technical professionals who all trust them to achieve their goals quickly and effectively.

Thanks to plenty of experience in physics research, CAEN instruments are now used in several advanced industrial applications.

► Products

Modular Pulse Processing Electronics

Waveform Digitizers

Digital Spectroscopy

Electronics for SiPM

Power Supplies

Digital Detector Emulators

Educational Kits

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Choose Your Educational Kit!

The table is intended as a practical guide to help identify the most suitable modular kit for each physics experiment. Experiments are organized by Physics Application field in the Section column. Within each section, the Subsection column groups the related topics, while the Experiment column lists the experimental activities that can be performed for each topic using the modular system.

Section	Subsection	Experiment	EXPERIENCE CODE	SP5600C Educational Gamma Kit	SP5600D Educational Beta Kit	
				p. 110	p. 113	
A. Particle Detector Characterization	Silicon Photomultiplier (SiPM)	SiPM Characterization	SG6011A	-	-	
		Dependence of the SiPM Properties on the Bias Voltage	SG6012A	-	-	
		Temperature Effects on SiPM Properties	SG6013A	-	-	
	Photomultiplier Tube (PMT)	Measurement of Photomultiplier Plateau Curves	SG6020E	-	-	
B. Nuclear Physics and Radioactivity	B.1 γ Spectroscopy	Detecting γ -Radiation	SG6111A	•	-	
		Poisson and Gaussian Distributions	SG6112A	•	-	
		Energy Resolution	SG6113A	•	-	
		System Calibration: Linearity and Resolution	SG6114A	•	-	
		A Comparison of Different Scintillating Crystals: Light Yield, Decay Time and Resolution	SG6115A	•	-	
		γ Radiation Absorption	SG6116A	•	-	
		Photonuclear cross-section/Compton Scattering cross-section	SG6117A	•	-	
		Study of the ^{137}Cs spectrum the backscatter peak and X rays	SG6118B	•	-	
		Activity of the ^{60}Co	SG6119B	•	-	
	B.2 γ Environmental Radioactivity Indoor	Energy calibration of System based on LYSO crystal and Fertilizer sample	SG6140C	-	-	
		Background Measurements	SG6141C	-	-	
		Fertilizer and photopeak identification	SG6142C	-	-	
		Soil sample identification	SG6143C	-	-	
		Samples Comparison	SG6144C	-	-	
		Test Sample Identification	SG6145C	-	-	
		Radon passive measurement	SG6146C	-	-	
	B.3 γ Environmental Radioactivity Outdoor	Environmental monitoring in field	SG6150E	-	-	
		Ground Coverage Effect on the Environmental Monitoring.	SG6151E	-	-	
		Human Body Radioactivity	SG6152E	-	-	
		Environmental detection as a function of the soil distance	SG6153E	-	-	
		Radioactivity maps production	SG6154E	-	-	
		Radiological evaluation of the building materials	SG6155E	-	-	
		Mapping of potential radon-prone areas	SG6156E	-	-	
		Soil water content evaluation with gamma ray spectroscopy	SG6157E	-	-	
		Geochemical and mineral exploration	SG6158E	-	-	

The conclusive matrix of the table allows to associate the equipments to the experiments. Each column is connected to one of the modular kits presented for educational purpose. The checked cells identify the experiments allowed by the chosen kit.

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Choose Your Educational Kit! (continued)

Section	Subsection	Experiment	EXPERIENCE CODE	SP5600C Educational Gamma Kit	SP5600D Educational Beta Kit	
				p. 110	p. 113	
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		β Spectroscopy	SG6122A	-	•	
		β -Radiation: Transmission through Matter	SG6123A	-	•	
		β -Radiation as a Method to Measure Paper Sheet Grammage and Thin Layer Thickness	SG6124A	-	•	
		Coating effect on the Light Collection	SG6125A	-	•	
B. Nuclear Physics and Radioactivity	B.5 Nuclear Imaging - PET	Basic Measurements: γ Spectroscopy and System Linearity	SG6131G	-	-	
		Positron Annihilation Detection	SG6132G	-	-	
		Two-dimensional Reconstruction of a Radioactive Source	SG6133G	-	-	
		Spatial Resolution	SG6134G	-	-	
	B.6 GM Detector	Statistics: Uncertainty as a function of live time	SG6160H	-	-	
		Environmental Background	SG6161H	-	-	
		Lead Shielding Effect on Environmental Radioactive Background	SG6162H	-	-	
		Detecting Ionizing-Radiation	SG6163H	-	-	
		Samples Comparison	SG6164H	-	-	
		Inverse Square Law: Gamma Rays	SG6165H	-	-	
		Dose Equivalent as a Function of Altitude	SG6166H	-	-	
		Statistics	SG6210D	-	•	
		Muons Detection	SG6211A	-	•	
		Muons Vertical Flux on Horizontal Detector	SG6212A	-	•	
		Random Coincidence	SG6213D	-	•	
		Detection Efficiency	SG6214D	-	-	
		Cosmic Flux as a function of the altitude	SG6215D	-	-	
		Zenith Dependence of Muons Flux	SG6216D	-	•	
		Cosmic Shower Detection	SG6217D	-	-	
		Environmental and Cosmic Radiation	SG6218D	-	-	
		Absorption Measurements	SG6219D	-	-	
		Solar Activity Monitoring	SG6220D	-	-	
	C.2 Photons	Quantum Nature of Light	SG6221A	-	-	
		Hands-on Photon Counting Statistics	SG6222A	-	-	
D. Pulse Processing	D.1 Open FPGA Experiments	LED Blinking Demo on DT1260 with Sci-Compiler	SG6301F	-	-	
		Using the Onboard Oscilloscope in Sci-Compiler	SG6302F	-	-	
		Threshold Discriminator with Event Counter	SG6303F	-	-	

EQUIPMENTS

	SP5600E Educational Photon Kit	SP5600AN Educational Kit Premium Version	SP5640 GammaEDU	SP5630EN Environmental Kit	SP5630ENP Environmental Kit Plus	SP5600EMU Emulation Kit	SP5620CH Cosmic Hunter	SP5700 EasyPet	SP5701 EasyPet Kit	SP5660 Portable geiger	SP5650 Open FPGA Kit
	p. 111	p. 110	p. 113	p. 112	p. 112	p. 111	p. 113	p. 119	p. 119	p. 114	p. 112
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Choose Your Educational Kit! (continued)

Section	Subsection	Experiment	EXPERIENCE CODE	SP5600C Educational Gamma Kit	SP5600D Educational Beta Kit	
				p. 110	p. 113	
D. Pulse Processing (CONTINUED)	D.1 Open FPGA Experiments	Using Python to Access the Threshold Discriminator Registers	SG6304F	-	-	
		Acquiring and Plotting Waveforms	SG6305F	-	-	
		Threshold Scan with Python	SG6306F	-	-	
		FPGA-Based Dwell Time for Precise Event Counting	SG6307F	-	-	
		Measuring Time-of-Flight and Time-over-Threshold	SG6308F	-	-	
		Reading and Plotting Two Spectra	SG6309F	-	-	
		Timestamp and Time-over-Threshold with List Data Buffer	SG6310F	-	-	
		Python Readout, Decoding, and Plotting of ToF and ToT	SG6311F	-	-	
		Leading Edge with Hysteresis, Derivative, and Trapezoidal Trigger Comparison	SG6312F	-	-	
		Measuring Signal Amplitude via Peak Detection	SG6313F	-	-	
		Charge Integration	SG6314F	-	-	
		Trapezoidal Filtering with a Fully Integrated MCA IP Core	SG6315F	-	-	
		CR-RC ² Shaping Amplifier	SG6316F	-	-	
		Implementing a Pulse Shape Discriminator (PSD) Based on Amplitude vs. Area Ratio	SG6317F	-	-	
		Implementing a Pulse Shape Discriminator (PSD) Based on Ratio between areas	SG6318F	-	-	
		Multichannel Readout Using the Round Robin Arbiter	SG6319F	-	-	
		Multichannel Design using Sub-Designs	SG6320F	-	-	
		Sub-Block Instances	SG6321F	-	-	
		Memory-Mapped Components in a Sub-Design	SG6322F	-	-	

EQUIPMENTS

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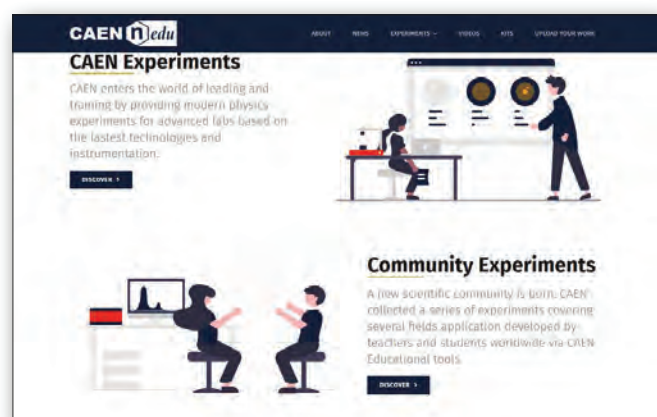
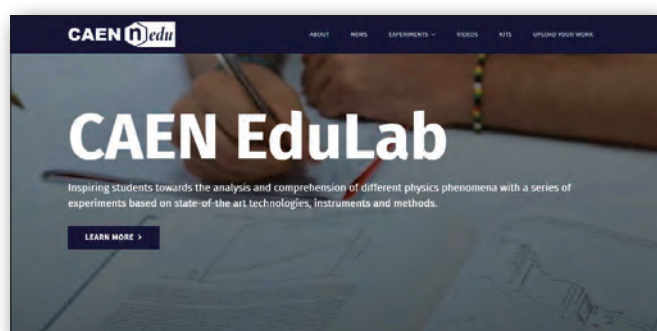
Discover, Learn, and Innovate with CAEN EduLab Learning Platform

Where science and technology meet your curiosity

CAEN EduLab Learning Platform is the dedicated portal for scientific and technological education, designed to support students, teachers, and enthusiasts in their STEM (Science, Technology, Engineering, and Mathematics) education. The platform offers a wide range of educational resources, including tutorials, virtual labs, and interactive learning materials, all aimed at facilitating the teaching and learning of the most advanced technologies.

Key Sections of the Platform:

Lab Toolkit



A section dedicated to educational toolkits, providing practical guides and tools to conduct experiments and laboratory activities effectively and safely.

Tutorials

Step-by-step video tutorials and guides that help students and educators explore scientific and

technical applications, with a particular focus on CAEN products and solutions.

Courses

Structured learning paths that cover various levels of expertise, offering the opportunity to learn progressively and in-depth.

Resources

A repository of educational materials, including handouts, articles, and technical manuals, accessible to enrich the learning process.

Support

A dedicated support service to answer questions and provide technical assistance, ensuring a smooth and uninterrupted learning experience.



Additionally, **registered users have the opportunity to collaborate with the platform by proposing new experiments and sharing their scientific experiences using CAEN Edu products.** This collaborative approach not only enhances the platform's content but also fosters a community of learners who can socialize and grow together through shared knowledge and experiences.

CAEN EduLab Learning Platform stands as a key resource for anyone looking to deepen their knowledge of cutting-edge sciences and technologies, offering tools and resources for innovative and engaging learning.

Detailed Information on
<https://edu.caen.it>



Navigating the Experiment Framework

Section & Subsection name

Related experiments

Experimental setup

Experiment name
Experiment reference ID

Overview grid

Equipment list

Experimental task

Block diagram

Experimental results

Data plots

The screenshot displays the CAEN Experiments website interface. At the top, there's a navigation bar with links like 'ABOUT', 'NEWS', 'EXPERIMENTS', 'VIDEOS', 'KITs', and 'UPLOAD YOUR WORK'. Below this, the breadcrumb trail reads 'Home > CAEN Experiments > γ Spectroscopy > Detecting γ-radiation'. The main content area is divided into several sections: a 'Search on the website' bar, a 'Categories' list (CAEN Experiments, Nuclear Physics and Radioactivity, Environmental radioactivity, Gamma Spectroscopy, Particle Detector Characterization, Silicon Photomultipliers, Particle Physics, Cosmic Rays), a 'Need help?' section (Support form, Quickstart Guides, CAEN Handbook, Glossary), and a 'Downloadable version' button. The experiment details section includes the title 'Detecting γ-radiation', the reference ID 'SG6111C', and a category list. An 'Overview grid' table shows 'Difficulty' (Easy), 'Execution Time' (1h 30m), 'Data Analysis' (No), and 'Radioactive Sources' (Yes). The 'Hardware setup' section mentions the 'SPS4300/EMP' and 'SPS900C/MP' modules. The 'Equipment' list includes 'SPS4300/EMP - Educational Environmental Kit' and 'Additional Gamma Radiation Source'. The 'Purpose of the experiment' describes gamma ray detection using a scintillating crystal and a photomultiplier. The 'Fundamentals' section explains the exponential law of attenuation and the Compton effect. A 'Block diagram' shows the experimental setup with a source, detector, and data acquisition system. The 'Results' section displays a data plot of counts versus energy (MeV) for different absorber thicknesses (0.5cm, 1cm, 1.5cm).

How to read this Handbook

EXPERIMENT PAGES

Experiment Reference ID
see next page below

Experiment description
(web version)

Experiment task

Short description

Block diagram

Experimental result

Data plots

SG6302F USING THE ONBOARD OSCILLOSCOPE IN SCI-COMPILER



Difficulty

Execution Time

SP5650 - OPEN FPGA KIT

Purpose of the experiment

This application demonstrates how to integrate and operate the Oscilloscope block in a Sci-Compiler FPGA design on the DT1260 board, to visualize analog and digital signals in real time.

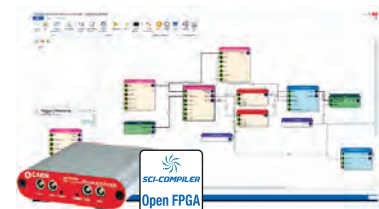
Fundamentals

An oscilloscope captures and displays signal waveforms, enabling time-domain observation of amplitude versus time. Analog input signals (after ADC conversion) and

internal digital signals inside the FPGA can be sampled and visualized through a memory-mapped interface. Triggering functions (edge detection, thresholds, pre/post trigger) stabilize the display of periodic or transient signals. A block, called "Oscilloscope", connects FPGA logic with external visualization tools for debugging and signal validation.

Requirements

No other tool is needed



Experimental setup

Carrying out the experiment

Activate your Sci-Compiler license and set up the software installation. Plug the USB Dongle in your PC and launch Sci-Compiler. Create a project for your DT1260 unit: press New Project.

Add the Oscilloscope block to the design and connect analog (A0) and digital (D0-D3) inputs.

Configure channels, buffer size, and enable capture.

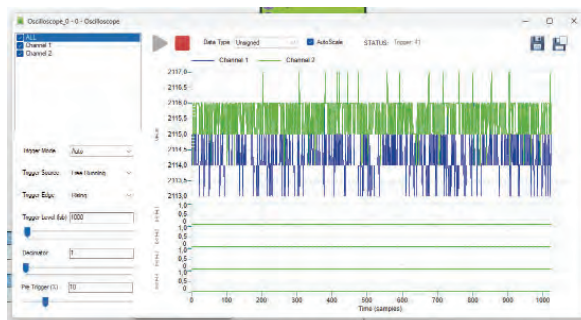
Assign memory addresses automatically, build the project, and program the DT1260.

Feed a test signal (e.g. PWM) to an input, open Oscilloscope_0 from the Resource Explorer, and set trigger source, mode, and level.

Start acquisition and adjust trigger settings to stabilize the displayed waveform.

Results

The Oscilloscope block provides real-time observation of FPGA-generated signals without external equipment. By adjusting trigger parameters, students can stabilize periodic waveforms or capture transient events, improving signal debugging, timing verification, and system validation.



Oscilloscope Screen

Experiment name

Experiment Overview & Kit Used

Additional requirements

Quick Guide

**SP5700
EASYPET**



2D image reconstruction in real-time to explore Nuclear Imaging World!

EasyPET is a simple, user-friendly and portable didactic PET system developed for high-level education, to explore the physical and technological principles of the conventional human PET scanners, using the same basic detectors of state-of-the-art systems.

- Positron Annihilation Detection
- Two-dimensional Reconstruction of Source
- Spatial Resolution

**SP5701
EASYPET KIT**



Explore PET Imaging and Gamma Spectroscopy through real-time detection and reconstruction!

EasyPET Kit is a simple, user-friendly and portable didactic PET system developed for high-level education, designed to explore the physical and technological principles of conventional human PET scanners while extending hands-on experiments to Gamma Spectroscopy through a compact portable Digital MCA.

- Gamma Spectroscopy and System Linearity
- Positron Annihilation Detection
- Nuclear Imaging
- Two-dimensional Reconstruction of a Radioactive Source

**SP5600AN PREMIUM
EDUCATIONAL KITS**



Advanced and compact solutions for Nuclear & Particle Physics experiments!

The CAEN Premium Educational kit is a modern, digital, and flexible platform developed by CAEN for teaching the fundamentals of Statistics & Nuclear, and Modern Physics.

The set-ups is based on Silicon Photomultipliers (SiPM) state-of-the-art sensors of light with single-photon sensitivity and unprecedented photon counting capability.

- Statistics
- γ and β Spectroscopy
- Cosmic rays
- Photon detection and light distribution

MORE INFO **CONTROL SOFTWARE**

Easy PET
Control
Software

MORE INFO **CONTROL SOFTWARE**

Easy PET
Control
Software

MORE INFO **CONTROL SOFTWARE**

HERA
Handy Educational
Radiation
Application

110 CAEN Educational Handbook

[Product Name](#)

[Product Tagline](#)

[Short Description](#)

[Application](#)

[Included Software](#)

[QR Code to Product Page](#)

Each experiment is identified by an alphanumeric code (e.g. ****SG1234A****). The numeric part of the code identifies the experiment itself, while the final letter identifies the reference educational kit for the corresponding experimental guide.

Since the same experiment can be performed using different modular kits, the numeric part of the code remains unchanged, while the final letter varies according to the reference kit.

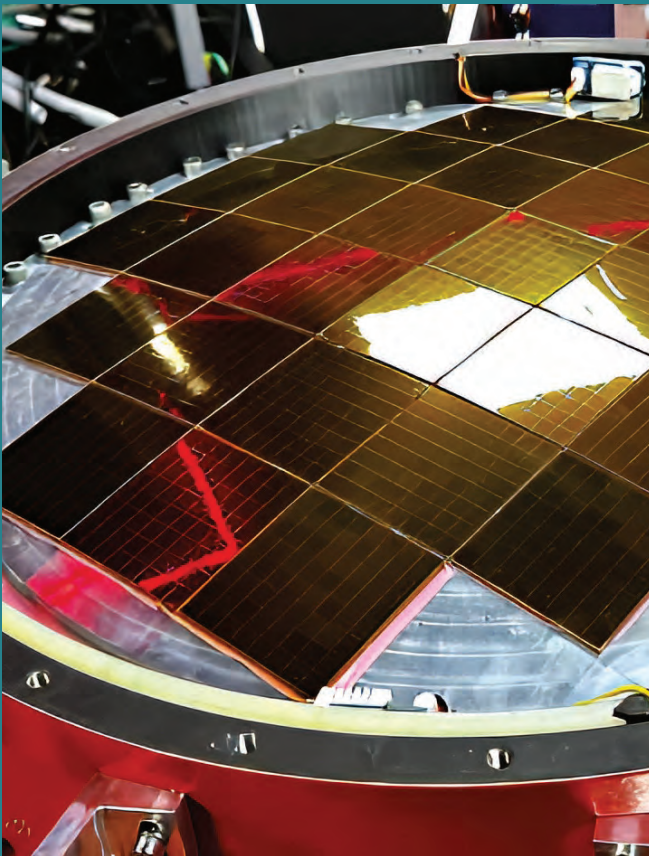
The table below shows the correspondence between each kit type and the final letter used in the experiment code. Kit types listed in the same row share the same experimental guide and are therefore identified by the same final letter.

Association between kit types and the final letter of the guide code

Kit type	Associated final letter	Code example
SP5600AN - P5600E - SP5600C - SP5600D	A	SG x x x x A
SP5600EMU	B	SG x x x x B
SP5630EN - SP5630ENP	C	SG x x x x C
SP5620CH	D	SG x x x x D
SP5640	E	SG x x x x E
SP5650	F	SG x x x x F
SP5700 - SP5701	G	SG x x x x G
SP5660	H	SG x x x x H

A. Particle Detector Characterization

A.1 Silicon Photomultipliers (SiPM)



Silicon Photomultipliers (SiPMs) have become one of the most important photodetectors in modern scientific instrumentation. Their ability to detect single photons, combined with high gain, excellent photon-counting capability, compact dimensions, and low operating voltage, has made them the preferred choice for a wide range of applications in physics, medical imaging, nuclear instrumentation, and industrial sensing.

Before a photodetector can be effectively employed in experimental applications, its operating principles and performance characteristics must be thoroughly understood. For this reason, the experiments presented in this section are dedicated to the characterization of SiPM devices through a series of hands-on laboratory activities.

Students will investigate the fundamental operating parameters of SiPMs, including gain, breakdown voltage, dark count rate, photon detection performance, and the influence of operating conditions on detector behavior. Through these experiments, they will become familiar with the methods used to characterize solid-state photodetectors, acquiring practical skills in electronic measurements, data acquisition, and experimental data analysis.

These activities provide the essential foundation for the subsequent experimental sections of the handbook, where SiPM technology is employed as the core photosensor in increasingly advanced physics experiments and detection systems.

SP5600E - EDUCATIONAL PHOTON KIT

Difficulty



Execution Time

**Purpose of the experiment**

Characterization of a SiPM detector using an ultra-fast pulsed LED. Estimation of the main features of the detector at fixed bias voltage.

Fundamentals

Silicon Photomultipliers (SiPM) consist of a high-density (up to $\sim 10^4/\text{mm}^2$) matrix of diodes connected in parallel on a common Si substrate. Each diode is an Avalanche Photo Diode (APD) operated in a limited Geiger-Müller regime connected in series with a quenching resistor, in order to achieve gain at level of $\sim 10^6$. As a consequence, these detectors are sensitive to single photons (even at room temperature) feature a dynamic range well above 100 photons/burst and have a high Photon Detection Efficiency (PDE) up to 50%. SiPM measure the light intensity simply by the number of fired cells. However, this information is

affected and biased by stochastic effects characteristic of the sensor and occurring within the time window: spurious avalanches due to thermally generated carriers (a.k.a. Dark Counts), delayed avalanches associated to the release of carriers trapped in metastable states (a.k.a. Afterpulses) and an excess of fired cells due to photons produced in the primary avalanche, travelling in Silicon and triggering neighboring cells (a phenomenon called Optical Cross Talk).

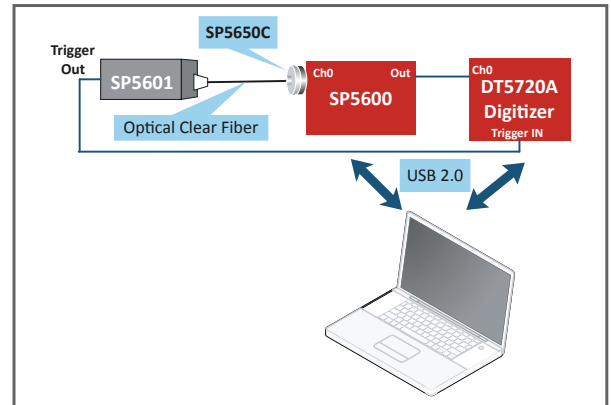
The typical SiPM response to a light pulse is characterized by multiple traces, each one corresponds to different numbers of fired cells, proportional to the number of impinging photons. Because of the high gain compared to the noise level, the traces are well separated, providing a photon number resolved detection of the light field.

Requirements

No other tools or instruments are needed.

Carrying out the experiment

The light pulse from the SP5601 ultra-fast LED-Driver is driven through an optical clear fiber into the SP5650C SiPM holder housing the sensor under test and connected to the SP5600. The output signal (from the SP5600) is connected to the input channel of the DT5720A Desktop Digitizer equipped with the charge integration firmware, and triggered by the SP5601 LED-driver. The SP5600 and the DT5720A are connected to the PC through the USB. Use the default software values or optimize the bias voltage and discriminator threshold. The horizontal axis of the acquired spectrum is the ADC channels, therefore ADC channel conversion ($\text{ADC}_{c.r.}$) factor can be calculated to perform the experiment and determine the main features of the SiPM.



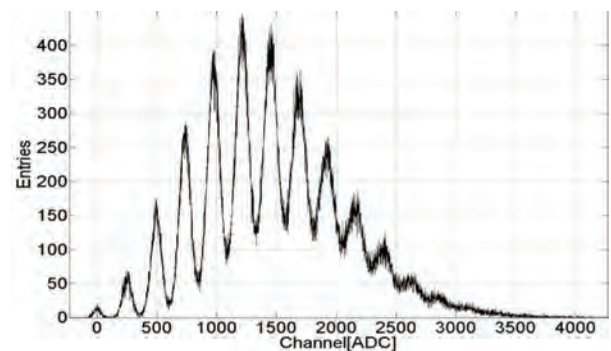
Experimental setup block diagram.

Results

The gain of the SiPM is evaluated from the output charge of the sensor. After the estimation of the ADC channel conversion factor ($\text{ADC}_{c.r.}$) and the distance between adjacent peaks ($\Delta \text{PP}(\text{ADC}_{ch})$), the SiPM gain can be calculated according to the following equation:

$$\text{Gain} = \frac{\Delta \text{PP}(\text{ADC}_{ch}) \cdot \text{ADC}_{c.r.}}{e}$$

The resolution power of the system can be evaluated plotting the σ of each peaks versus the number of peaks. The counts frequency, in absence of light, at 0.5 p.e. threshold represents the DCR. The ratio between the dark count at 1.5 p.e. threshold ($\text{DCR}_{1.5}$) and the value at 0.5 p.e. threshold ($\text{DCR}_{0.5}$) give the crosstalk estimation of the detector.



Spectrum of Hamamatsu S10362-11-100C.



Difficulty



Execution Time



SP5600E - EDUCATIONAL PHOTON KIT

Purpose of the experiment

Study the dependence of the main SiPM figures of merit on the bias voltage. Measurement of the breakdown voltage and identification of the optimal working point. The experiment requires the use of the LED source included in the kit.

Fundamentals

The main features of the SiPM are expected to depend on the bias voltage or, more specifically, on the overvoltage, the voltage in excess of the breakdown value:

- The gain is expected to depend linearly on the overvoltage
- The triggering efficiency, i.e. the probability for a charge carrier to generate an avalanche by impact ionization,

increases with the overvoltage till a saturation value is achieved. As a consequence, the Photon Detection Efficiency (PDE) increases together with the stochastic events (Dark Count Rate, Cross Talk and After Pulses) affecting the sensor response.

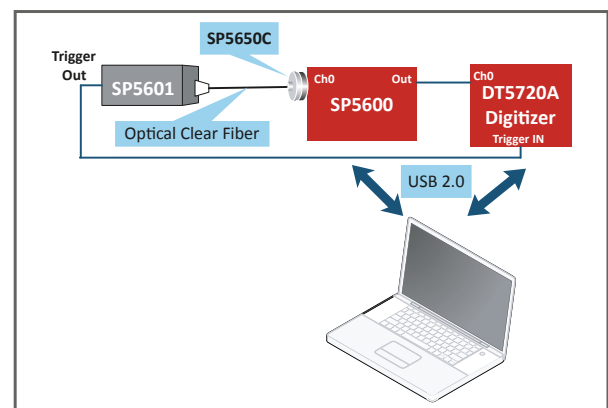
Actually, spurious events are expected to grow super-linearly and the determination of the optimal working point requires the definition of a proper figure of merit. Referring to the photon number resolving capability of the SiPM, the bias can be set to optimize the resolution power, i.e. the maximum number of resolved photons.

Requirements

No other tools or instruments are needed.

Carrying out the experiment

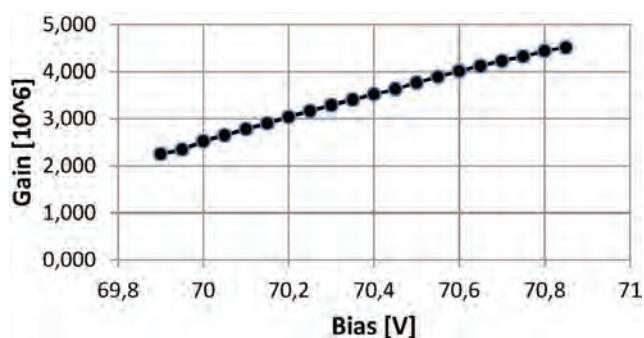
Mount one of the sensors (SP5650C) on the SP5600 and connect the analog output to the input of the DT5720A digitizer. Optically couple the LED and the sensor via the optical fiber, after having used the index matching grease on the tips. Set the internal trigger mode on the SP5601 and connect its trigger output on the DT5720A trigger IN. Connect via USB the modules to the PC and power ON the devices. Through the LabView graphical user interface (GUI), properly synchronize the signal integration and, for every voltage value, record the photon spectrum and measure directly the Dark Count and the Optical Cross talk. The measurement of the After Pulse is also possible but it requires most advanced analysis techniques.



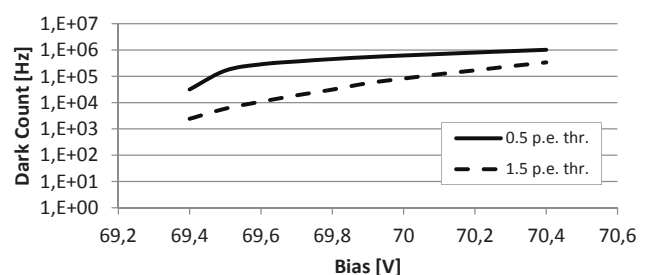
Experimental setup block diagram.

Results

As exemplary illustration, the trend of the gain vs. the bias voltage is shown, allowing as well the measurement of the breakdown voltage corresponding to the value at zero gain. The optimal working point by a measurement of the resolution power on the multi-photon peak spectrum is also evaluated in this experiment.



SiPM gain versus bias voltage.



Dark count versus bias voltage.

SP5600E - EDUCATIONAL PHOTON KIT

Difficulty



Execution Time



Purpose of the experiment

Gain, noise and photon detection efficiency (at fixed bias voltage) are affected by temperature. The student is driven through the measurement of the dependence of these critical figures.

Fundamentals

The gain in a SiPM biased at fixed voltage changes with temperature since the breakdown voltage V_{br} does it. Gain stabilization is a must and can be pursued tracking the V_{br}

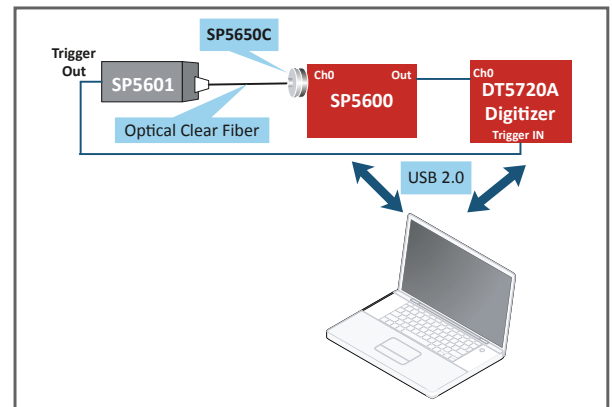
changes and adjusting the bias voltage accordingly. The rate of variation depends on the sensor, through the material properties. Noise depends on the thermal generation of charge carriers, so a significant dependence is expected as well.

Requirements

A temperature controlled box/room is essential.

Carrying out the experiment

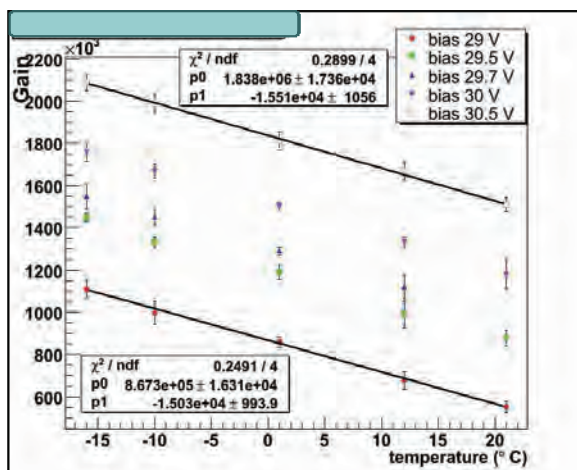
In a temperature controlled box, mount one of the sensors (SP5650C) on the SP5600 and connect the analog output to the input of the DT5720A digitizer. Optically couple the LED and the sensor via the optical fiber, after having used the index matching grease on the tips. Set the internal trigger mode on the P5601 and connect its trigger output on the DT5720A trigger IN. Connect via USB the modules to the PC and power ON the devices. Through the LabView graphical user interface (GUI), properly synchronize the signal integration and, for every temperature & voltage value, record the photon spectrum and measure directly the Dark Count and the Optical Cross talk..



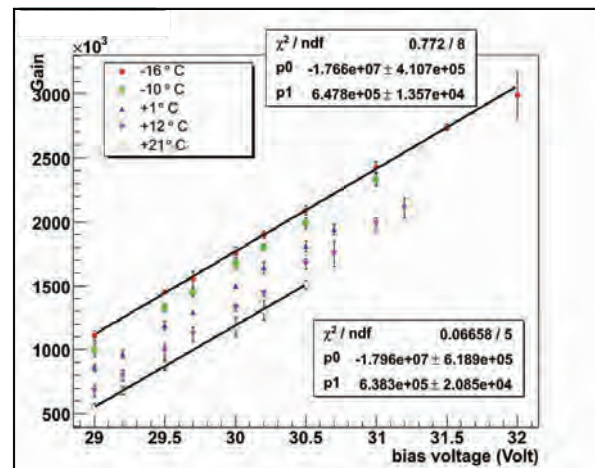
Experimental setup block diagram.

Results

Figures show the dependence of the gain upon temperature at various voltages and the voltage dependence at various temperatures. By the two set of results, the temperature coefficient of the sensor, i.e. the variation of the breakdown voltage with temperature, can be measured.



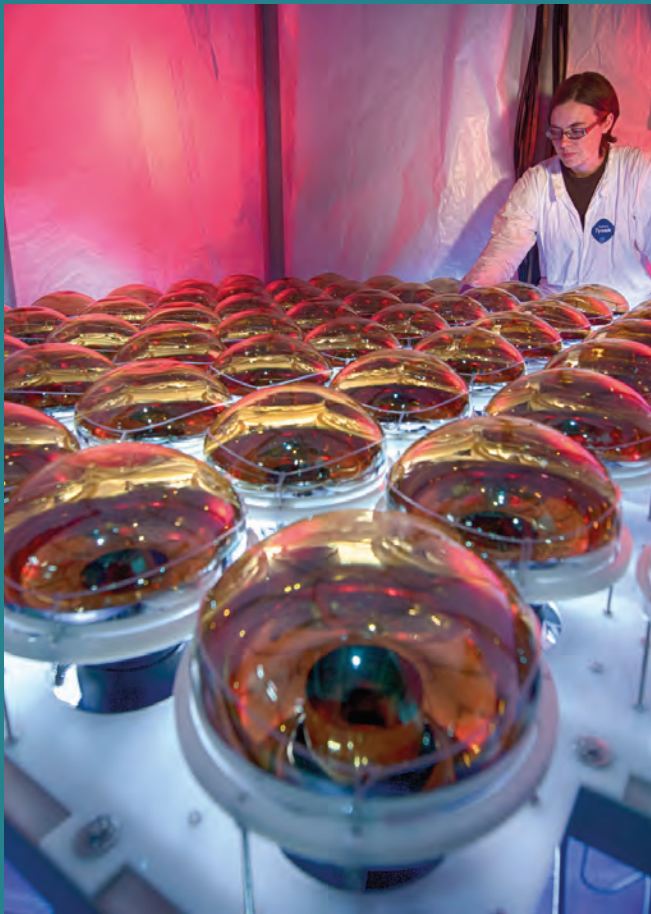
SiPM gain as a function of temperature, at different bias voltage values.



SiPM gain as a function of the bias voltage, at different temperature values.

A. Particle Detector Characterization

A.2 Photomultiplier Tube (PMT)



Photomultiplier Tubes (PMTs) have been one of the most important photon detection technologies in experimental physics for decades. Owing to their extremely high sensitivity, fast response, and excellent signal amplification capabilities, they have become essential instruments in a wide range of scientific and industrial applications, including nuclear and particle physics, medical diagnostics, analytical instrumentation, fluorescence spectroscopy, and radiation detection.

PMTs operate by exploiting the photoelectric effect to convert incident photons into electrical signals, which are then amplified through a cascade of dynodes to achieve gains of several orders of magnitude. This unique operating principle enables the detection of extremely weak light signals, making PMTs an ideal choice whenever high sensitivity and precise timing are required.

Before photomultiplier tubes can be effectively employed in experimental measurements, it is essential to understand their operating principles and performance characteristics. The experiments presented in this section introduce students to the characterization of PMTs through a series of hands-on laboratory activities. Typical measurements include the investigation of gain, operating voltage, signal response, linearity, and other parameters that determine detector performance under different operating conditions.

Through these experiments, students will gain practical experience in the characterization of vacuum photodetectors while developing skills in electronic measurements, data acquisition, signal analysis, and experimental data processing. This knowledge provides the foundation for the subsequent experimental activities of the handbook, where PMTs are employed as high-performance light sensors in a variety of physics experiments.

MEASUREMENT OF PHOTOMULTIPLIER PLATEAU CURVES

SG6020E

SP5640 - GAMMAEDU

Difficulty



Execution Time



Purpose of the experiment

The goal of this experiment is the identification of the working point of a photomultiplier by determining the plateau curve.

Fundamentals

Photomultiplier tubes (often abbreviated as PMT) are widely used Physics, in medical equipment, analytical instruments and industrial measurement systems. The PMTs make use of the photoelectric effect and have good response speed and sensitivity (low-light-level detection). Photomultiplier tubes are usually tested in combination with a ^{137}Cs radiation source and a NaI(Tl) scintillator. There are two characterization measurement methods in scintillation counting. One is the spectrum method which uses a pulse height analyzer to measure an energy spectrum. The other

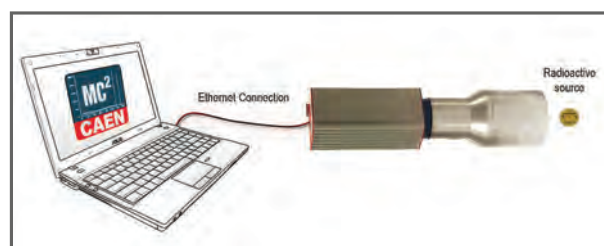
one, described in this experimental activity, is the counting method. Plateau characteristics are measured by setting a threshold value and counting all pulses with amplitudes greater than that value while changing the supply voltage for the photomultiplier tube. The plateau region is such that the count rate will not vary even if the supply voltage is changed within this region. The importance of operating the photomultiplier in the plateau zone is then understood for a correct use of each particle detection apparatus that includes this instrument.

Requirements

The present experiment was performed using ^{137}Cs source but the background can be use in replacement . 

Carrying out the experiment

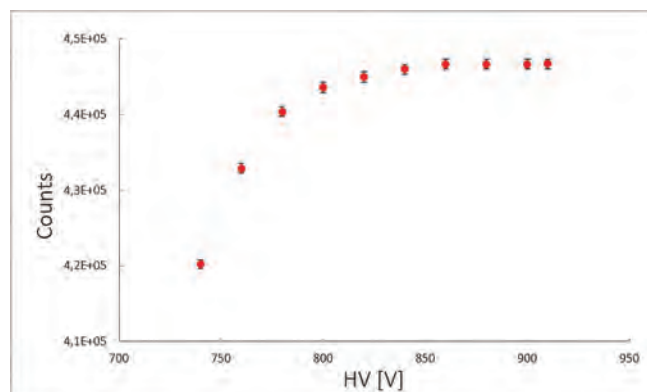
The experiment can be performed both by taking off the instrumentation from the backpack and using the backpack with the open zipper. To power ON ystream, press the ON/OFF button. Take care that the ystream internal battery is charged, otherwise use the external power system. Connect the Ethernet cable from ystream to the PC and configure the Ethernet network of your PC. Connect ystream to the MC²Analyzer software through Ethernet connection. Place the radioactive source close to the scintillator/under the central part of the backpack and run the software. Set the threshold value and keep it fixed for the whole measurement time, by varying the PMT supply voltage.



Experimental setup block diagram.

Results

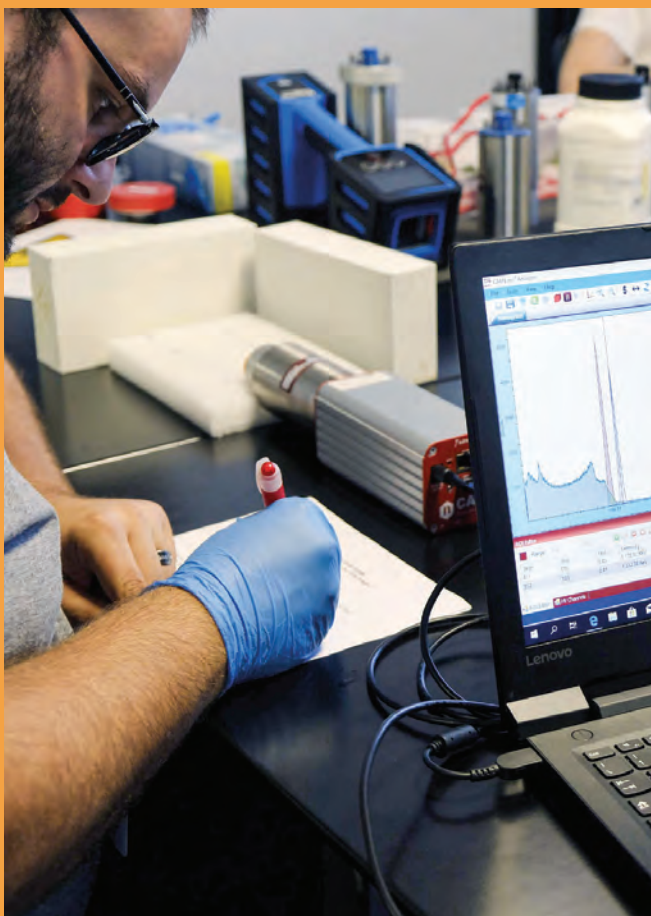
The identification of the working point where the output signals of the photomultiplier are less affected by variations in the power supply voltage.



Example of plateau characteristics.

B. Nuclear Physics and Radioactivity

B.1 γ Spectroscopy



The study of gamma radiation is one of the fundamental topics of nuclear physics and radiation detection. Gamma rays are high-energy photons emitted during the de-excitation of unstable atomic nuclei, often following radioactive decay processes. Their interaction with matter provides valuable information about both the properties of the radiation itself and the characteristics of the materials through which it passes.

The experiments presented in this section introduce the principles of gamma-ray spectroscopy through a series of hands-on laboratory activities. Students will investigate the mechanisms of gamma-ray interaction with matter, become familiar with the operation and calibration of radiation detectors, and learn how to acquire and analyze energy spectra. These experiments provide a solid foundation for understanding both the physical principles of nuclear radiation and the techniques employed in modern radiation measurements.

Gamma-ray spectroscopy is widely used in many scientific and technological fields, including nuclear physics, medical imaging, environmental monitoring, industrial inspection, archaeometry, and homeland security.

The experiments described in this section can be performed using different educational setups, including the Educational Gamma and Premium kits, the Emulation Kit, the Environmental and Environmental Plus kits, the GammaEDU Backpack, and the Open FPGA Kit.

SP5600C - EDUCATIONAL GAMMA KIT

Difficulty



Execution Time



Purpose of the experiment

Gamma radioactivity detection by using a system composed of a scintillating crystal coupled to a photon detector.

Fundamentals

Gamma rays interact with matter by three processes: Compton Scattering, Photoelectric Effect and Pair Production (whenever the energy exceeds the 1.022 MeV threshold corresponding to the $e^+ e^-$ rest mass). The cross section of each process depends on the energy of the gamma ray.

The Compton Effect is the inelastic scattering between the incoming photon and an atomic electron. In the Photoelectric Effect, the incident gamma ray transfers all of its energy to a bound electron which acquires a kinetic

energy equal to the incoming gamma energy decreased by the binding energy.

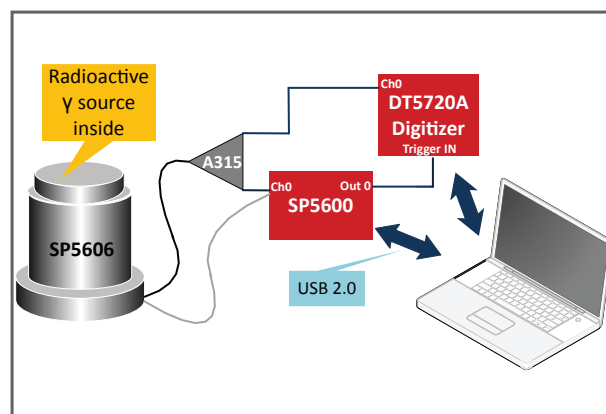
These processes convert, totally or partially, the gamma ray energy into kinetic energy of electrons (or positrons, in case of pair production). The interaction of the charged particles with the atomic and molecular systems of the medium results in excited states whose decay, possibly mediated, leads to light in the visible or UV region, eventually detected by the light sensor. A wide range of scintillator products is available today, differing for the light yield, the material properties, the time characteristics of the scintillation light and, last but not least, cost. The choice of the scintillator is essentially dependent on the specific targeted application.

Requirements

Gamma Radioactive Source. 

Carrying out the experiment

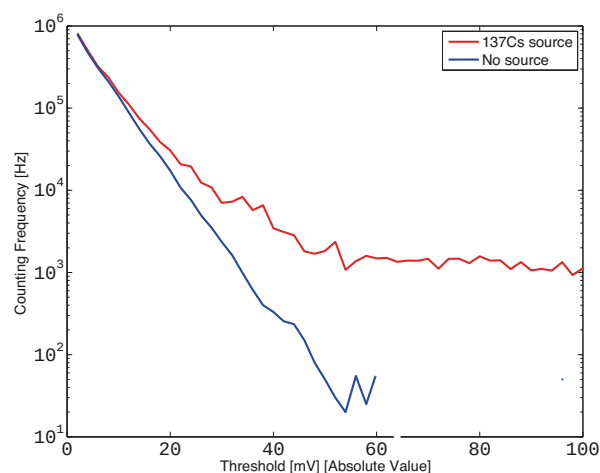
The selected scintillator crystal shall be coupled to the SiPM in the SP5607, through a thin layer of index matching grease to maximize the light collection. In order to avoid saturation, the output of the SiPM is divided using the A315 splitter: one branch is connected to the DT5720A and will be digitized. The other branch will be amplified by the SP5600 module, generating the trigger for the integration signal by the on-board leading edge discriminator or simply counting the pulses induced by the detected gamma ray.



Experimental setup block diagram.

Results

The student may get acquainted with the presence of radioactivity with a simple preliminary measurement, namely comparing the counting frequency as a function of the discriminator threshold with/without the source. Presuming the source, essentially in contact to the crystal, to be point like with respect to the crystal surface, and assuming its activity is known, the student may estimate for every threshold value the detection efficiency and the signal over noise ratio, building up an efficiency-purity plot. Exemplary results obtained with a ^{137}Cs source are shown. Moving away the source from the crystal, the law governing the variation of the flux can also be investigated.



Sensor output frequency as a function of the threshold in mV, with and without ^{137}Cs source.



Difficulty



Execution Time



SP5600C - EDUCATIONAL GAMMA KIT

Purpose of the experiment

Study the statistical distribution of the counting rates of a gamma radioactive source. Comparison of the data to the Poisson distribution, turning into a Gaussian as the mean number of counts grows.

Fundamentals

The number of radioactive particles detected over a time Δt is expected to follow a Poisson distribution with mean value μ . It means that for a given radioactive source, the probability that n decays will occur over a given time period Δt is given by:

$$P_{\mu}(n) = \frac{\mu^n}{n!} e^{-\mu}$$

Where μ is proportional to the sample size and to the time

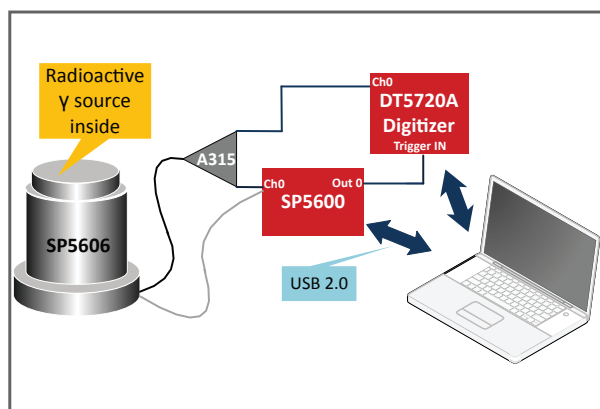
Δt and inversely proportional to the half-life $T_{1/2}$ of the unstable nucleus. As long as μ grows, the probability $P_{\mu}(n)$ is well approximated by a Gaussian distribution:

$$P(n) = \frac{1}{\sqrt{2\pi}\sigma} e^{-\frac{(n-\mu)^2}{2\sigma^2}}$$

Where $\sigma = \sqrt{\mu}$ is the standard deviation.

Requirements

Gamma Radioactive Source.



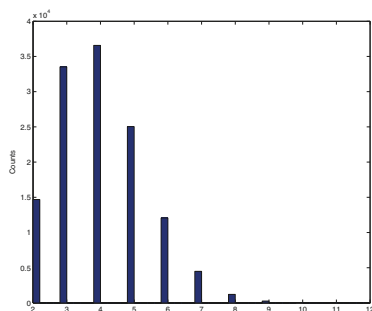
Block diagram of the experimental setup that makes use of the "Educational Gamma Kit".

Carrying out the experiment

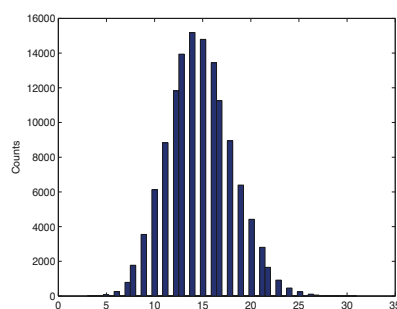
The selected scintillator crystal shall be coupled to the SiPM in the SP5607, through a thin layer of index matching grease to maximize the light collection. In order to avoid saturation, the output of the SiPM is divided using the A315 splitter: one branch is connected to the DT5720A and will be digitized. The other branch will be amplified by the SP5600 module, generating the trigger for the integration signal by the on-board leading edge discriminator or simply counting the pulses induced by the detected gamma ray. The discriminator threshold shall be defined looking at the spectrum and evaluating the dark count rate. Once this is properly set, the counting experiment shall be performed.

Results

Changing the counting window and/or the activity of the source or the threshold, the number of counts changes, with a probability density function moving from a Poissonian to a Gaussian shape. The student may play with the data, fitting them and comparing the expectations to the measurement.



Poissonian distribution.



Gaussian distribution.

SP5600C - EDUCATIONAL GAMMA KIT

Difficulty



Execution Time

**Purpose of the experiment**

Analysis of the spectrum of the deposited energy by a γ ray in a detector discloses the essence of the interaction of high energy photons with matter and allows to learn by doing the detector related effects.

Fundamentals

For γ -energy less than 2MeV, the interaction with matter is dominated by Compton scattering and Photo-absorption. The analysis of the Compton continuum of the deposited energy and of the photopeak conveys information on the characteristics of the decaying isotope as well as the effects due to the system noise, the detected photon statistics, the stochastic

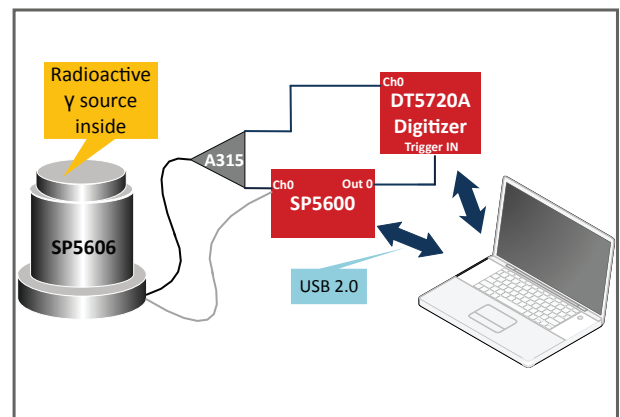
terms in the detector and the intrinsic resolution of the scintillator. The experiment presumes to use ^{137}Cs with its decays detected by a CsI crystal coupled to a Silicon Photomultiplier. The ^{137}Cs source is particularly interesting due to its low energy X ray line at 30 keV and the high energy gamma emission at 662 keV. The former is relevant to optimize the lower detection limit of the system; the latter is a standard to evaluate the energy resolution. The use of the 2 lines and the analysis of the Compton spectrum characteristics allow to perform a rough measurement of the linearity with a single isotope.

Requirements

Gamma Radioactive Source. 

Carrying out the experiment

The CsI scintillator crystal shall be coupled to the SiPM in the SP5607, through a thin layer of index matching grease to maximize the light collection. In order to avoid saturation, the output of the SiPM is divided using the A315 splitter: one branch is connected to the DT5720A and will be digitized. The other branch will be amplified by the SP5600 module, generating the trigger for the integration signal by the on-board leading edge discriminator. The discriminator threshold shall be defined looking at the spectrum and evaluating the dark count rate. Once this is properly set and the radioactive source is properly positioned, the spectrum can be recorded.



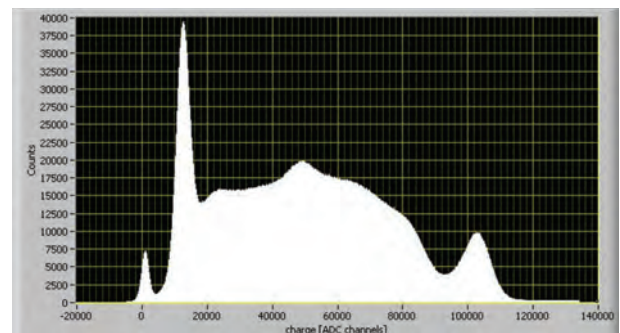
Block diagram of the experimental setup that makes use of the "Educational Gamma Kit".

Results

The figure shows a typical gamma spectrum, recorded with a very low energy threshold. The left over from the system noise is clearly visible, as well as the low energy line at 30 keV and the photopeak. For this specific spectrum, the energy resolution on the 662 keV peak corresponds to:

$$\text{Energy Resolution} = \frac{\text{FWHM}_{\text{peak}}}{\mu_{\text{peak}}} \cdot 100 \sim 10\%$$

$\text{FWHM}_{\text{peak}}$ = full width at half maximum of the peak μ_{peak} = channel number of the peak centroid.



^{137}Cs spectrum.



Difficulty



Execution Time



SP5600C - EDUCATIONAL GAMMA KIT

Purpose of the experiment

Recording and comparing the γ energy spectra of several radioactive sources is the main goal of the experiment. The photopeaks are used to calibrate the response of the system and to measure the energy resolution.

Fundamentals

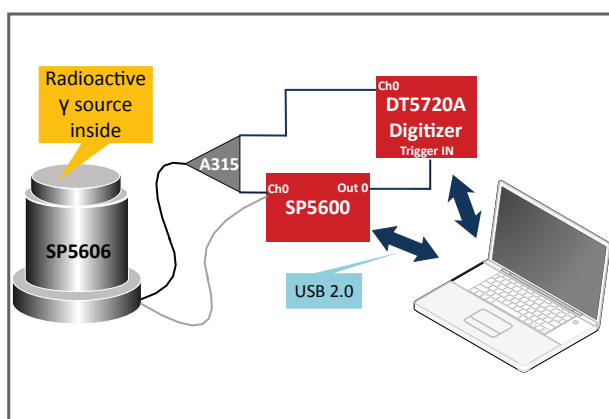
Linearity and energy resolution are the main figures of merit of a spectrometric system. In the proposed experiment, based on a scintillating crystal coupled to a Silicon Photomultiplier, deviations in the linearity may be due to the sensor or the front-end electronics saturation. The student is guided through the analysis of the response curve using a series of isotopes up to the MeV energy by a ^{60}Co source and to disentangle the

different effects. At the same time, the energy resolution of the system is measured by the width of the photopeaks and the results compared to what is expected by the fluctuations in the number of detected scintillation photons, the system noise, the sensor stochastic effects, the intrinsic resolution of the scintillator.

This is following an initial activity on the optimization of the operating parameters by an analysis of the photopeak position and the resolution for a single isotope.

Requirements

Gamma Radioactive Source. 



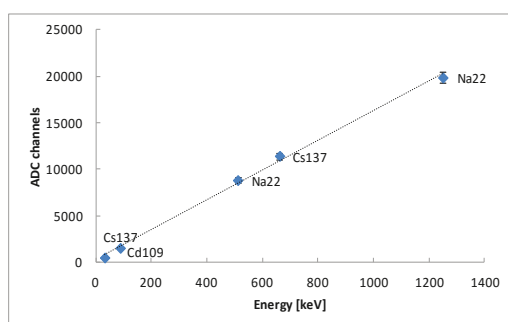
Block diagram of the experimental setup that makes use of the "Educational Gamma Kit".

Carrying out the experiment

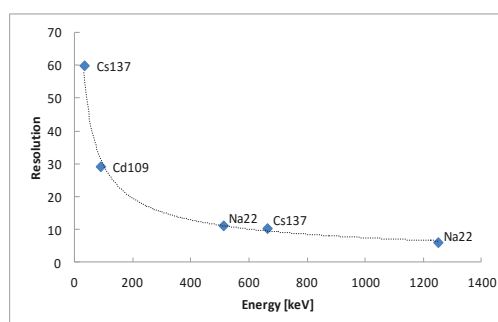
The scintillator crystal shall be coupled to the SiPM in the SP5607, through a thin layer of index matching grease to maximize the light collection. In order to avoid saturation, the output of the SiPM is divided using the A315 splitter: one branch is connected to the DT5720A and will be digitized. The other branch will be amplified by the SP5600 module, generating the trigger for the integration signal by the on-board leading-edge discriminator. The discriminator threshold shall be defined looking at the spectrum and evaluating the dark count rate. Once this is set and the radioactive source is properly positioned, the spectrum can be recorded.

Results

By fitting the photopeaks with a Gaussian curve, the system linearity as a function of energy is verified. The peak widths are determining the energy resolution. At more advanced level, the interpretation of the results accounting for the system properties may be performed.



Energy Calibration.



Energy dependence of the system resolution.

A COMPARISON OF DIFFERENT SCINTILLATING CRYSTALS: LIGHT YIELD, DECAY TIME AND RESOLUTION

SG6115A



SP5600C - EDUCATIONAL GAMMA KIT

Difficulty



Execution Time



Purpose of the experiment

Compare the basic characteristics of different scintillating crystals, namely the light yield and the decay time of the scintillation light. Verify the effect on the energy resolution.

Fundamentals

Scintillating materials exhibit various characteristics related to light yield and the characteristic time of emission. The CAEN spectrometer is equipped with three different crystals: BGO (Bismuth Germanate), LYSO(Ce) (Cerium-doped Lutetium Yttrium Orthosilicate), CsI(Tl) (Thallium-doped Cesium Iodide). All of them have the same volume ($6 \times 6 \times 15 \text{ mm}^3$), are polished on all sides, and coated with a white epoxy on 5 faces. One $6 \times 6 \text{ mm}^2$ face is open to be coupled with the Silicon Photomultiplier. The main characteristics

of the crystals are summarized in the table alongside. The light yield affects the energy resolution. This is also influenced by the decay time, which constrains the integration time and implies a different effect of the sensor's stochastic effects (dark counts and afterpulses).

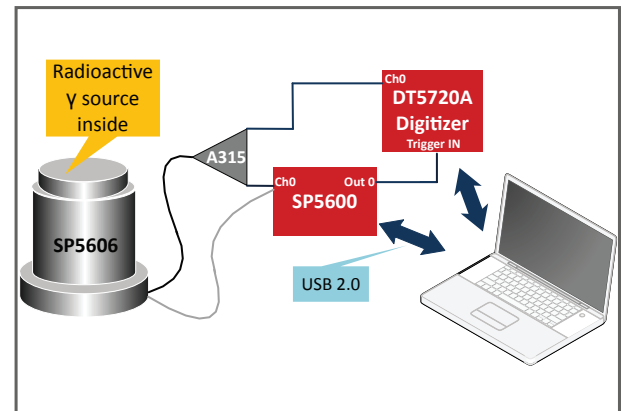
	BGO	LYSO(Ce)	CsI(Tl)
Density (g/cm^3)	7.13	7.4	4.51
Decay Time (ns)	300	40	1000
Light Yield (ph./MeV)	8200	27000	52000
Peak emission (nm)	480	420	560
Radiation length (cm)	1.13	1.14	1.85
Reflective index	2.15	1.82	1.78

Requirements

Gamma Radioactive Source.

Carrying out the experiment

The scintillator crystal shall be coupled to the SiPM in the SP5607, through a thin layer of index matching grease to maximize the light collection. In order to avoid saturation, the output of the SiPM is divided using the A315 splitter: one branch is connected to the DT5720A and will be digitized. The other branch will be amplified by the SP5600 module, generating the trigger for the integration signal by the on-board leading edge discriminator. The discriminator threshold shall be defined looking at the spectrum and evaluating the dark count rate. Once this is set and the radioactive source is properly positioned, the spectrum can be recorded. The procedure shall be repeated for every crystal.

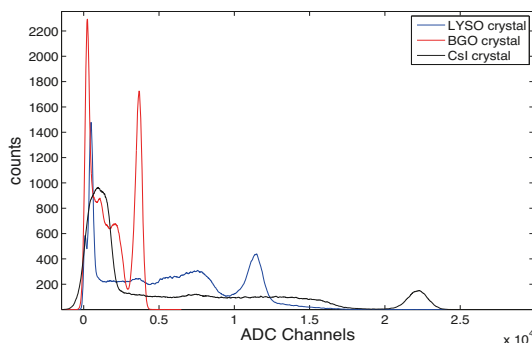


Block diagram of the experimental setup that makes use of the "Educational Gamma Kit".

Results

The crystal characteristics are investigated recording a source spectrum (for example ^{137}Cs) with the three different crystals, optimizing the integration time as a function of the scintillation decay time.

According to table, the Light Yield of the three crystal is very different. LYSO(Ce) has a light yield three times greater than the BGO, and CsI(Tl) light yield is twice than LYSO(Ce). The analysis of the signal waveform or the trend of the charge vs integration time leads to the measurement of the time characteristics of the scintillator.



^{137}Cs energy spectra. Blue spectrum corresponds to the acquisition through LYSO crystal, the red and black ones respectively with BGO and CsI crystals.

	Light Yield Ratio (from datasheet)	Peak Position Ratio
LYSO/CsI	0.52	~0.51
LYSO/BGO	3.29	~3.11
BGO/CsI	0.16	~0.16

Experimental results of Light Yield Ratio.



Difficulty



Execution Time



SP5600C - EDUCATIONAL GAMMA KIT

Purpose of the experiment

The main goal of the experiment is the measurement of the γ radiation attenuation coefficient for different materials and different energies.

Fundamentals

The attenuation of a γ radiation flux passing through matter is described by the exponential law

$$I(x) = I_0 \cdot e^{-\mu x}$$

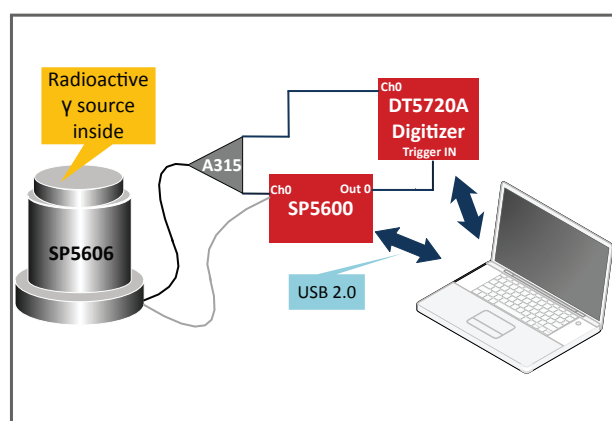
where I_0 is the incident photon flux and $I(x)$ measures the flux of γ rays emerging from a layer x of material without

having interacted. The coefficient μ depends on the material properties (atomic number, density) and on the energy of the impinging photon.

The student is guided towards the development of complementary measurement techniques based on counting and on the analysis of the spectrum, performing the experiment for different materials (including PMMA, a water equivalent solid state organic material used in medical dosimetry).

Requirements

Gamma Radioactive Source. ☢



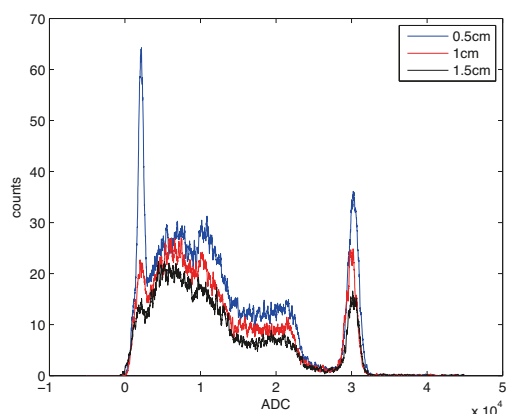
Block diagram of the experimental setup that makes use of the "Educational Gamma Kit".

Carrying out the experiment

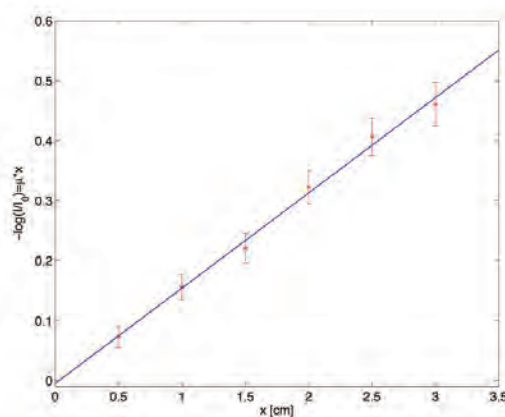
The scintillator crystal shall be coupled to the SiPM in the SP5607, through a thin layer of index matching grease to maximize the light collection. In order to avoid saturation, the output of the SiPM is divided using the A315 splitter: one branch is connected to the DT5720A and will be digitized. The other branch will be amplified by the SP5600 module, generating the trigger for the integration signal by the on-board leading edge discriminator. The discriminator threshold shall be defined looking at the spectrum and evaluating the dark count rate. Once this is set the SP5609 absorption tool shall be mounted. The experiment can be performed for every absorber thickness in counting mode and analysing the spectrum, measuring the events in the photopeak for a constant predefined time interval.

Results

Exemplary results are shown below, reporting the variation of the events in the photopeak for different absorber thickness, a plot verifying the exponential absorption law and the dependence of the absorption coefficient on the energy.



Gamma spectra acquired with different absorber thicknesses.



Linear dependence of logarithmic intensity of gamma rays as a function of penetration thickness.

PHOTONUCLEAR CROSS-SECTION / COMPTON SCATTERING CROSS-SECTION

SG6117A

SP5600C - EDUCATIONAL GAMMA KIT

Difficulty



Execution Time



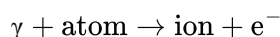
Purpose of the experiment

Determination of the ratio of the effective cross-sections due to Compton and Photoelectric effects as a function of photons energy.

Fundamentals

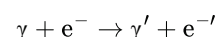
Gamma rays interact with matter by three processes: Compton Scattering, Photoelectric Effect and Pair Production (whenever in the energy range up to 2 MeV, gamma rays interact with matter by two processes:

- Photoelectric Effect, dominant at energy less than 100 KeV. In this process the photon energy is completely transferred to atomic electron bounded



- Compton Scattering, linked to the elastic collision

between electrons and photons and relevant at 1 MeV energy level



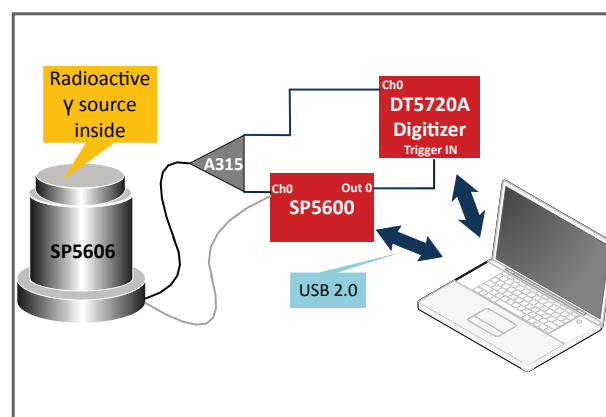
The predominant mode of interaction depends on the energy of the incident photons and the atomic number of the material with which they are interacting. From the acquired γ -spectrum, it is possible to estimate the fraction of events due to Compton scattering and those caused by the photoelectric. The ratio of the event fractions is used to determine the ratio of the two effective cross-sections that depends on the detector size.

Requirements

Gamma Radioactive Source. 

Carrying out the experiment

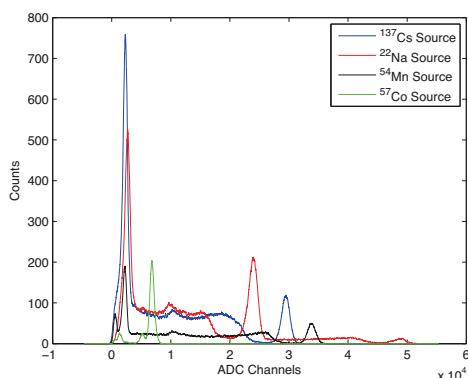
Spread the optical grease on the open face of the scintillating crystal, insert this crystal side in the SP5607 spectrometer. Connect the power cable to the SP5600 module and connect the other cable of the spectrometer to the splitter A315. Connect the two split outputs to SP5600 channel 0 and DT5720A channel 0. Use the SP5600 digital output as DT5720A "trigger IN". Use the default software values or optimize the parameters to choose the discriminator cut-off threshold in mV. Switch off the power supply, open the spectrometer and insert the radioactive gamma source to acquire the first spectrum. After that, switch off the power supply, open the spectrometer, change the radioactive gamma source and repeat the measurement.



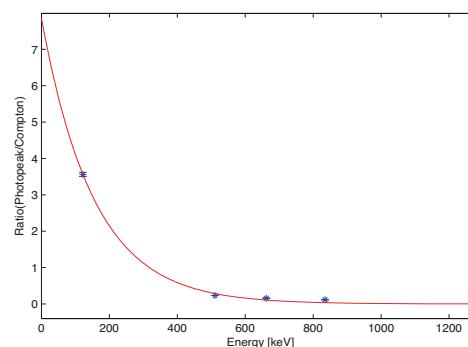
Block diagram of the experimental setup that makes use of the "Educational Gamma Kit".

Results

By using several radioactive sources, the energy dependence of the ratio between the cross-sections of two phenomena can be examined, by verifying that the Photoelectric Effect cross section decreases with increasing energy compared to the Compton Scattering cross section for the used detector size.



Spectra of radioactive sources used to estimate the ratio of Photonuclear and scattering Compton cross sections.



Behaviour of the ratio between Photopeak and Compton contributions as a function of energy.



Difficulty



Execution Time



SP5600EMU - EMULATION KIT

Purpose of the experiment

Study the characteristics of the ^{137}Cs spectrum, with special relevance given to the low energy spectrum. The student can learn effects related to the experimental observation of a gamma decay and have basic information about the experimental setup used in gamma spectroscopy. Estimate the energy of the backscatter peak and of the K_{α} line.

Fundamentals

The Compton effect is linked with experimental issues, since it is caused by the interaction of photons with the electrons in an instrument that measures the gamma radiation. In a real detector setup, some photons can and will undergo one or potentially more Compton scattering processes (e.g. in the housing material of the radioactive source, in shielding material or material otherwise surrounding the experiment) before entering the detector material. This leads to a peak structure, the so-called backscatter peak.

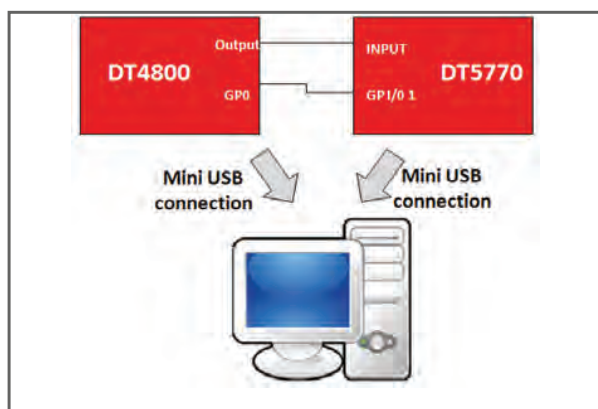
The basic principle for the backscatter peak formation is the following: gamma-ray sources emit photons isotropically, some photons will undergo a Compton scattering process

with a scattering angle close to 180° and some of these photons will subsequently be detected by the detector. The result is an excess of counts in the Compton part of the spectrum, the so-called backscatter peak. This peak has an energy approximately equal to the photopeak energy minus the Compton edge energy.

The ^{137}Cs gamma photopeak at 661 keV is responsible also for a low energy emission (i.e. emission of an X-ray). This is due to the decay mechanism of ^{137}Cs : it decays via β decay into an excited state of Barium-137, which then passes to the ground state, giving rise to the 661 keV photopeak. Emission of a 661 keV γ photon is not the only way excited barium gives off its energy. In some cases Barium-137 can transfer its energy to an electron of its 1s atomic shell ("internal conversion"). The hole in the 1s shell is replenished from higher shells. This process gives rise to the emission of the characteristic X radiation of barium, which is the K_{α} line nearly at 32 keV (X rays are photons in the range 100 eV÷100 keV).

Requirements

No other tool is needed



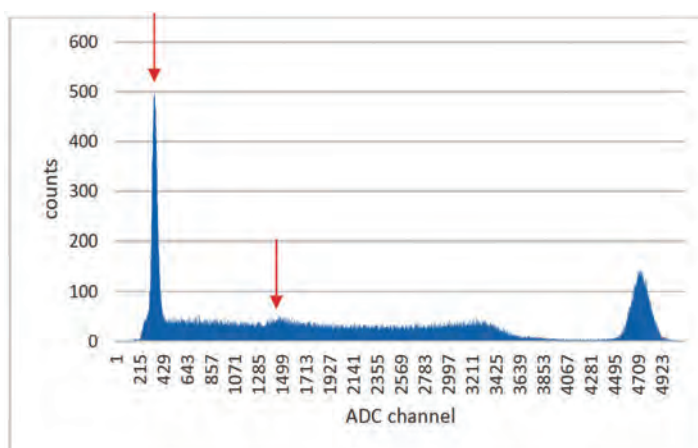
Experimental setup block diagram for the experiment.

Carrying out the experiment

To perform the experiment, connect the DT4800 output to the input channel of the MCA DT5770 and use the DT4800 GP0 as digitizer "trigger IN". The Emulation Control Software Interface allows user to generate exponential decay signals with programmable rise time and fall time and it is possible to emulate signals from ^{137}CsI radioactive. The spectrum can be recorded and analyzed by the MCA.

Results

The user can calibrate the system by using the spectrum itself. The backscatter peak and the K_{α} line can be identified. After calibrating the spectrum, it is possible to estimate the energy of the two peaks and compare them with theoretical predictions.



and the K_{α} line are indicated with the red arrows.

SP5600EMU - EMULATION KIT

Difficulty



Execution Time

**Purpose of the experiment**

Determine the activity of a ^{60}Co source from its gamma spectrum. Learn about the meaning of the sum peak, visible in the spectrum of some radioactive sources.

Fundamentals

The ^{60}Co spectrum presents two distinct gamma photopeak in its spectrum, respectively corresponding to photons γ_1 and γ_2 at 1.17 MeV and 1.33 MeV. For the purpose of this experiment, we can assume that each of these gamma rays are isotropically distributed. In other words, if γ_1 departs in a particular direction, γ_2 can go in any direction that it wishes. There is a certain probability that γ_2 will go in the same direction as γ_1 . If this occurs the energies of γ_1 and γ_2 will be summed in the detector. Hence a sum peak will show up in the spectrum, at nearly 2.5 MeV.

We can estimate the activity of the source by calculating the counts under the two main peaks and under the sum peak, i.e. calculating their area Σ . For the case of ^{60}Co , we have that the counts under the sum peak can be evaluated as

$$\Sigma_{\text{SUM}} = \frac{\Sigma_1 \Sigma_2}{A t}$$

Where A is the activity of the source and t is the acquisition time.

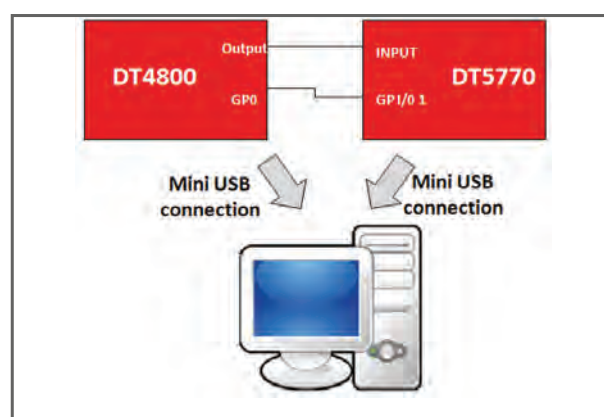
Therefore, fitting the peaks with a gaussian and calculating their area Σ , it is possible to estimate the activity of the ^{60}Co source used to record the available spectrum.

Requirements

No other tool is needed.

Carrying out the experiment

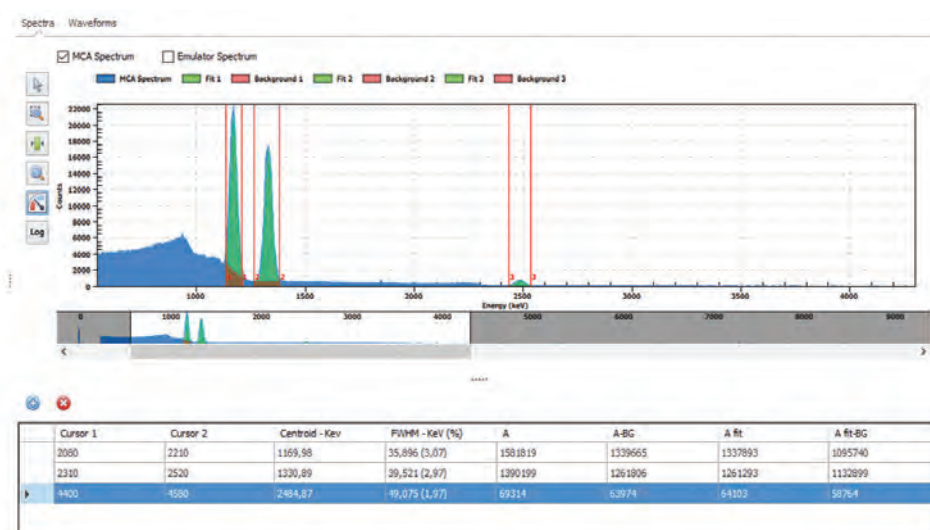
To perform the experiment, connect the DT4800 output to the input channel of the MCA DT5770 and use the DT4800 GP0 as digitizer "trigger IN". The Emulation Control Software Interface allows user to generate exponential decay signals with programmable rise time and fall time and it is possible to emulate signals from C0-60 radioactive source. The spectrum can be recorded and analyzed by the MCA.



Experimental setup block diagram for the experiment.

Results

The student should verify that, after the spectrum calibration, the sum peak is nearly at 2.5 MeV. From the formula given above, using the live time in seconds, the student can estimate the activity of ^{60}Co directly in Bq. A calculation made for a spectrum acquired in 100 seconds gives an activity of nearly 264 kBq.



The ^{60}Co complete spectrum acquired by the MCA and plotted by the Emulation Software.

B. Nuclear Physics and Radioactivity

B.2 γ Environmental Radioactivity Indoor



Radioactivity is often associated only with nuclear accidents or weapons. In reality, naturally occurring radioactive isotopes are constantly present in our environment, and their emissions can be safely detected and studied using appropriate instrumentation.

The experiments presented in this section introduce the fundamental principles of environmental radioactivity through a series of hands-on laboratory activities. Using the Environmental Kit and Environmental Kit Plus, students will investigate gamma radiation emitted by common natural and everyday materials, such as soil samples and camping lantern mantles, learning how to acquire, interpret, and compare radiation measurements.

These activities provide a practical introduction to radiation detection techniques while helping students develop a deeper understanding of natural radioactivity and its many applications in environmental monitoring, science, and education.

ENERGY CALIBRATION OF SYSTEM BASED ON LYSO CRYSTAL AND FERTILIZER SAMPLE

SG6140C

SP5630EN - ENVIRONMENTAL KIT

Difficulty



Execution Time



Purpose of the experiment

Recording γ energy spectra of several radioactive sources and detecting the photopeaks to calibrate the response of the system is the main goal of the experiment.

Fundamentals

The calibration of the spectrum is the first step to be done in a typical experiment. The settings, like the trigger threshold, gate width, etc., used in the calibration should be used in the following measurements proposed in the Environmental kit. It is usually convenient to use radioactive sources with a wide range of energies, from

hundreds keV to MeV. In the proposed experiment we take advantage of the LYSO(Ce) (Cerium-doped Lutetium Yttrium Orthosilicate) crystal (202 keV and 307 keV) and the Fertilizer sample (1468 keV) to have a calibration curve for the full spectrum range. The LYSO is also a scintillator material which can be coupled with SiPM or PMTs to detect gamma rays.

Requirements

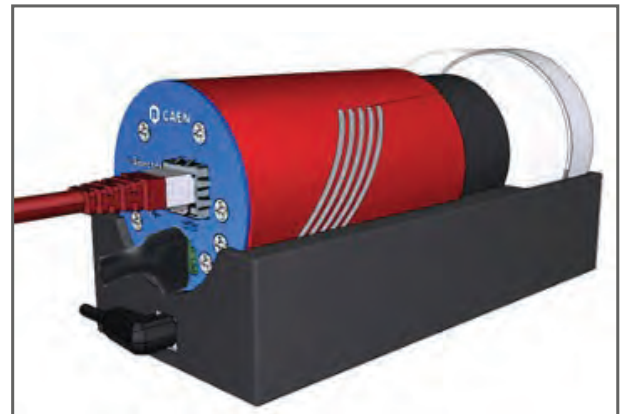
No other tool is needed..

Carrying out the experiment

Put the i-Spector digital into the base and place, one at a time, the radioactive sources to be used for the calibration, like, for example, the LYSO crystal and the Fertilizer to have two/three points for calibration. Power on the i-Spector and connect the Ethernet cable. Wait until the temperature is stable from the web interface (it can take half an hour from power on).

Check the waveform, modify the threshold and gate width, if needed, then start the measurement of the energy spectrum.

Take for example 5 minutes of acquisition with the LYSO crystal sample and 30 minutes of acquisition with the Fertilizer. Acquisition time with laboratory radioactive sources can be reduced according to the source activity. Select the ROIs and use the calibration tool to calibrate the spectrum.



Experimental setup.



Linear dependency in the Energy Calibration.

Results

By fitting the photopeaks with a Gaussian curve, the system linearity as a function of energy is verified. The final calibration function is used for the consecutive activities.



Difficulty



Execution Time



SP5630EN - ENVIRONMENTAL KIT

Purpose of the experiment

Measurement of the background radioactivity to be subtracted from the energy spectra of the samples.

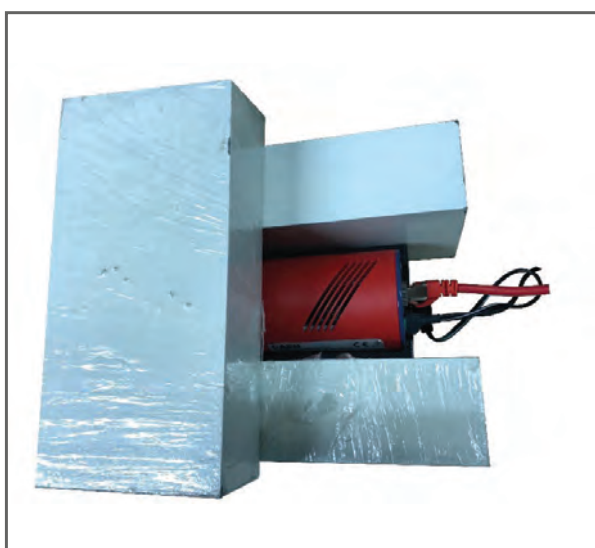
Fundamentals

The main contributors to the background energy spectrum are the gamma radiations that originate from naturally occurring radioactive isotopes dispersed in the environment and the materials that surround the detector, and the radiations whose origin can be traced to cosmic rays. To

properly identify the radioactive source and its activity, the background must be acquainted. The background spectrum is obtained by removing the radioactive source and must be acquired in the same conditions of the desired spectra. A possibility is to use lead blocks to cover the system and reject as much as possible environmental radioactivity that could hide interesting peaks.

Requirements

Lead blocks are strongly suggested.



Experimental setup block with Lead blocks covering the active scintillator of i-Spector digital.

Carrying out the experiment

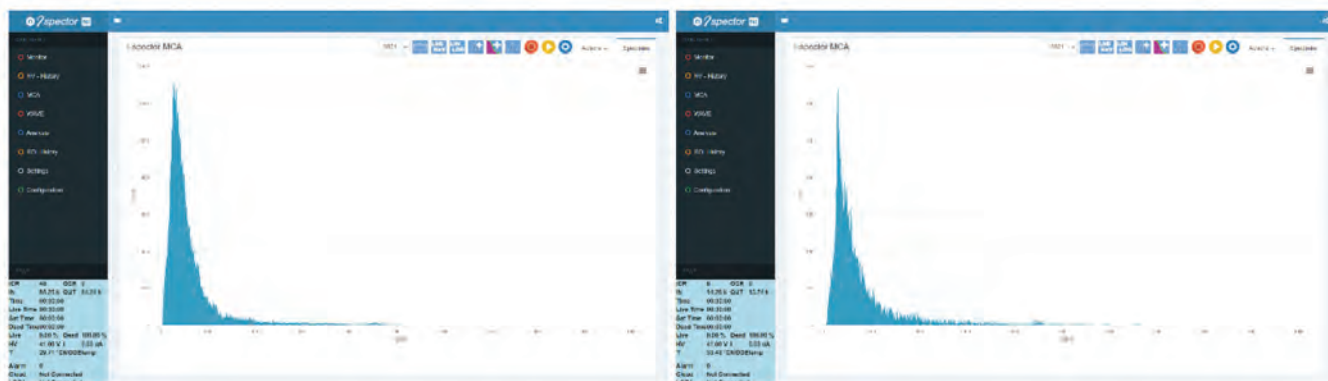
Decide whether or not to use the Lead blocks to cover the system. The entire system can be covered by lead blocks, as shown in the figure below, just taking care to leave air flow for the i-Spector base fans. In any case, it is important to make all the measurements on the same conditions of the background one, so that the background subtraction can be made easily. The same software settings must be applied as well, including the acquisition time, so that the background subtraction can be done bin-by-bin in the energy spectrum.

Put the i-Spector digital into the base. No sample is required in this experiment. Power on the i-Spector and connect the Ethernet cable. Wait until the temperature is stable from the web interface (it can take half an hour from power on).

Check the waveform, modify the threshold and gate width, if needed, then start the measurement of the energy spectrum. Take for example 30 minutes of spectra acquisition.

Results

The user can easily check how lead blocks reduce the gamma radioactivity, by comparing the spectra with and without lead blocks (left and right respectively). A factor of 4 in the background reduction is visible when using the Lead blocks.



Environmental background acquired without Lead blocks (on the left) and with Lead blocks (on the right). Note the different scale on the y-axis. The radioactivity is reduced by a factor of about 4 when using the blocks.

FERTILIZER AND PHOTOPEAK IDENTIFICATION

SG6142C

SP5630EN - ENVIRONMENTAL KIT

Difficulty



Execution Time



Purpose of the experiment

Record the energy spectrum of Fertilizer sample and identify the Potassium peak. The experience will guide the user to select a ROI and perform a Gaussian fit on the peak. This sample can be used also as a reference for the spectrum calibration.

Fundamentals

Potassium is a natural element whose radioactive isotope ^{40}K is widely available on Earth, especially in food and in human bodies. It plays a key role in geologic fields for the dating samples and rocks. Indeed, one of the main decay is in ^{40}Ar , which remains locked up in minerals. Knowing the decay time of ^{40}K into ^{40}Ar , and measuring the ratio

between the two elements, it is possible to give a precise estimate about the origin of that material.

Another interesting application is the so-called Banana Equivalent Dose (BED), a “user-friendly” unit to measure radioactivity. Bananas naturally contains ^{40}K and 1 BED corresponds to $0.1 \mu\text{Si}$ of equivalent dose. To understand the proportions, consider that a dental X-ray corresponds to eating 50 bananas, an average daily dose of natural background is 100 BED, a fatal dose is 100 million bananas. This quantity has been introduced to get users familiar with natural low-radioactive objects.

Requirements

No other tool is needed.

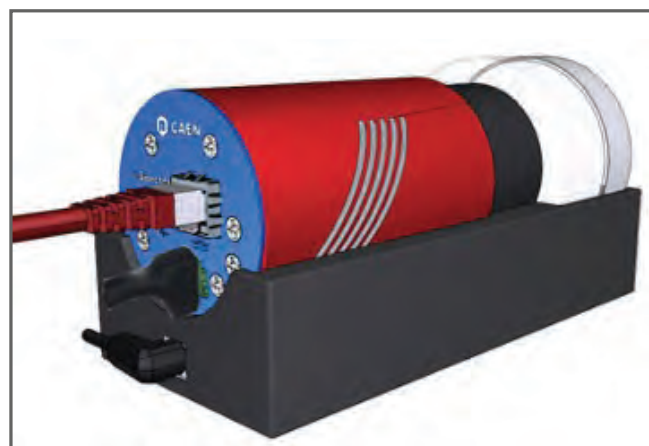
Carrying out the experiment

Put the i-Spector digital into the base and place the Fertilizer box into the place-holder. Power on the i-Spector and connect the Ethernet cable. Wait until the temperature is stable from the web interface (it can take half an hour from power on).

Check the waveform, modify the threshold and gate width, if needed, then start the measurement of the energy spectrum.

Take 30 minutes of acquisition with the Fertilizer.

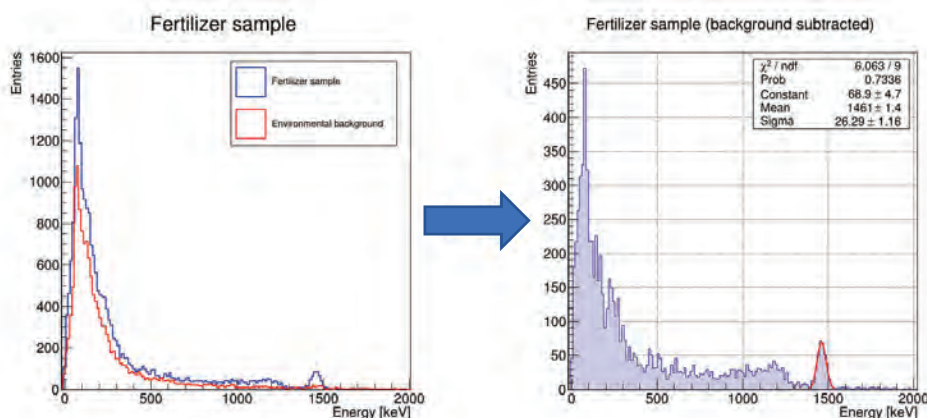
NOTE: in case of background measurement, settings and acquisition time must be the same. Lead blocks could help in distinguish a clearer peak but they must be used if just employed in background measurement only.



Experimental setup.

Results

Several steps can be done in this experiment. First, the background subtraction by saving the .csv of the two and by making a bin-by-bin subtraction of the two spectra. A small portion of the ^{40}K peak can be seen in the background spectrum too. The ^{40}K peak can be then selected through a ROI and fitted by means of a Gaussian function. The peak can be used together with the LYSO crystal for the energy calibration of the system (SG6140C).



Fertilizer sample: total contribution and background on the left; background subtracted on the right with a Gaussian fit on the ^{40}K peak. The mean value is in agreement with the expected value of 1460.8 keV



Difficulty



Execution Time



SP5630EN - ENVIRONMENTAL KIT

Purpose of the experiment

Record the energy spectrum of the Soil sample and identify the peaks, after the energy calibration, by knowing the decay chain of Thorium and Uranium.

Fundamentals

Natural radioactivity has several sources that can be classified into two broad categories: high energy cosmic rays incident on the Earth's atmosphere and releasing secondary radiation (cosmic contribution); and radioactive nuclides generated during the formation of the Earth and still present in the Earth's crust (terrestrial contribution).

The terrestrial contribution is mainly composed of the radionuclides of the uranium and thorium decay chains

together with radioactive potassium. In most circumstances, radon, a noble gas produced in the radioactive decay of uranium, is the most important contributor to radiation exposure.

Natural radionuclides, both terrestrial and cosmogenic, migrate in the environment through different pathways: air, water, rock, soil, and the food chain. Radionuclides may then enter the human body through ingestion (food and drinking water) and inhalation giving the so-called internal exposure. External exposure is due to cosmic radiation and radiation from terrestrial radionuclides present in soil, rocks, and building materials.

Requirements

No other tool is needed

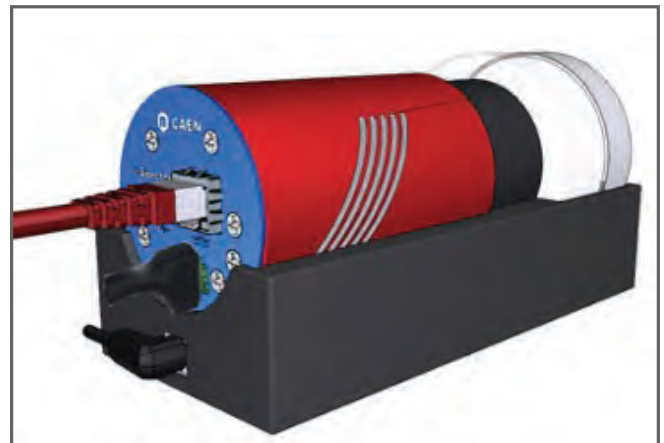
Carrying out the experiment

Put the i-Spector digital into the base and place the Soil box into the place-holder. Power on the i-Spector and connect the Ethernet cable. Wait until the temperature is stable from the web interface (it can take half an hour from power on).

Check the waveform, modify the threshold and gate width, if needed, then start the measurement of the energy spectrum.

More than 30 minutes of acquisition need with the Soil sample.

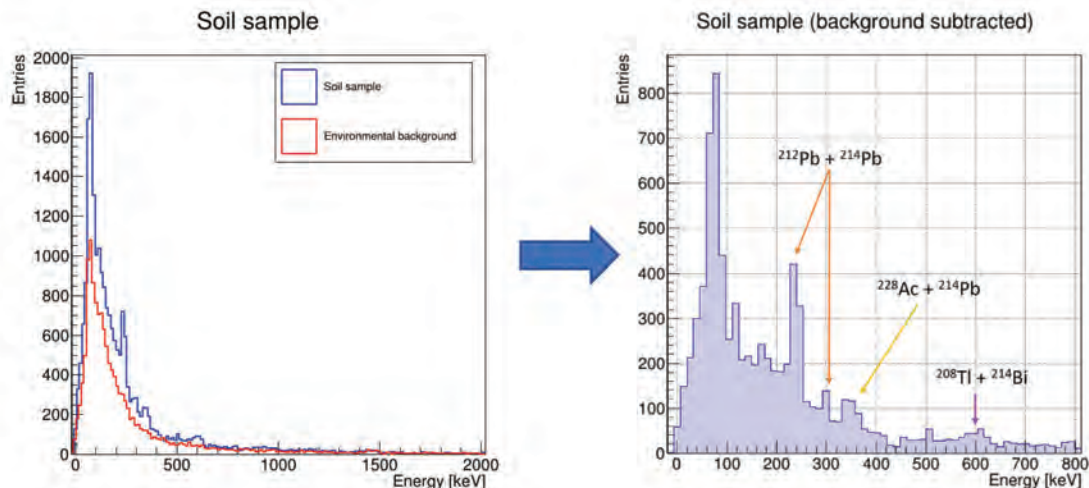
NOTE: in case of background measurement (SG6140C), settings and acquisition time must be the same. Lead blocks could help in distinguish clearer peaks but they must be used if just employed in background measurement only.



Experimental setup.

Results

After the background subtraction, it is possible to recognize peaks coming from the Uranium or Thorium chain, as shown in the picture below.



Soil sample: total contribution and background on the left; background subtracted on the right. The visible peaks from the ^{238}U and ^{232}Th are highlighted in the spectrum.

SP5630EN - ENVIRONMENTAL KIT

Difficulty



Execution Time



Purpose of the experiment

This activity shows how to compare different spectra together.

Fundamentals

Spectra comparison is a very common procedure in statistics and physics and consist of the superposition of different spectra, taken in the same conditions, or normalized to a common state. For example, radioactive sample and background spectra can be superimposed to visually show the differences and highlight the signal contribution.

Different sample spectra can be superimposed too, like

for example the Soil and Fertilizer samples to see how in the same amount of time the two samples emitted. In the case of comparison of radioactive samples with a big activity difference, the normalization could be done for the total number of events.

Another possible comparison is by using a different detector, like the High Purity Germanium detector (HPGe), or a different system, like the GammaEDU backpack SP5640, composed of photomultiplier tube (PMT) coupled to a NaI scintillating crystal (0,3 L).

Requirements

No other tools or instruments are needed.

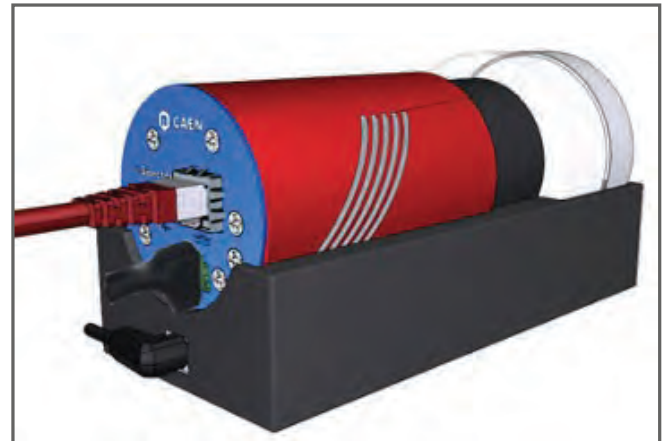
Carrying out the experiment

Put the i-Spector digital into the base and place the Soil box into the place-holder. Power on the i-Spector and connect the Ethernet cable. Wait until the temperature is stable from the web interface (it can take half an hour from power on).

Check the waveform, modify the threshold and gate width, if needed, then start the measurement of the energy spectrum.

Take 30 minutes acquisition with the Soil sample and then repeat the measurement by using Fertilizer sample.

NOTE: Settings and acquisition time must be the same. Lead blocks could help in distinguish clearer peaks but they must be used if just employed in background measurement only.

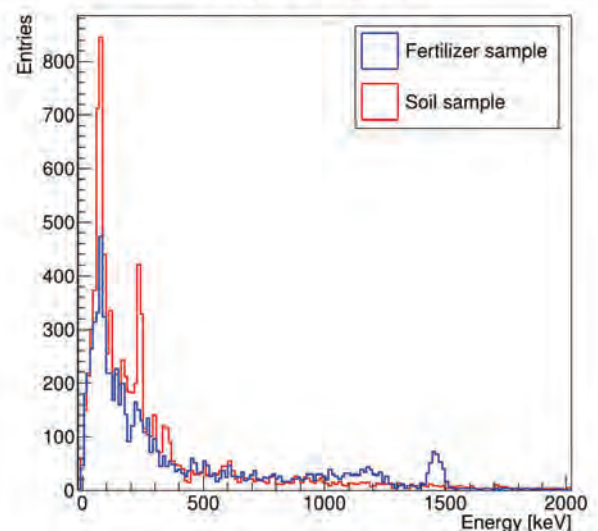


Experimental setup.

Results

Superimpose the Fertilizer and Soil spectra in the same histogram. The different contributions are clearly visible on the left plot below, where the Uranium and Thorium peaks are visible in the region 200÷400 keV of the Soil sample, while no contribution appears in the Fertilizer sample, and viceversa, the ^{40}K peak with its Compton edge is visible in the Fertilizer sample, with no contribution in other energy areas.

Sample comparison



Sample comparison: two samples taken with the same i-Spector in the same experimental conditions.



SP5630EN - ENVIRONMENTAL KIT

Difficulty



Execution Time

**Purpose of the experiment**

Record the energy spectrum of the Test sample and identify the peaks, after the energy calibration, by knowing the decay chain of Thorium and Uranium.

Fundamentals

Naturally occurring radiative material (NORM) is material found in the environment that contains radioactive elements of natural origin (uranium, thorium, and potassium). NORM is often found in its natural state in rocks or sand but it can also be present in consumer products, including common building products (like brick and cement blocks), granite counter tops, glazed tiles, phosphate fertilizers, and tobacco products. Moreover, there are some of the materials and products sitting around

your house could be emitting low levels of radiation. In the past, radioactive materials were employed by humans in objects of common use, like ceramics dishes (once uranium oxides were used to create a bright red-orange dinnerware), drinking glasses (glassmakers widely used uranium to color glasses a transparent yellow or yellow-green), clocks (glow in the dark with radium in the paint), camping lanterns (white light due to thorium), etc.

The test sample available in the kit contains old objects containing radioactive elements. The user can acquire the energy spectrum and try to recognize the source by knowing the decay products of Thorium and Uranium.

Requirements

No other tools or instruments are needed.

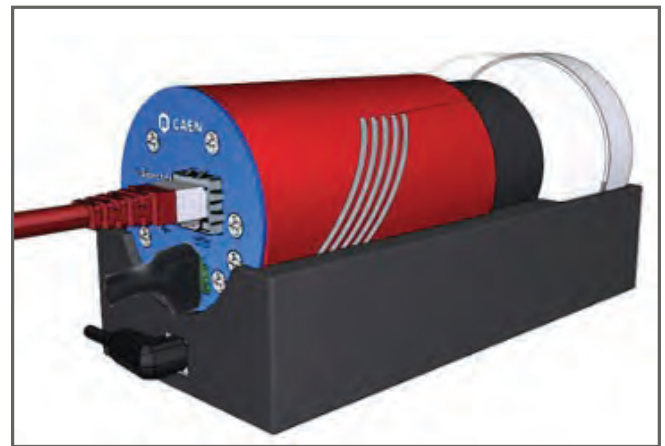
Carrying out the experiment

Put the i-Spector digital into the base and place the Test sample box into the place-holder. Power on the i-Spector and connect the Ethernet cable. Wait until the temperature is stable from the web interface (it can take half an hour from power on).

Check the waveform, modify the threshold and gate width, if needed, then start the measurement of the energy spectrum.

Take few minutes of acquisition according to the sample activity

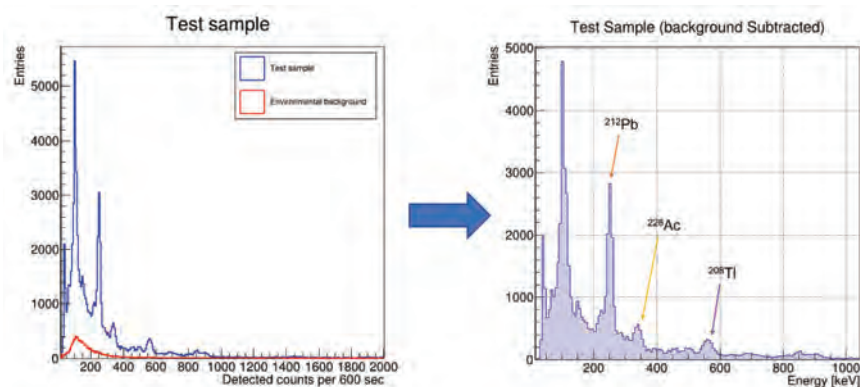
NOTE: in case of background measurement, settings and acquisition time must be the same. Lead blocks could help in distinguish clearer peaks but they must be used if just employed in background measurement only.



Experimental setup.

Results

The background subtraction can be made with the background spectrum. After that, it is possible to recognize peaks and identify the source, either Thorium, Uranium, or both, as shown in the picture below. The user can identify which source is contained in the Test sample by knowing the product decay of the two elements.



Test sample: total contribution and background on the left; background subtracted on the right. The visible peaks are highlighted in the spectrum.

Difficulty



Execution Time



SP5630EN - ENVIRONMENTAL KIT



Purpose of the experiment

Get familiar with radon passive measurements by taking care of the proper sample preparation and exposure, as well as of acquiring the spectrum to calculate the Radon concentration.

Fundamentals

Radon is a naturally occurring radioactive gas produced by the breakdown of uranium in soil, rock, and water. Radon can be dangerous since it accumulates inside houses or buildings. Air pressure inside your home is usually lower than the pressure in the soil around the building foundation. Because of this difference in pressure, the

building acts like a vacuum, drawing radon in through foundation cracks and other openings. Additionally, building materials (such as granite and certain concrete products) can give off radon.

It is usually recommended to make screening measurements to have a quick estimate of the highest concentration and take action in case the measurement exceeds 4 pCi/L (or 100 Bq/m³), which is the limit for a non-dangerous exposure to this element.

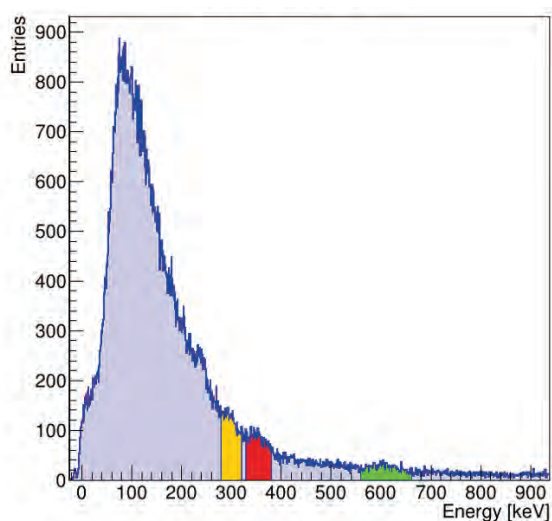
Requirements

Oven.

Carrying out the experiment

Detailed instructions for this activity are reported in GD8359 - SP5630EN QuickStartGuide.

Check the expiration date of the charcoal sample; if expired, or if the sample has already been used, bake it for some hours. Acquire the background spectrum with the i-Spector. Before starting the acquisition, make sure that the temperature is stable from the web interface. Once done, expose the sample for about 5-6 days, following the requirements of the closed house, and far away from wall, windows, etc., according to the Radon measurement procedure. Once ready, seal again the sample, wait at least three hours, and acquire the energy spectrum. Take few hours of acquisition with the exposed sample in the same condition of background acquisition.



Radon spectrum: counts of the three ROI are summed and combined with the calibration curves. The result is 124 ± 85 Bq/m³. Longer acquisition time will improve the measurement resolution.



Experimental setup.

Results

After the energy calibration and background subtraction, it is possible to select the region of interest (ROI) of the ²¹⁴Pb and ²¹⁴Bi decay products at 295 keV, 352 keV, and 609 keV. The counts can be used together with the calibration curves to calculate the Radon concentration. On request, Excel® spreadsheets examples can be provided to customers.

B. Nuclear Physics and Radioactivity

B.3 γ Environmental Radioactivity Outdoor



Natural radioactivity is an integral part of our environment. Minerals and materials originating from the Earth's crust contain naturally occurring radionuclides (NORM), which contribute to the background radiation continuously present around us.

The most relevant primordial radionuclides include Potassium-40, Uranium-238, Uranium-235, and Thorium-232, together with their radioactive decay products. Other naturally occurring radionuclides, such as Tritium and Carbon-14, are produced through natural activation processes.

The experiments presented in this section allow students to explore outdoor gamma environmental radioactivity through direct measurements in real environments. Using the GammaEDU Backpack, students can investigate the spatial variability of background radiation, identify the contribution of natural radioactive sources, and become familiar with portable radiation detection techniques.

These activities provide a practical introduction to environmental radiation monitoring and help students understand the presence and role of natural radioactivity in the world around them.

SP5640 - GAMMAEDU

Difficulty



Execution Time



Purpose of the experiment

Increase of the familiarity with environmental radioactivity topic via measurements in field which combine nuclear engineering and computer science for a better comprehension of basic physics concepts.

Fundamentals

Potassium is a natural element whose radioactive isotope ^{40}K is widely available on Earth, especially in food and in human bodies. Radioactivity is a physical phenomenon occurring when an unstable nucleus undergoes a transition from one energy state to another. In addition to the cosmogenic radionuclides, natural sources include the so-called primordial radionuclides existing since the Earth formed and that have not completely decayed due

to their long half-life ($\sim 10^9$ years and longer). The most common isotopes in the Earth responsible for the so-called terrestrial radiation are Uranium (^{238}U), Thorium (^{232}Th), and Potassium (^{40}K), together with their multiple daughter products. It is estimated that 80% of the average annual dose for the world's population comes from natural background radiation. While ^{40}K undergoes one single decay, ^{238}U and ^{232}Th produce decay chains that comprise α , β , and/or γ decays. In the outside environment, especially in case of in-situ γ -ray spectroscopy, there are many variables that could interfere with the measurement, such as the presence of vegetation or buildings and the morphology of the area affecting the field of view of the spectrometer.

Requirements

No other tools or instruments are needed.

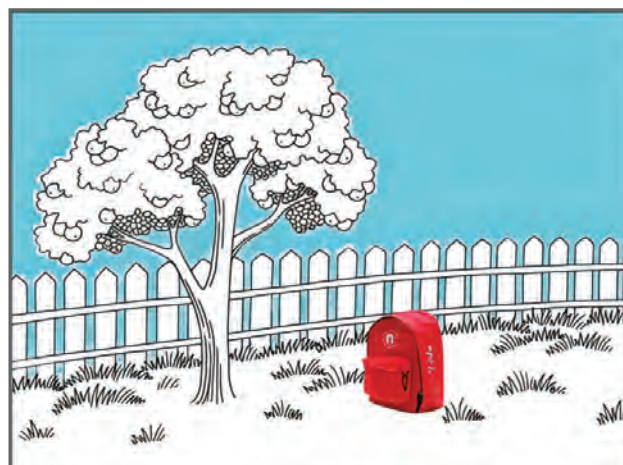
Carrying out the experiment

Power on the ystream inside the red backpack. Power on the tablet and associate the two devices via Bluetooth.

Take care that the ystream internal battery is charged, otherwise use the external power system.

Start the measurement campaign in land field and place the backpack on the floor almost 1m far from the trees, manhole or other construction. Set the acquisition time to about 5 minutes and see the results. If the statistic is not enough increasing the acquisition time.

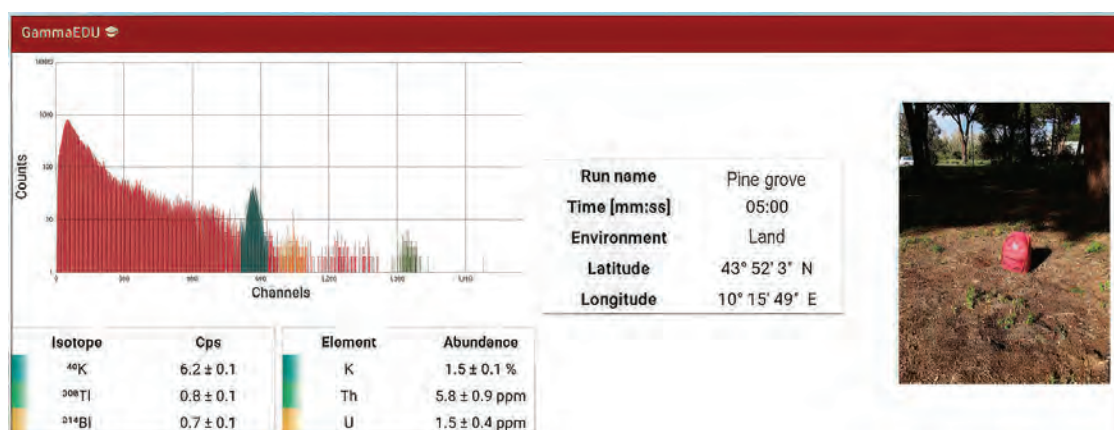
It is good practice to repeat the measurement in order to obtain the mean and standard deviation of the result.



Experimental setup.

Results

The measurement results are compared to the reference values in the terrestrial crust. The discrepancy in the reference levels can be explained by the building material, distance from soil and more. This kind of measurement is important for the evaluation of natural radiation exposure from building materials [2013/59/Euratom Directive and by UNSCEAR (United Nations Scientific Committee on the Effects of Atomic Radiation)].



Experimental result of in-situ γ -ray spectroscopy taken place in Viareggio, Italy.



Difficulty



Execution Time



SP5640 - GAMMAEDU

Purpose of the experiment

The experimental activity aims to give to the user a critical understanding of environmental radioactivity phenomenon.

Fundamentals

The use of portable gamma-ray spectrometers (NaI) as a probe for exploring the natural radioactivity allows the users to be able to grasp quantitative insights of the spatial distribution of the terrestrial radionuclides (i.e. U, Th and K) in the daily environment.

In the specific case of in-situ gamma ray spectroscopy, there are many variables that could interfere with the measurement, such as the presence of vegetation or buildings and the morphology of the area affecting the field of view of the spectrometer. In addition, soil humidity has an attenuating effect on gamma radiation and sources having

weak intensities need longer acquisition times. Moreover, the different types of ground coverage (like asphalt, grass, or brick) affect the measurement considerably. It is interesting to observe and understand how some type of ground coverage can be most or least abundant in natural radioactivity terms.

Requirements

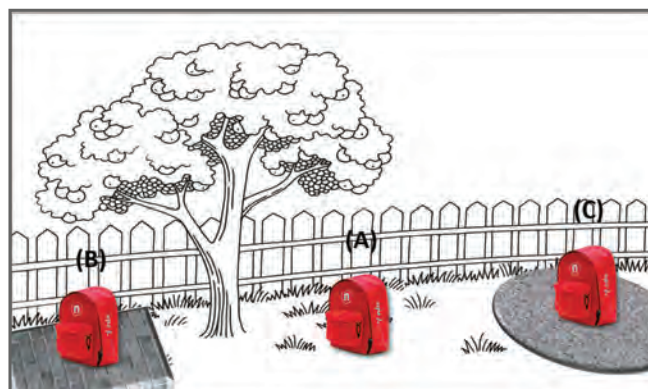
No other tools or instruments are needed.

Carrying out the experiment

Power on the ystream inside the red backpack. Power on the tablet and associate the two devices via Bluetooth.

Take care that the ystream internal battery is charged, otherwise use the external power system.

Start the measurement campaign in field and place the backpack on the floor almost 1m far from the trees, manhole or other construction. Set the acquisition time to about 5 minutes and see the results. If the statistic is not enough increasing the acquisition time. Repeat the measurements for the different types of ground coverage, like asphalt, grass, or brick and compare the results.



Experimental setup.

Results

Different ground coverage types are investigated by recording in-situ γ -ray spectra. The mean and standard deviation of the ^{40}K , ^{238}U , and ^{232}Th concentrations can be compared and discussed critically.

Ground Coverage	Number of Measurements	^{40}K [10^{-2} g/g]	^{238}U [$\mu\text{g/g}$]	^{232}Th [$\mu\text{g/g}$]
Brick	7	0.82 ± 0.19	1.8 ± 0.5	4.1 ± 1.0
Grass	28	2.08 ± 0.32	1.7 ± 0.4	9.5 ± 1.8
Asphalt	7	1.20 ± 0.10	1.9 ± 0.4	5.1 ± 0.7

Mean and standard deviation of the K, U, and Th concentrations that were obtained from the in-situ γ -ray measurements distinguished according to the different ground coverage types (Data from University of Ferrara).



Purpose of the experiment

The purpose of the experiment is to become aware of the radioactivity of the human body.

Fundamentals

Potassium is essential to all living beings, including humans, where it's found especially in the muscle tissue. It can be found in most soils, building materials, plants and animals and it is typically used in fertilizers.

In nature there are only three isotopes of potassium: ^{39}K (93.3% of weight abundance), ^{41}K (6.7%) and ^{40}K (0.0117%). While ^{39}K and ^{41}K are stable, ^{40}K is a radioactive isotope with a half-life of 1.28×10^9 years and it is one of the most common responsible for the so-called terrestrial radiation.

Considering the relative abundance, only twelve of a hundred thousand potassium atoms are actually

radioactive, i.e. approximately for 1 g of potassium, 31 nuclei decay per second [$\sim 31 \text{ Bq/g}$]. This fact implies that one banana of 150 g contains about 525 mg of potassium which corresponds to $\sim 16 \text{ Bq}$ activity, and similarly, an adult man (70 kg) has about 140 g of potassium which corresponds to $\sim 4400 \text{ Bq}$.

^{40}K decays 89.3% of the time to the ground state of ^{40}Ca by pure β -emission and 10.7% of the time by electron capture to an excited state of ^{40}Ar which then decays γ reaching the stability. The emitted photon has an energy of 1460.86 keV and can be used in order to identify and quantify the activity concentration of ^{40}K in sites of measurement and in the environmental samples.

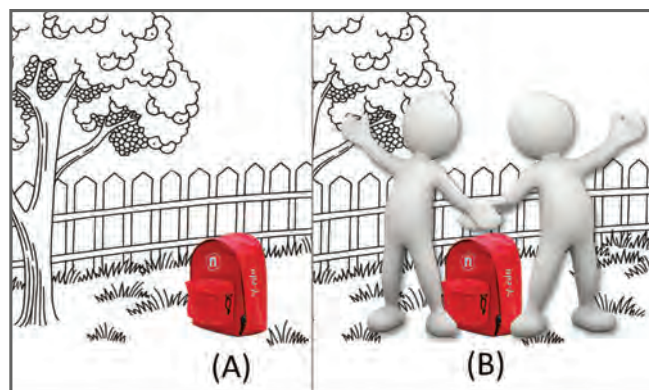
Requirements

No other tools or instruments are needed.

Carrying out the experiment

Power on the γ stream inside the red backpack. Power on the tablet and associate the two devices via Bluetooth. Take care that the γ stream internal battery is charged, otherwise use the external power system.

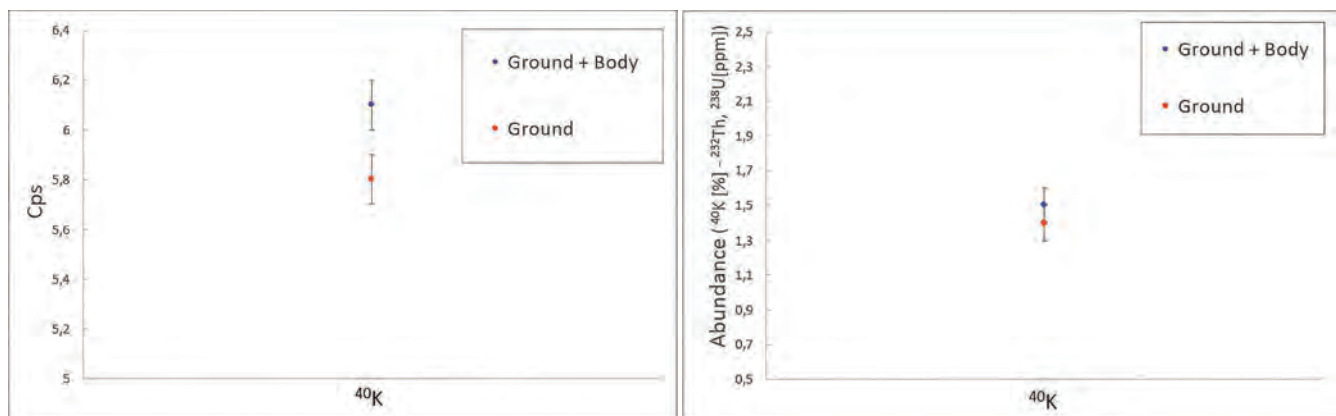
Start the experiment by placing the backpack on the ground and be sure that your presence is far enough from the measure point not to be revealed (A). Set the acquisition time to about 5 minutes and see the results. If the statistic is not enough increasing the acquisition time. Repeat the measurements leaving the backpack in the same position together with just your presence or more (B).



Experimental setup.

Results

The measurements results show how the detection of the ^{40}K in situ is dependent of the human presence weakly.



Experimental result of in-situ γ -ray coming from ^{40}K [1460 keV] with and without people presence.



Purpose of the experiment

The main goal of the experiment is to understand how the measurement of the γ environmental radiation can be affected by the distance of the point of measurement.

Fundamentals

The linear attenuation coefficient of gamma radiation μ represents the inverse of the distance at which the number of photons is reduced by a factor $1/e$, as can be inferred by the following equation: $N = N_0 e^{-\mu x}$, where μ in cm^{-1} . This Equation is the key for understanding the lateral horizon of in-situ gamma ray spectroscopy. The horizontal field of view of a gamma-ray detector expresses the relative contribution to the total signal that is produced within a given radial distance from the detector vertical axis. The lateral horizon depends on the height of the detector: for instance, a spectrometer that was placed at ground level detects gammas coming from

the first 25 cm of depth and it receives 90% of the signal from a radius of ~ 0.5 m. At a height of 0.5 m, 95% of the signal comes from a radius of ~ 8 m and the maximum percentage contribution to the flux comes from the concentric hollow cylinder of soil having a ~ 0.6 m radius centered at the detector vertical axis. When it's carried on the shoulders of the operator (1.5 m of height) the signal reaches $\sim 95\%$ at ~ 20 m and the maximum percentage contribution to the flux comes from the concentric hollow cylinder with a radius of ~ 1.2 m.

Requirements

No other tools or instruments are needed.

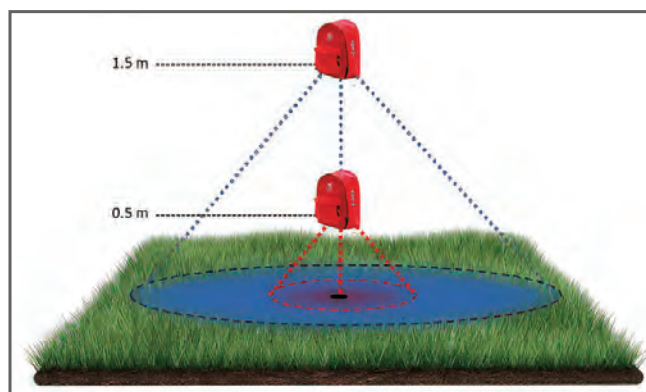
Carrying out the experiment

Power on the γ stream inside the red backpack. Power on the tablet and associate the two devices via Bluetooth.

Take care that the γ stream internal battery is charged, otherwise use the external power system.

Start the experiment by placing the backpack on the floor/soil. Set the acquisition time to about 5 minutes and see the results. If the statistic is not enough increasing the acquisition time.

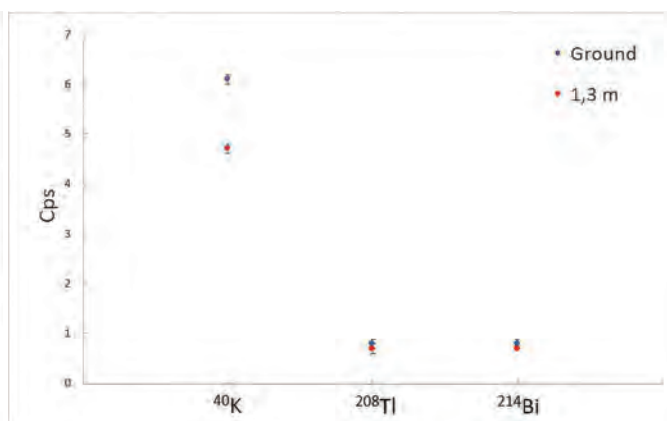
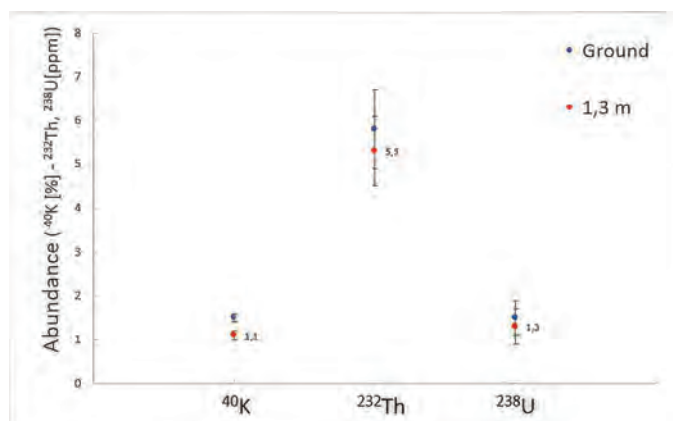
Repeat the measurements at different heights/distances from soil and pay attention to perform the measurements in the same conditions exactly.



Experimental setup.

Results

The measurements results show a gamma detection decrease as a function of the soil distance.



Result of the in-situ γ -ray measurements that were performed at different heights: the counts per second go three isotopes (Plot on the right) and the abundance (Plot on the left).



Purpose of the experiment

Starting from outdoor spectroscopy measurements to create the map of the natural radioactivity expressed in total specific activity in Bq/kg of the investigated area.

Fundamentals

The human population is continuously exposed to ionizing radiation from various natural sources (cosmic and terrestrial ones). Moreover, the exposure to natural sources exceeds that of all artificial, i.e., due to medical use, power generation and associated fuel cycle facilities,

radioisotope production waste management and from military ones. In this context, the radiological monitoring of the geographical areas became very important. All over the World, several institutions are missioned to develop collections of maps showing the levels of natural radioactivity caused by different sources (e.g., indoor radon, cosmic radiation, terrestrial gamma radiation, and natural radionuclides in soil and bedrock).

Requirements

No other tools or instruments are needed.

Carrying out the experiment

Power on the ystream inside the red backpack. Power on the tablet and associate the two devices via Bluetooth.

Take care that the ystream internal battery is charged, otherwise use the external power system.

The in-situ survey must be planned to keep in mind the spatial resolution of the desired information: it is important choosing the sampling points in order to cover the surveyed area comprehensively for the different types of ground coverage, like asphalt, grass, or brick.

Start the measurement campaign and place the backpack on the floor almost 1 m far from the buildings, manhole or other construction. Set the acquisition time to about 5 minutes and see the results. If the statistic is not enough increasing the acquisition time.



Experimental setup.

Results

The results that were obtained during the outdoor experiment in terms of total activity originating from ^{40}K , ^{238}U , and ^{232}Th are visualized via Google Earth. From these data, a natural radioactivity map of the investigated area can be developed.



Maps of the measurement points (yellow triangles) reported in the Google Earth app and the example of the measurement result reporting total activity concentration and Isotopic abundances [Viareggio, Italy].



Purpose of the experiment

The main goal of the experiment is the estimation of the natural radioactivity content in several dwellings and/or buildings representative of the different geological construction materials and commonly used in building constructions.

Fundamentals

The main contributors on the overall natural indoor effective dose to which population is exposed are ^{222}Rn and ^{220}Rn isotopes of radon gas, by-products of the ^{238}U and ^{232}Th series.

Only a fraction of radon atoms preserves enough kinetic energy to leave the grain of the material where it has been generated and to reach the empty space in the porous materials (emanation process that depends on the material itself). Moreover, only a fraction of the radon atoms reaching the pore volume of the material mass

can escape into the air and reaches the spaces where people live (exhalation process). The exhalation rate and the emanation coefficient.

The study of the natural radionuclides ^{232}Th , ^{40}K , ^{226}Ra , and the radon emanation coefficient exhalation rate is essential to estimate the actual risk for human health associated to a given natural material used for building construction. The natural radioactivity content of building materials depends on the local geology of each region on Earth. One of the requirements of estimate the radiation hazards in closed spaces, aiming to better protect against natural ionizing radiations exposure, is the assessment of the radiation hazards arising from the use of natural building materials in the construction of dwellings, since the majority of people in the World spend most time in indoor environments.

Requirements

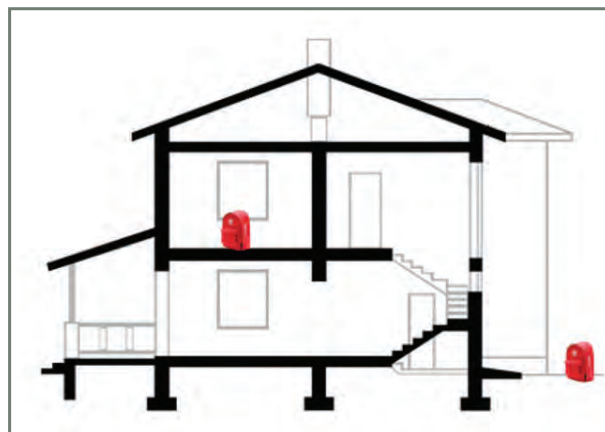
No other tools or instruments are needed.

Carrying out the experiment

Power on the ystream inside the red backpack. Power on the tablet and associate the two devices via Bluetooth.

Take care that the ystream internal battery is charged, otherwise use the external power system.

Start the measurement campaign and place the backpack on the floor far from the room walls. Set the acquisition time to about 5 minutes and see the results. If the statistic is not enough increasing the acquisition time. Repeat the measurements in a different place where the building material is different and compare the results.



Experimental setup block diagram.

Results

The measurement results are compared to the reference values in the terrestrial crust. The discrepancy in the reference levels can be explained by the building material, distance from soil and more. This kind of measurement is important for the evaluation of natural radiation exposure from building materials [2013/59/Euratom Directive and by UNSCEAR (United Nations Scientific Committee on the Effects of Atomic Radiation)].

	Isotopic Abundances		
	^{238}eU [ppm]	^{232}eTh [ppm]	^{40}K [%]
<i>Reference Values Range</i>	[2 ; 2.5]	[8 ; 12]	[2 ; 2.5]
<i>Tuff Dwelling (4° floor)</i>	10 ± 1	31 ± 1	6.9 ± 0.2
<i>Modern Building (1° floor)</i>	2.8 ± 0.6	8.8 ± 1.1	1.6 ± 0.1
<i>Country House (0° floor)</i>	6.8 ± 0.9	17.6 ± 1.6	3.4 ± 0.2

Isotopic abundances evaluated in buildings located in different places and made with several construction materials.



SP5640 - GAMMAEDU

Purpose of the experiment

The experiment topic is aimed to study and understanding the radioactive radon gas produced in uranium decays.

Fundamentals

It is now widely known that radon inhalation, in particular its progeny, significantly contributes to the public exposure. Radon is widely distributed in our living and working environment, soil and building materials contain meaningful tracks of its source and its exhalation rates must be determined in order to prevent human health. Radon concentration measurements, both in air and in gas from the soil are very important. The latest ones are used to realize geogenic maps. These maps link the gas to the geology and lithology of the area, allowing the development of more strict criteria for assessing the risk associated with the presence of radon. The radon monitoring is important also for another essential aspect: it is an indicator of the earth crust dynamics. In recent decades, many attempts to connect it to earthquakes prediction have been developed. Currently there is no confirmation about that, but, certainly, the correct radon measurement gives a valuable tool for taking information from the deeper Earth crust layers. As a noble gas, the radon

produced by radium alpha decay is relatively free to move. All the rocks contain some empty interstices through which the gas can migrate. The features of gas production areas are function of temperature, pressure, mechanical stress, precipitation and chemical reactions. Only a fraction of the radon, called the "emanation coefficient", generated in soil leaves the solid grains and enters the pore volume of the soil.

The study of the natural radionuclides ^{232}Th , ^{40}K , ^{226}Ra , and the radon emanation coefficient exhalation rate is essential to estimate the actual risk for human health associated to a given natural material used for building construction. The natural radioactivity content of building materials depends on the local geology of each region on Earth. One of the requirements of estimate the radiation hazards in closed spaces, aiming to better protect against natural ionizing radiations exposure, is the assessment of the radiation hazards arising from the use of natural building materials in the construction of dwellings, since the majority of people in the World spend most time in indoor environments.

Requirements

No other tools or instruments are needed.

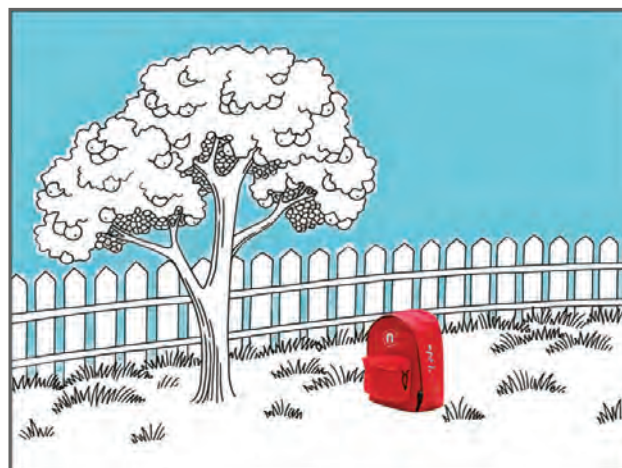
Carrying out the experiment

Power on the ystream inside the red backpack. Power on the tablet and associate the two devices via Bluetooth.

Take care that the ystream internal battery is charged, otherwise use the external power system.

Start the measurement campaign in land field and place the backpack on the floor almost 1m far from the trees, manhole or other construction. Set the acquisition time to about 5 minutes and see the results. If the statistic is not enough increasing the acquisition time.

It is good practice to repeat the measurement to obtain the mean and standard deviation of the result.



Experimental setup block diagram.

Results

The radon emanation has a big dependence on humidity variations, namely from the water content in the material. It is interesting to observe how this phenomenon affects the measurement of the Uranium concentration in the same place with different weather conditions.



SOIL WATER CONTENT EVALUATION WITH GAMMA RAY SPECTROSCOPY

SP5640 - GAMMAEDU

Purpose of the experiment

The experiment topic is aimed at understanding how gamma-ray measurements can provide information about the water content of the soil.

Fundamentals

The global warming effects put in danger global water availability and make it necessary to decrease water wastage. A lot of researchers are focusing their attention on monitoring global irrigation due to global irrigation information is scarce due to the absence of a solid estimation technique. Recent studies show that proximal gamma-ray spectroscopy represents an innovative

approach able to fill the spatial gap between punctual and satellite soil water content measurements.

A gamma-ray station measures the ^{40}K in the soil and monitors the moisture for the rational use of irrigation water. When it rains, the gamma signal is attenuated by the water and it drops down, while when the soil dries up, the gamma signal rises again.

Requirements

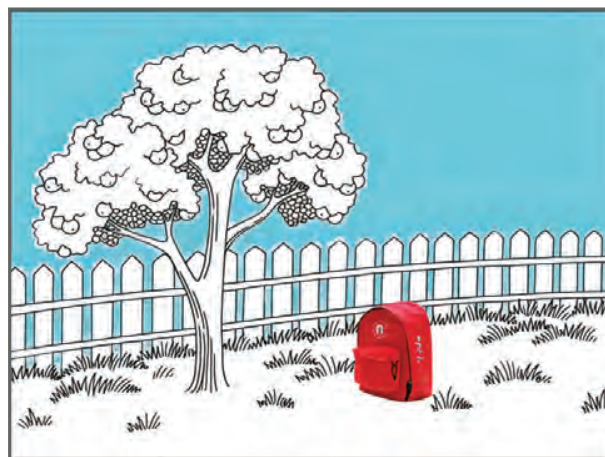
No other tools or instruments are needed.

Carrying out the experiment

Power on the ystream inside the red backpack. Power on the tablet and associate the two devices via Bluetooth. Take care that the ystream internal battery is charged, otherwise use the external power system.

Start the measurement campaign in the land field and place the backpack on the floor almost 1m far from the trees, manhole or other construction. Set the acquisition time to about 5 minutes and see the results. If the statistic is not enough to increase the acquisition time.

Repeat the measurements in the same place but in different weather conditions. Remember that it is good practice to repeat the measurement to obtain the mean and standard deviation of the result.



Experimental setup block diagram.

Results

This experiment represents a simple way to observe how Potassium 40 detection is affected by the water content in the soil.

Difficulty



Execution Time



SP5640 - GAMMAEDU



Purpose of the experiment

Large area survey to evaluate the radioactivity concentration of Uranium, Thorium, and Potassium.

Fundamentals

A geochemical exploration campaign aims at locating economic mineral deposits through the recognition of concentrations of chemical components, to be called as geochemical anomaly, in surface materials such as rocks, soils, stream sediments, glacial till, water, plants, and air. The radiological characterization of surface soil, in terms of Uranium, Thorium and Potassium, proves to be also a good tool to direct excavations for mines. The main advantages of using in situ measurements are quick feedback, a large sample size, immediate repeatability of the

measurement and low management costs. The areas with an enormous geodiversity have a considerable variety of stone materials that can be used both as building materials and as ornamental elements. This enormous variety also corresponds to considerable variability in the abundance of radionuclides. The world average radioactivity content in the upper continental crust is (33 ± 7) Bq/kg for ^{238}U , (43 ± 4) Bq/kg for ^{232}Th and (727 ± 60) Bq/kg for ^{40}K . Igneous plutonic rocks are characterized by relatively high concentrations of natural radionuclides varying over a wide range of up to 2000 Bq/kg for ^{40}K , 600 Bq/kg for ^{238}U and 900 Bq/kg for ^{232}Th .

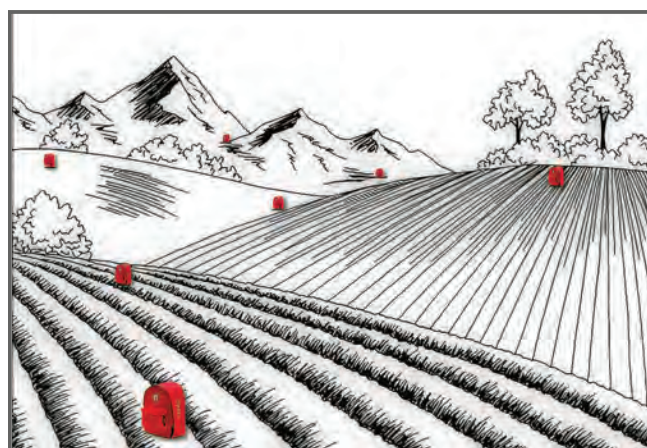
Requirements

No other tools or instruments are needed.

Carrying out the experiment

Power on the ystream inside the red backpack. Power on the tablet and associate the two devices via Bluetooth. Take care that the ystream internal battery is charged, otherwise use the external power system.

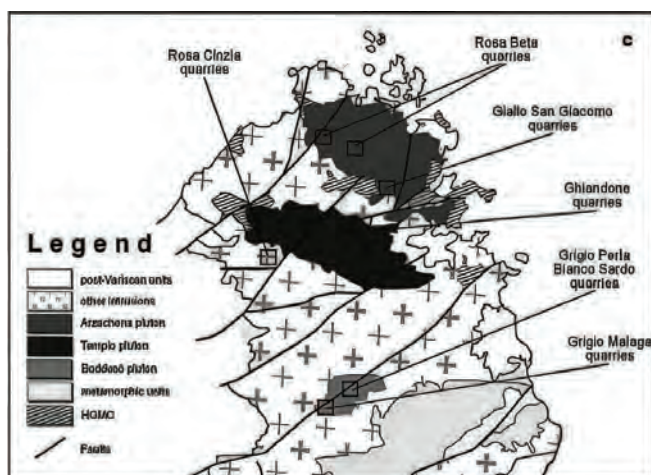
Start the measurement campaign in land field and place the backpack on the floor almost 1m far from the trees, manhole or other construction. Set the acquisition time to about 5 minutes and see the results. If the statistic is not enough increasing the acquisition time. Repeat the measurements along the survey area.



Experimental setup block diagram.

Results

Exemplary of in situ survey performed by using a portable NaI(Tl) scintillation detector for the determination of the radioactivity concentration of ^{40}K , ^{238}U and ^{232}Th on intrusive granite outcrops in Corsica-Sardinia (FR-IT) (*).



Position of extractive districts in Sardinia where in situ measurements were performed.

Granite Quarries	^{40}K [Bq/kg]	^{238}U [Bq/kg]	^{232}Th [Bq/kg]
Rosa Beta	1144 ± 120	42.3 ± 7.1	55.0 ± 6.3
Ghilandone	1092 ± 198	56.3 ± 12.7	68.9 ± 10.4
G. San Giacomo	1335 ± 206	50.1 ± 13.8	61.9 ± 9.4
Rosa Cinzia	1313 ± 64	56.0 ± 6.8	69.4 ± 3.4
Grigio Malaga	848 ± 121	34.5 ± 4.6	61.1 ± 5.5
Grigio Perla	1222 ± 155	39.1 ± 5.2	60.6 ± 5.7
Bianco Sardo	1269 ± 64	44.8 ± 7.1	51.6 ± 8.8

Activity concentration of ^{40}K , ^{238}U and ^{232}Th in situ measurements.

(*) Radiological characterization of granitoid outcrops and dimension stones of the Variscan Corsica-Sardinia Batholith, Puccini, A., Xhixha, G., Cuccuru, S., Oggiano, G., Xhixha, M. K., Mantovani, F., Alvarez, C. R., and Casini, L., Environmental Earth Sciences, 71, 393-405, (2014).

B. Nuclear Physics and Radioactivity

B.4 β Spectroscopy



Following the discovery of radioactivity, E. Rutherford classified radioactive emissions into different types based on their interaction with matter and ionization properties. Among them, beta radiation is characterized by higher penetration capability and lower specific ionization compared with alpha radiation.

Beta particles are electrons (β^-) or positrons (β^+) emitted during the decay of unstable atomic nuclei. Unlike alpha and gamma decays, beta decay is a three-body process involving the emitted particle, the recoiling nucleus, and a neutrino or antineutrino. As a consequence, beta particles are emitted with a continuous energy spectrum, a feature that provides important information about the underlying nuclear decay mechanism.

The experiments presented in this section introduce students to the principles of beta spectroscopy, allowing them to measure and analyze beta energy distributions and understand the fundamental concepts of nuclear decay and radiation detection.

The beta spectroscopy experiments can be performed using the Educational Beta Kit or, alternatively, the Premium Kit.

RESPONSE OF A PLASTIC SCINTILLATING TILE

SG6121A

SP5600D - EDUCATIONAL BETA KIT

Difficulty



Execution Time



Purpose of the experiment

To get acquainted with a set-up based on a plastic scintillator tile coupled to a Silicon Photo-multiplier.

Fundamentals

Particle detectors based on scintillating material coupled to a photosensor are in common use in nuclear and particle physics, medical, industrial and environmental applications. The choice of the scintillator is dependent on the end-user specifications but for a large set of applications plastic scintillators represent a cost effective viable solution. The CAEN kit comprises a plastic

scintillator tile of $5 \times 5 \times 1 \text{ cm}^3$ volume, directly coupled to a $6 \times 6 \text{ mm}^2$ SiPM. The sensitive area is a trade off between the requests for some of applications (e.g. cosmic ray detection or inspection of thin layers or filters) and the homogeneity of the response of the system.

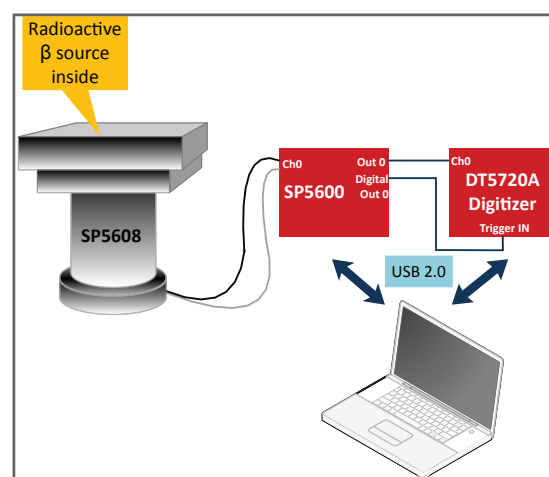
Before addressing a variety of lab applications, the student is guided through the basics of the system.

Requirements

Beta Radioactive Source.

Carrying out the experiment

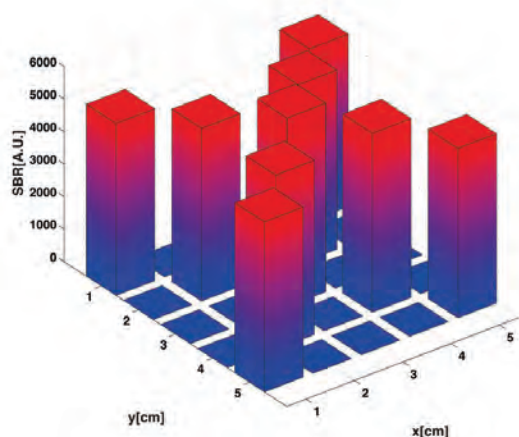
Connect the power and the MCX cables of the SP5608 tile to one channel of the SP5600. Connect the two channel outputs to DT5720A: the analog output to the channel 0 and the digital output to "trigger IN" of the digitizer. Use the GUI to optimize the system parameters (bias, gain, discriminator threshold). Once this is done, switch off the power supply, open the SP5608 top cover and position the beta source on the scintillating tile in the center. Close the support top, switch ON the power supply and measure the counting rate. Repeat the measurement moving the source in several positions over the tile and acquiring the signal/background ratio.



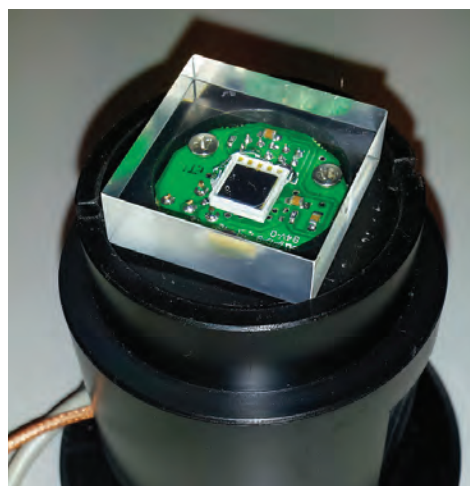
Experimental setup block diagram.

Results

In response to the incoming beta particles, the system is designed to deliver a high signal. However, the student shall consider the optimal setting of the discriminator threshold, taking into account the dark count rate, the variation in the beta source counts, the signal to noise ratio and the quality of the recorded beta spectrum. Moreover, for the optimal setting it is significant to monitor the homogeneity of the response as the source is moved across the tile.



Homogeneity of tile response to a beta source.



Scintillating tile coupled to a sensor.



Difficulty



Execution Time



SP5600D - EDUCATIONAL BETA KIT

Purpose of the experiment

After gamma spectrometry, the student is introduced to the measurement and interpretation of β spectra, using a plastic scintillator tile.

Fundamentals

There are three different beta decays:

β^- decay (electron emission): $n \rightarrow p + e^- + \bar{\nu}_e$

β^+ decay (positron emission): $p \rightarrow n + e^+ + \nu_e$

Electron capture (EC): $p + e^- \rightarrow n + \nu_e$

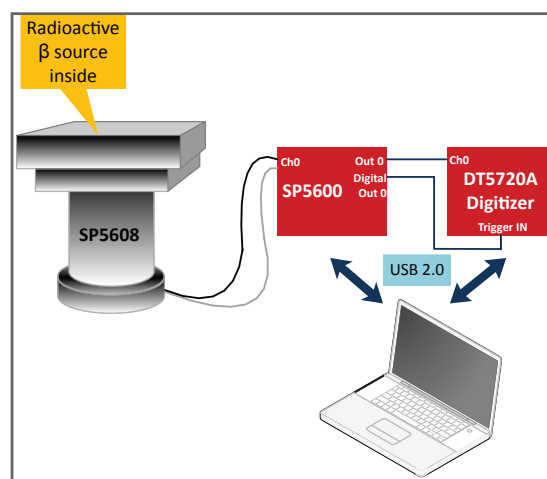
Where p identifies the proton, n the neutron and ν the weakly interacting neutrino. Because of the three body kinematics and the energy associated to the neutrino, the β spectrum is continuum up to a maximum energy depending on the isotope under study (and the neutrino mass).

Requirements

Beta Radioactive Source. 

Carrying out the experiment

Connect the power and the MCX cables of the SP5608 tile to one channel of the SP5600. Connect the two channel outputs to DT5720A: the analog output to the channel 0 and the digital output to "trigger IN" of the digitizer. Use the default software values or optimize the parameters to evaluate the contribution not coming from the beta source and choose the discrimination threshold in mV. After that, switch off the power supply, open the SP5608 top and place the beta source on the scintillating tile. close the support top, switch ON the power supply and acquire the beta spectrum.



Experimental setup block diagram.

Results

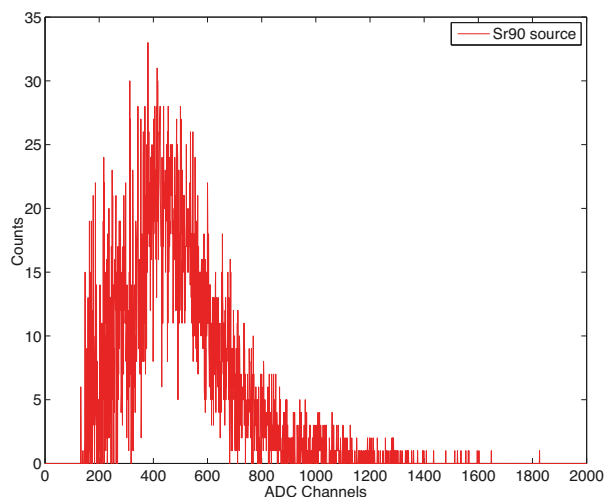
Measurement and interpretation of β spectra introduce the student into the field of special relativity and weak interactions of radioactive decays. Observation of the beta spectrum is very important to understand the theory of beta decay. Historically, experimental beta-ray spectra introduced enormous problems in the interpretation of beta decay due to the ostensible violation of the energy conservation. The introduction of neutrinos explaining the continuous beta-ray spectra solved not the problem conservation of energy, momentum and lepton number.

As first approach to beta spectroscopy, it is interesting to determine the maximum energy available in the decay process and to verify that the most probable energy value E_{avg} can be expressed as:

$$E_{avg} \cong 1/3 \cdot E_{max}$$

By using several β -sources, different energy values E_{avg} can be estimated, each one corresponds to the total energy released in the specified β decay.

An example of ^{90}Sr spectrum is shown in the figure. For a most complete analysis on beta spectrum, other application notes are recommended.



Experimental beta spectrum of ^{90}Sr radioactive source.

β RADIATION: TRANSMISSION THROUGH MATTER

SG6123A

SP5600D - EDUCATIONAL BETA KIT

Difficulty



Execution Time



Purpose of the experiment

Attenuation measurement of the intensity of β radioactive source as a function of the absorber thickness by using two absorber materials: aluminium and paper sheets.

Fundamentals

β -particle is a charged particle that interacts with matter in several ways depending on its initial energy: ionization process, Bremsstrahlung process, Cherenkov and Transition radiation. When β -radiation crosses a matter thickness, it releases completely or part of its energy due to collisions with absorber atoms; this phenomenon depends on the initial β -energy and on the crossed material density. Beta particles are less massive than alpha particles and only carry a charge of $1e$; consequently, beta particles can appreciably penetrate many potential shielding materials although their penetrating capacity is considerably lower compared with γ -rays. These different

radiation behaviours are essential for those attempting to shield locations from gamma radiation, either for sensitive experiments or for the safety of humans.

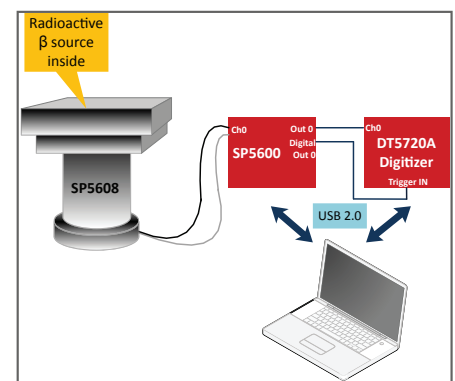
The transmission of beta particles is frequently calculated in the same fashion as that of gamma rays, where the mass attenuation coefficient is defined by the slope of the exponential function. Due to the fact that the β -particles with lower energies are less penetrating hence they are completely absorbed at smaller values of thickness, the initial decrease of the absorption curve is too rapid to be fit by exponential function. This approximation is verified only in a particular region of the transmission curve: a minimal absorber thickness so that the beta counting are very well separated from the “background level”.

Requirements

Beta Radioactive Source.

Carrying out the experiment

Insert the beta source support in the SP5608 and connect power and MCX cables to one channel of the SP5600. Connect the two channel outputs to DT5720A: the analog output to the channel 0 and the digital output to “trigger IN” of the digitizer. Use the default software values or optimize the parameters to evaluate the contribution not coming from the beta source and choose the discrimination threshold in mV. After that, switch off the power supply, open the SP5608 top and place the beta source on the plastic support and close the support top. Switch ON the power supply and measure the counting rate. Repeat the measurement by adding layers of the same absorber and later change the absorber type.



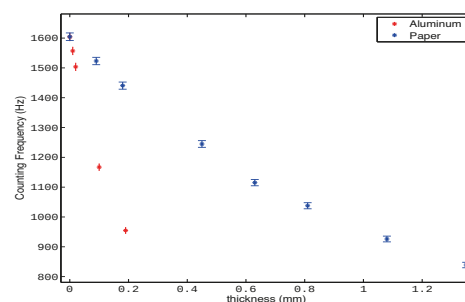
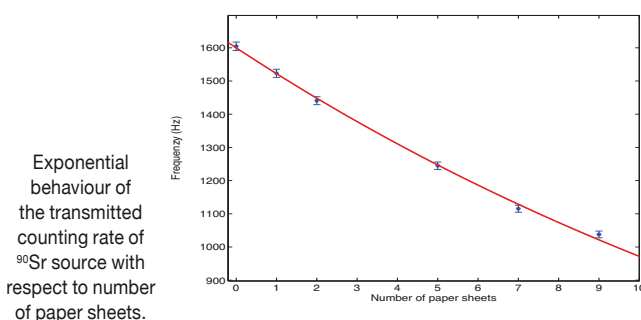
Experimental setup block diagram.

Results

By using different absorber thicknesses, the near-exponential decreasing of β -radiation intensity I as a function of the absorber thickness x , is verified. This behaviour does not have a fundamental basis like gamma rays attenuation, but it is very well described by

$$I = I_0 \cdot e^{-\mu x}$$

where n is the absorption coefficient. This coefficient correlates the endpoint energy of beta source for a particular absorbing material. From absorption curves of beta particles, the absorption coefficients and ranges of β particles in aluminium and in paper sheets can be determined.





Difficulty



Execution Time



SP5600D - EDUCATIONAL BETA KIT

Purpose of the experiment

Estimate of the instrument sensitivity in the measurement of thin layer thickness by beta particle attenuation.

Fundamentals

Beta attenuation represents a golden standard in the quality control of paper industry and in the measurement of thin layer thickness. The latter has several applications, including the

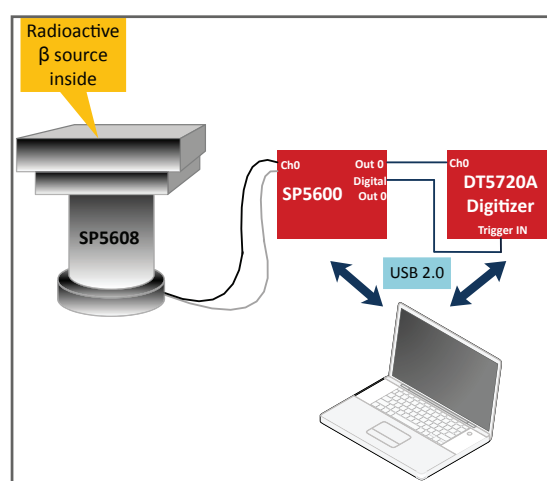
concentration of fine particulate matter deposited on a filter. The use of high activity sources with relatively soft spectrum and highly efficient detectors guarantees that this technique, used since the 50's, is yet today a standard.

Requirements

Beta Radioactive Source. 

Carrying out the experiment

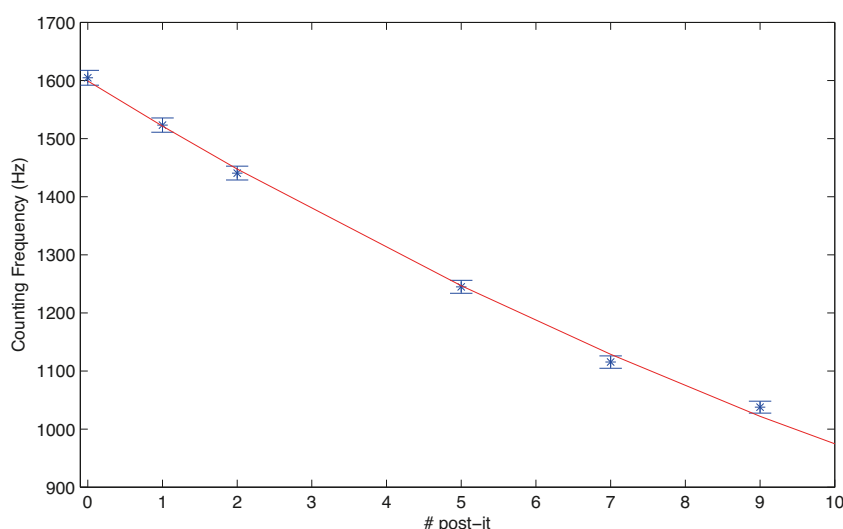
Insert the beta source support in the SP5608 and connect power and MCX cables to one channel of the SP5600. Connect the two channel outputs to DT5720A: the analog output to the channel 0 and the digital output to "trigger IN" of the digitizer. Use the default software values or optimize the parameters to evaluate the contribution not coming from the beta source and choose the discrimination threshold in mV. After that, switch off the power supply, open the SP5608 top and place the beta source on the plastic support and close the support top. Switch ON the power supply and measure the counting rate. Repeat the measurement by adding paper sheets.



Experimental setup block diagram.

Results

The industrial results are provided by using high activity β source (1 GBq). This experiment allows to estimate the instrument sensibility and the time needed to obtain a certain percentage of sensibility through the attenuation curve of a β source with "student compliant" activity. The results are very surprising: 3σ of confidence level to distinguish one or two post-it in 250 ms and 25 seconds to reach sensibility 10%.



Counting frequency of the beta rays as a function of the number of crossed paper sheets.

COATING EFFECT ON THE LIGHT COLLECTION

SG6125A

SP5600D - EDUCATIONAL BETA KIT

Difficulty



Execution Time



Purpose of the experiment

This experiment investigates the impact of a reflective coating on the light collection efficiency in a plastic scintillating tile.

Fundamentals

Scintillating materials are commonly used in high energy physics and medical applications because of their capability to convert high energy radiation into optical photons and they are usually coupled with a photosensor. Scintillator has a key role in the detection chains and it is often mandatory to extract and detect the generated scintillation light as efficiently as possible. The amount of light generated during the scintillation process is, in

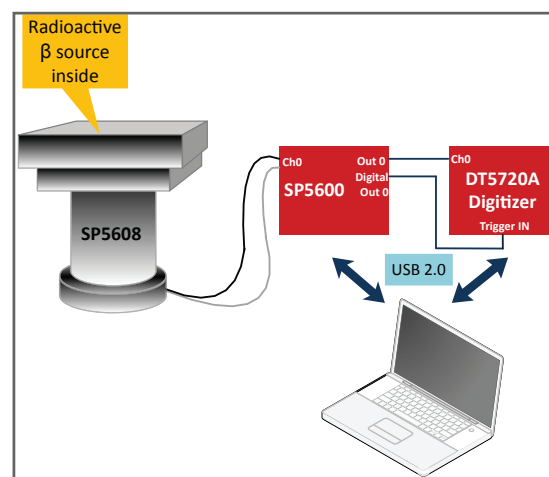
standard configurations, only a small percentage of this light reaches the photodetector. Extracting as much light as possible from the crystal becomes this crucial, given that both energy and time resolution depend strongly on the amount of detected light. Indeed, extracting more light enables a more accurate estimation of the energy absorption in the scintillator itself, and, moreover, if not covered by any material, the scintillator can let light escape through its lateral surfaces, thus losing a significant number of optical photons.

Requirements

Beta Radioactive Source.

Carrying out the experiment

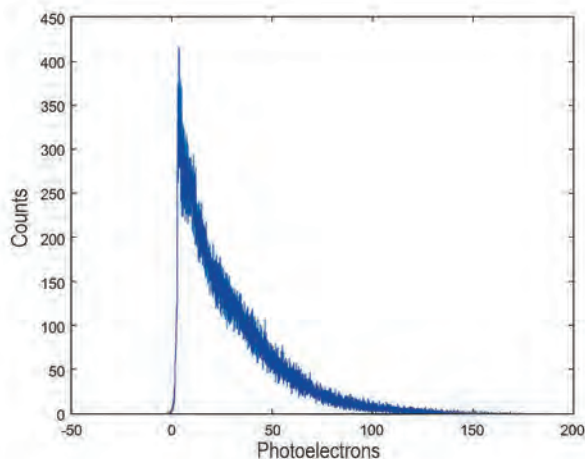
Connect the power and the MCX cables of the SP5608 tile to one channel of the SP5600. Connect the two channel outputs to DT5720A: the analog output to channel 0 and the digital output to "trigger IN" of the digitizer. Use the default software values or optimize the parameters to evaluate the contribution not coming from the beta source and choose the discrimination threshold in mV. After that, switch off the power supply, open the SP5608 top and place the beta source on the scintillating tile. Close the support top, switch ON the power supply and acquire the beta spectrum. Repeat the spectrum acquisition after having uniformly covered the scintillator with the Teflon tape leaving only a window open for the optical coupling with the SiPM.



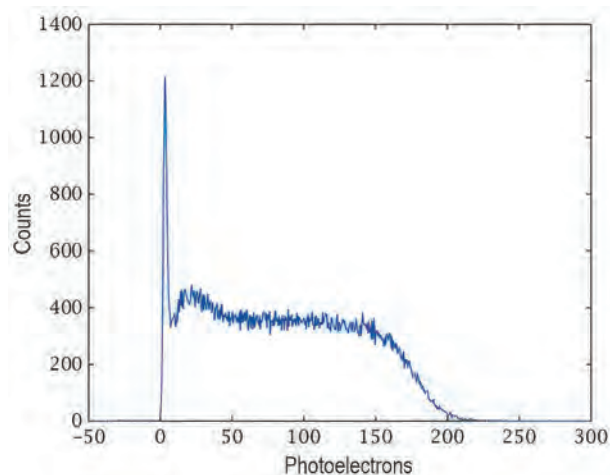
Experimental setup block diagram.

Results

The presence of a white coating allows the user to observe the improvement of the light collection via the acquisition of ^{90}Sr spectrum.



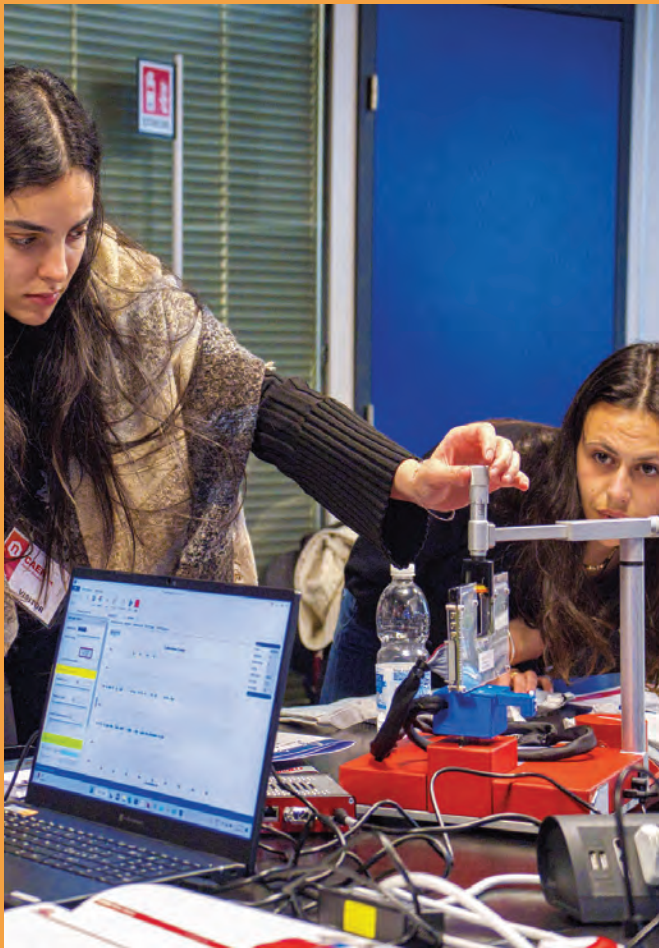
^{90}Sr spectrum acquired just by using optical grease as coupling between scintillator and SiPM.



^{90}Sr spectrum acquired by using Teflon coating and Optical interface sheet between scintillator and SiPM.

B. Nuclear Physics and Radioactivity

B.5 Nuclear Imaging - PET



Positron Emission Tomography (PET) is one of the most advanced medical imaging techniques, providing detailed information about physiological processes inside the human body. Its development represents a successful integration of different fields, including medicine, nuclear physics, radiochemistry, detector technology, and information processing.

The experiments presented in this section introduce students to the fundamental principles behind PET imaging through a hands-on approach. Using a dedicated educational PET system, students can explore the concepts of positron emission, gamma-ray detection, coincidence measurements, and image reconstruction, gaining insight into the physical processes underlying modern medical imaging techniques.

The proposed activities are performed using the CAEN EasyPET portable educational PET system, developed in collaboration with the University of Aveiro (Portugal). Depending on the experiment, additional data acquisition and analysis instrumentation can be used together with the EasyPET system to investigate the different stages involved in PET measurements.

This experimental approach allows students to understand the basic principles of PET technology and appreciate the role of physics and instrumentation in advanced diagnostic applications.

BASIC MEASUREMENTS: γ SPECTROSCOPY AND SYSTEM LINEARITY

SG6131G

SP5701 - EASYPET KIT

Difficulty



Execution Time



Purpose of the experiment

Gamma spectroscopy studies by using a gamma radioactive sources and by analysing the signals produced by the interaction of the gamma with one of the scintillating crystals of the system.

Fundamentals

The EasyPET detector system is composed of two Silicon Photomultipliers (SiPM) coupled to scintillating crystals. The EasyPET operation principle is simple: the two small detector cells, each composed of a small scintillator crystal coupled to a silicon photomultiplier (SiPM), develop a signal when they detect a photon emitted by the source. In order to perform the gamma spectroscopy measurements using one of the two detector systems, it is important underline that the detector is characterized by a noise component, caused by spurious events occurring randomly and independently

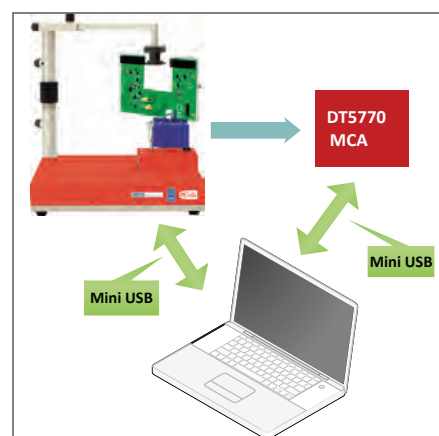
from the illumination field. This noise, called Dark Count Rate (DCR), depends mainly on the sensor technology and on the operating temperature, with a rate from 100 kHz up to several MHz per mm² at 25 °C. The DCR decreases with the lowering of the temperature (about a factor 2 of DCR reduction every 8 °C). In addition, the operating voltage has an impact on the DCR since it's connected to the electric field and as a consequence to the active volume of the sensor and to the triggering probability of the charge carrier. This noise component affects the resolution of a generic gamma spectrum composed of system noise peak, Compton distribution and Photopeak.

Requirements

²²Na Radioactive source (recommended: 1/2 inch disc, 10 μ Ci). 

Carrying out the experiment

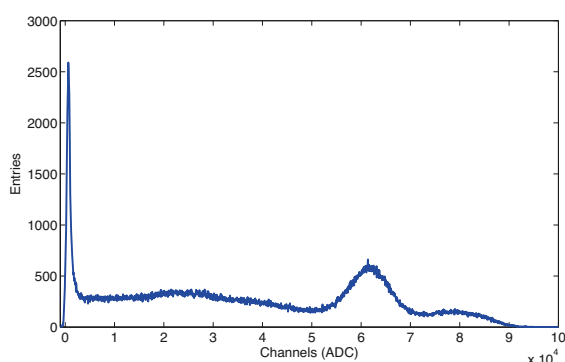
Mount the arm of the source holder on the column fixed to the system base, fix the U-shaped board to the top stepper motor and connect the flat cable to the U-shaped board and to the control unit. Connect to PC and power ON the system. Choose one detection system and connect its analog output to channel input of the DT5770, then use the comparator output to trigger the MCA and choose the threshold in mV of the signal output. Place the radioactive source as close as possible to the detector chosen and acquire the energy spectrum thanks to a Multi Channel Analyzer. Repeat the measurements with several gamma radioactive source in order to study the linearity system.



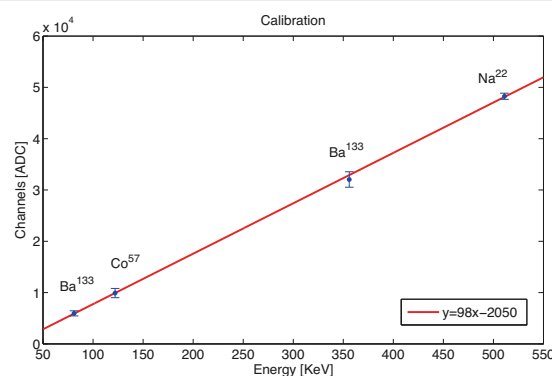
Experimental setup block diagram.

Results

The γ spectrum shows the Compton continuum, related to the continuum of energies released by the Compton scattered electrons, and the Photopeak, the full-energy peak corresponding to the photoelectric absorption of the incident gamma. The peak around zero represents the system noise. The conversion between the channels number and the energy can be performed by a calibration. The system linearity is checked by using several radioactive sources. If the response of the system is linear, the output signals are directly proportional to the incident gamma energies.



Energy spectrum of ²²Na source.



Energy Calibration.



Difficulty



Execution Time



SP5701 - EASYPET KIT

Purpose of the experiment

Positron annihilation detection by using a couple of detectors composed of a LYSO scintillating crystal coupled to a Silicon Photomultiplier (SiPM).

Fundamentals

The underlying principle to PET systems is the detection of high energy radiation emitted from a chemical marker, a molecule labelled with a radioisotope, administered to a patient. The marker is properly chosen in order to associate to molecules involved in biochemical or metabolic processes under investigation. This allows studying the function of a particular organ or evaluating the presence of disease, revealed by the excessive concentration of the marker in specific locations of the body. The radioisotope emits positrons which, after

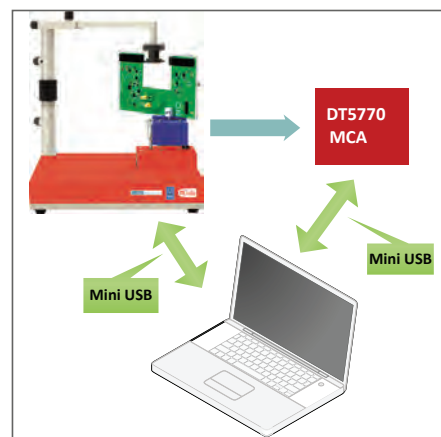
annihilating with atomic electrons, result in the isotropic emission of two photons back to back with an energy of 511 keV. The two photons are detected by a ring of detectors, which allows a pair of them to detect two back to back photons in any direction. EasyPET comprehends only two detector modules that move together and execute two types of independent movements, around two rotation axes, so as to cover a field of view similar to that of a complete ring of detectors. A fast electronic readout system allows detecting coincident events resulting from the same decay process.

Requirements

^{22}Na Radioactive source (recommended: 1/2 inch disc, 10 μCi).

Carrying out the experiment

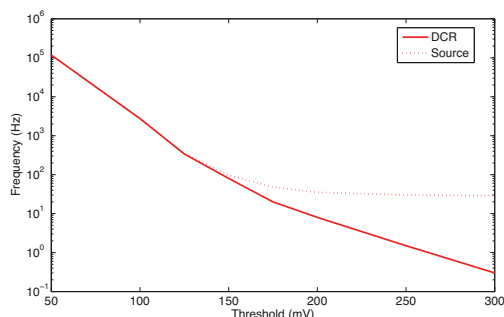
Mount the arm of the source holder on the column fixed on the system base, fix the U-shaped board to the top stepper motor and connect the flat cable to the U-shaped board and to control unit. Connect to PC and power ON the system. Connect the analog output of one detector to channel input of the DT5770 and use as MCA "trigger IN" the coincidence output characterized by the occurring of the comparator output of each detector within a time window. Place the source holder between the two detectors and measure the DCR frequency as a function of the threshold. Place the ^{22}Na radioactive source in the holder and repeat the measurement. Chose a threshold and acquire the coincidence spectrum thanks to a Multi Channel Analyzer.



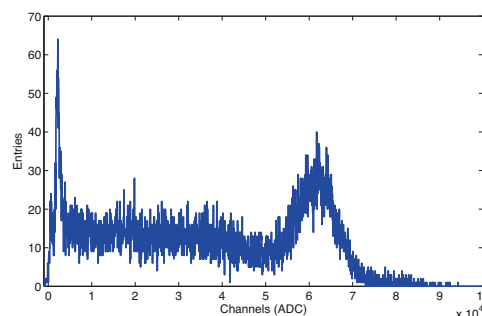
Experimental setup block diagram.

Results

The coincidence detection allows to reduce significantly the system noise due to the SiPM DCR. In the optimization of the acquisition conditions, the coincidence detection introduces the parameter of the time window width in addition to the bias voltage and the threshold. In order to find the best parameter values is necessary to analyse the response of the system in coincidence mode to the radioactive source with respect to the random events, at fixed operating voltage. The simple geometry of the system with only two opposite and aligned detectors and the implementation of the coincidence detection ensures that, in the energy distribution, the Compton scattering occurring in one or even in both scintillating crystals comes from the same annihilation event.



Coincidence frequency, with and without ^{22}Na source, as a function of the threshold.



Coincidence spectrum of ^{22}Na radioactive source.

TWO-DIMENSIONAL RECONSTRUCTION OF A RADIOACTIVE SOURCE

SG6133G

SP5700 - EASYPET

Difficulty



Execution Time



Purpose of the experiment

Understanding the technique of the nuclear imaging and the setup optimization of the parameters by performing two-dimensional image reconstruction of ^{22}Na radioactive source.

Fundamentals

The EasyPET operation principle is simple: two detector modules move together and execute two types of independent movements, around two rotation axes, so as to cover a field of view similar to that of a complete ring of detectors.

The rotation movements are executed by two stepper motors. The bottom motor has a fixed axis, whose position defines the center of the field of view. The bottom motor supports and performs a complete rotation of a

second motor, in predefined steps of amplitude α . The axis of the top motor is thus always positioned within a circumference of radius equal to the distance between the two axes. The top motor, in its turn, supports and moves a U-shaped printed circuit board, where a pair of aligned and collinear detector modules is mounted, performing a symmetric scan of range θ around the center, for each position of the bottom motor. In this way, EasyPET can reconstruct an image of a radioactive source placed anywhere within a cylindrical field of view between the pair of detectors. The diameter of the field of view is defined by the amplitude of θ , the range of the top motor scan.

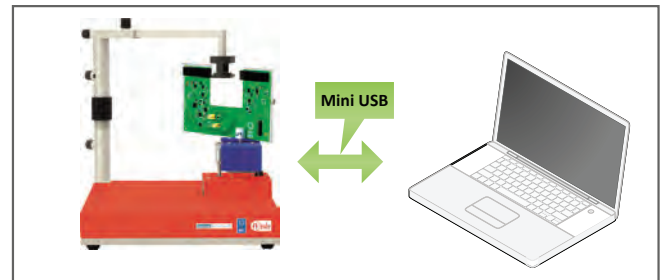
Requirements

^{22}Na Radioactive source (recommended: 1/2 inch disc, 10 μCi). 

Carrying out the experiment

Mount the arm of the source holder on the column fixed on the system base, fix the U-shaped board to the top stepper motor and connect the flat cable to the U-shaped board and to control unit. Connect to PC and power ON the system. The parameters involved in the setup optimization for the two-dimensional reconstruction of the source image are three: the detectors operating voltage, the coincidence time window and the threshold. Place the source holder between the two detector modules and tune the parameters to estimate the DCR contribution.

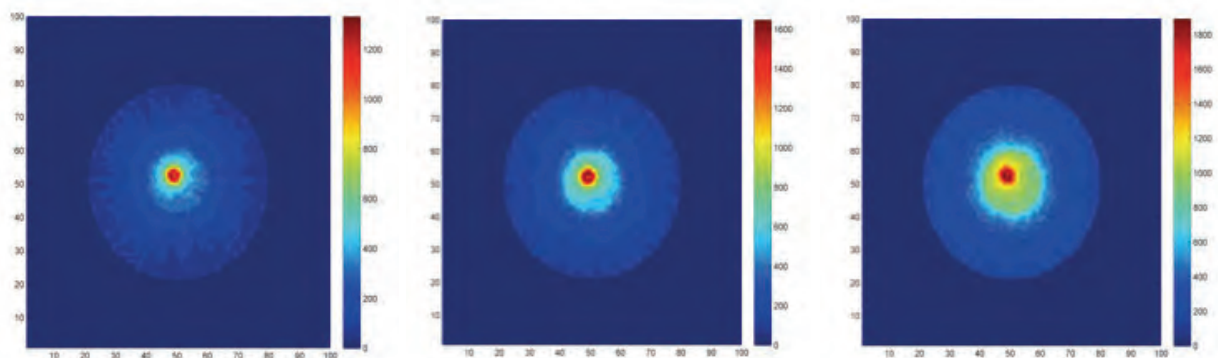
Place the ^{22}Na radioactive source in the holder and repeat the measurement tuning the parameters in order to obtain a good image reconstruction of the radioactive source.



Experimental setup block diagram.

Results

Tuning the parameters, the students can directly observe and understand their effects on the imaging measurements. At fixed threshold, the image contrast changes due to the time window width. The use of the lowest possible coincidence time window of the system is mandatory to achieve a good image contrast. Fixing the bias voltage and the time window, it is interesting to observe how the threshold affects the image contrast. This parameter choice is dictated by a trade off between the signal to noise ratio and efficiency maximization. The threshold value and the coincidence time window should be set by choosing the best compromise.



^{22}Na source distribution image as a function of coincidence time window, at fixed threshold and bias voltage.



Difficulty



Execution Time



SP5700 - EASYPET

Purpose of the experiment

Evaluation of the spatial resolution of a PET system composed of two detector modules..

Fundamentals

The main goal of the PET studies is to obtain a good quality and detailed image of an object by the PET scanner. The parameters involved and critical to good quality image formation are several: spatial resolution, sensitivity, noise, scattered radiations, and contrast.

The spatial resolution is a fundamental characteristics of a tomographic system and its determination is mandatory for a PET system. The spatial resolution of a PET scanner is a measure of the ability of the device to faithfully reproduce the

image of an object. It is empirically defined as the minimum distance between two points in an image that can be detected by a scanner.

In the EasyPET the dominant factor determining the spatial resolution is represented by the width of the scintillating crystals. Another effect that degrades the spatial resolution of the system is the so-called sampling error. It is associated to the distribution of the lines of response in the field of view and is a direct consequence of the rotation and scanning granularity.

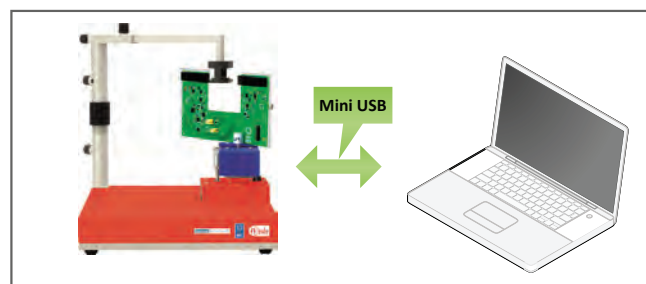
Requirements

^{22}Na Radioactive source (recommended: 1/2 inch disc, 10 μCi).

Carrying out the experiment

Mount the arm of the source holder on the column fixed on the system base, fix the U-shaped board to the top stepper motor and connect the flat cable to the U-shaped board and to control unit. Connect to PC and power ON the system. Set and optimize the parameters as bias voltage, threshold and coincidence time windows. In order to perform the spatial resolution measurement, the radioactive source is placed between the two detectors, on the line of response passing through the center. Its position is kept fixed while the system acquires the number of coincidence counts for successive scanning positions of the detector pair. The acquisition time is chosen in relation to the source activity to have enough statistics. The system response function is obtained plotting the number of coincidence counts for each position as a function of the distance between the source and the line

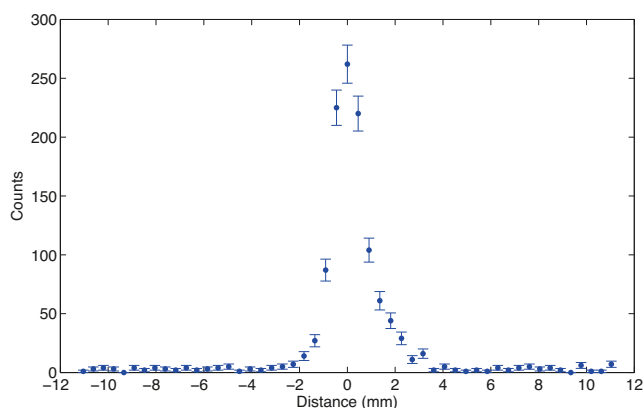
of response (the distance is calculated as the product of the source-scanning axis distance and the scanning angle tangent). The resulting curve can be interpreted as the radioactive source distribution convoluted with the system spatial resolution.



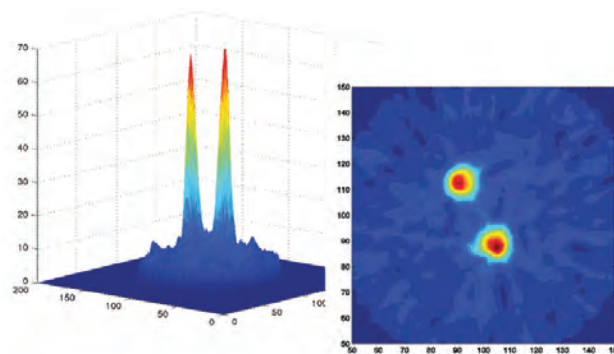
Experimental setup block diagram.

Results

The estimated spatial resolution is $\sim (1.45 \pm 0.4)$ mm, which is comparable to the spatial resolution of the small animal PET systems.



Resolution Plot.



^{22}Na sources, 5 μCi , 2.7 mm $\varnothing$ and 9 mm apart.

B. Nuclear Physics and Radioactivity

B.6 GM Detector

Geiger-Müller (GM) detectors, developed in the early 20th century by Hans Geiger and Walther Müller, are among the most widely used instruments for the detection of ionizing radiation. Their simple operating principle, based on the ionization produced by radiation in a gas-filled tube, makes them reliable and accessible tools for measuring different types of radiation.

Despite their long history, GM detectors remain widely used in education, radiation monitoring, and many practical applications due to their robustness, simplicity, and ease of operation. They provide an effective way to introduce the fundamental concepts of radiation detection and measurement.

The experiments presented in this section, based on the CAEN RockyRAD detector, allow students to explore the operating principles of Geiger-Müller counters and their applications in everyday radiation measurements. Through hands-on activities, students will become familiar with radiation detection techniques and learn how ionizing radiation can be measured and interpreted in different environments.





Purpose of the experiment

Study of relationship between uncertainty analysis and the duration of data acquisition.

Fundamentals

In the experimental Physics field, the accurate assessment of uncertainties is paramount to ensure the reliability and precision of measurements.

Measurement, an essential aspect of scientific inquiry, inherently involves some degree of uncertainty. Uncertainty refers to the range within which the true value of a physical quantity is expected to lie. Two key dimensions of uncertainty are relative uncertainty and absolute uncertainty. Relative uncertainty, often expressed as a percentage, gauges the precision of a measurement in relation to the size of the measured quantity. It is calculated by dividing the absolute uncertainty by the measured value and multiplying by

100. Absolute uncertainty is the quantitative measure of the range within which the true value of a measured quantity is expected to lie. It is typically expressed in the same units as the measured quantity. The determination of absolute uncertainty involves considering various factors, including instrumental limitations and experimental procedures.

Live time, as a parameter in this experiment, represents the duration for which data is actively collected. By systematically varying the live time during measurements, we aim to observe the influence of this temporal factor on both relative and absolute uncertainties. The statistical nature of measurements becomes apparent as we analyze how uncertainties change as a function of live time.

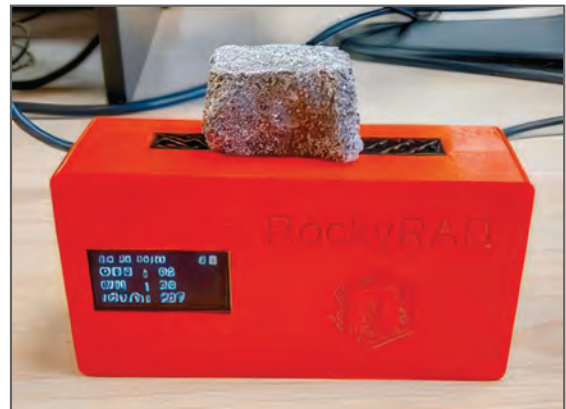
Requirements

No other tools or instruments are needed.

Carrying out the experiment

The experiment involves several data-taking with different acquisition time.

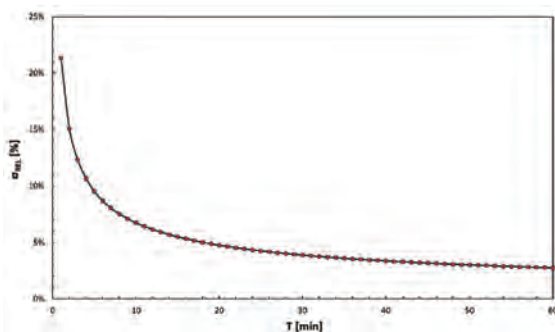
Begin by placing the GM detector on the desk and powering on the system. The experiment could be performed with or without a rock sample. GM detector will immediately initiate measurements and record data every minute during acquisition. The detected particles are counted and displayed on the monitor (CNTS), along with the average counts per minute (CPM) and dose (nSv/h). The system produces a sound for each detection.



Experimental setup.

Results

The experiment explores how the relative uncertainty evolves with varying live times, providing insights into the impact of data acquisition duration on the precision of our measurements. This experiment not only provides valuable insights into the statistical aspects of measurements but also sheds light on the dynamic relationship between uncertainty and the temporal dimension of data acquisition.



Relative uncertainty as a function of the live time.

T [min]	σ_{REL} [%]	σ_{ASS} [cpm]
1	21	4.7
5	10	2.1
15	6	1.2
30	4	0.9
60	3	0.6
120	2	0.4

Experimental results.

Difficulty



Execution Time



SP5660 - ROCKYRAD



Purpose of the experiment

Estimation of the measurement of the background radioactivity.

Fundamentals

The main contributors to the background energy spectrum are the gamma radiations that originate from naturally occurring radioactive isotopes dispersed in the environment and the materials that surround the detector, and the radiations whose origin can be traced to cosmic

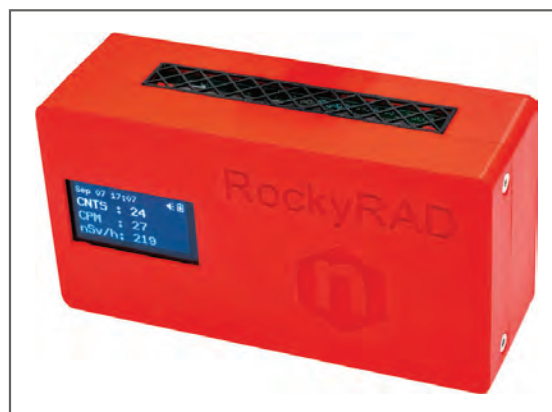
rays. To properly identify a sample from radioactivity point of view, the background must be acquainted. The background radioactivity measurement must be obtained without using any sample, specifically with the GM tube window free.

Requirements

No other tools or instruments are needed.

Carrying out the experiment

Place the GM detector on the desk if you are indoors or on an outdoor surface. Power ON the system. The GM detector immediately starts measurements and records data every minute of acquisition. The background counts must be acquired in the absence of samples, specifically with the GM tube window uncovered. The detected particles are counted and displayed on the monitor (CNTS), along with the average counts per minute (CPM) and dose (nSv/h). The system produces a sound for each detection. A significant statistical dataset is necessary for an accurate estimation of the environmental background. It is recommended to conduct an acquisition for at least 24 hours.



Experimental setup.

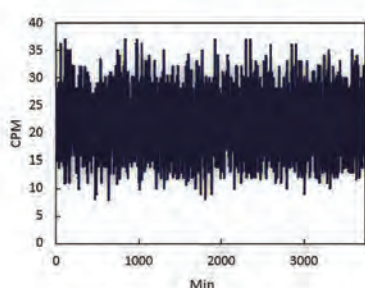
Results

The user can check for the presence of environmental radiation by observing non-zero counts on the GM counter. The statistical analysis of the distribution of this background plays a crucial role in accurately estimating the radioactive contribution of the samples under investigation.

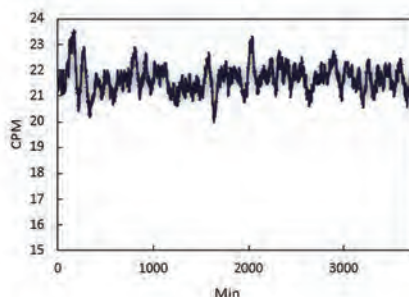
An example of the typical measurement outcome is shown in the table and figures provided below. However, it is important to note that the measured background value strongly depends on the environment in which the detection is carried out.

CPM Max	37.0
CPM Min	11.0
CPM Mean	22.0
σ_{STAT}	0.1
STD	4.5
Live Time [m]	3739

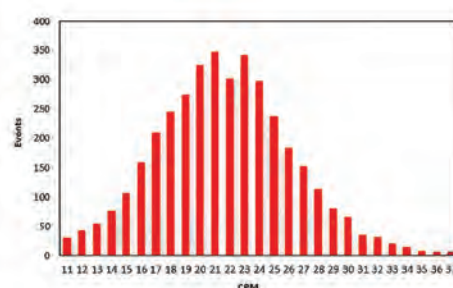
Experimental results.



CPM - Raw data.



CPM - Moving average (1h)



CPM Distribution

LEAD SHIELDING EFFECT ON ENVIRONMENTAL RADIOACTIVE BACKGROUND



SP5660 - ROCKYRAD

Difficulty



Execution Time



Purpose of the experiment

The experiment aims to analyze the impact of lead shielding on the environmental background particles detected by the GM detector.

Fundamentals

For precise spectral measurements, resolution in energy and signal-to-noise ratio are the key parameters. Therefore, it is crucial to shield the detector with lead to minimize background. Lead is the most widely used material for shielding due to its high density and atomic number. The photoelectric absorption cross-section predominates at energies above 0.5 MeV, making it effective in easily absorbing relatively hard external background gamma rays (such as those at 1.46 MeV from ^{40}K). Owing to its high

density, thin layers of a few centimeters of Pb significantly reduce background for typical gamma-ray detectors. Additionally, it can eliminate many components of cosmic rays, although thicknesses of about 10 cm contribute to the background with secondary radiation due to cosmic interaction with the lead itself. It is often used in the form of rectangular "bricks." Common lead exhibits a notable level of natural radioactivity; if refined, it may still contain ^{210}Pb , a product of the decay of ^{226}Ra , with a half-life of 20.4 years. While some types of Pb exhibit an activity of around 1.5 Bq/g, more refined lead is an order of magnitude or two below this value.

Requirements

Lead blocks are required.

Carrying out the experiment

The experiment involves two data-taking phases: one with lead blocks covering and one without. Begin by placing the GM detector on the desk and powering on the system. The GM detector will immediately initiate measurements and record data every minute during acquisition. Background counts, essential for calibration, should be obtained in the absence of samples, specifically with the GM tube window uncovered. It is advisable to conduct a background acquisition for a minimum of 2 hours.

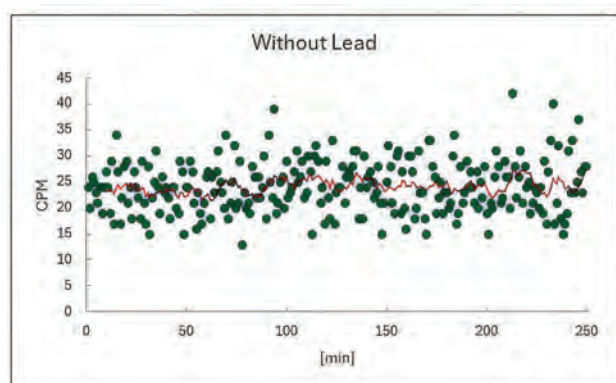
Upon completing the background measurement, cover the GM detector entirely with lead blocks. Maintain the same acquisition time to facilitate straightforward background subtraction.



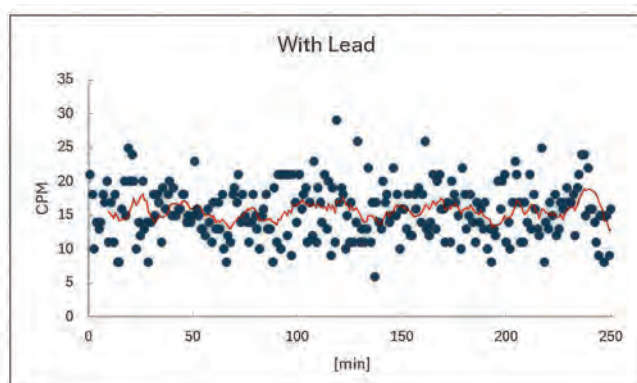
Experimental setup.

Results

The user can easily check how lead blocks reduce the gamma radioactivity from the background, by comparing the results obtained by GM detector with and without lead blocks. The subsequent results illustrate how the mean counts per minute (CPM) decrease from approximately 24 to around 15 when lead shielding is employed.



No shielding. CPM - Raw data in green and moving average (10 min) in red.



Lead Shielding. CPM - Raw data in blue and moving average (10 min) in red.

DETECTING IONIZING-RADIATION

SC6163H

Difficulty



Execution Time



SP5660 - ROCKYRAD



Purpose of the experiment

Radioactivity detection by using a GM detector..

Fundamentals

In the Nuclear Physics field, ionizing particles play a pivotal role in understanding the fundamental building blocks of matter. These particles possess sufficient energy to liberate electrons from atoms, a process known as ionization. This ionization capability stems from their inherent ability to penetrate matter and impart energy to atomic structures. Ionizing particles in nuclear physics include alpha particles, beta particles, and gamma rays. Alpha particles consist of two protons and two neutrons, making them relatively massive and charged. Beta particles can be either electrons (β^-) or positrons (β^+) and can interact with atomic electrons. Gamma rays are electromagnetic waves of extremely high energy and no mass.

A GM detector is a device specifically designed to detect ionizing radiation. The operational principle of the GM

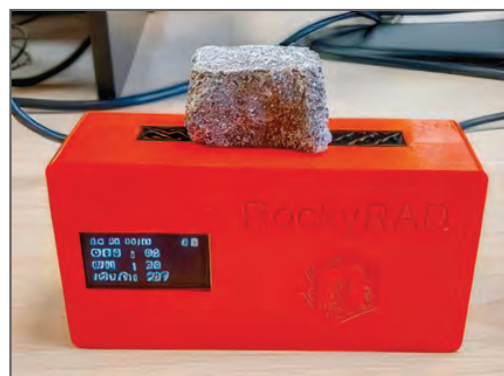
detector hinges on the ionization generated by incoming radiation. Within the GM detector, there exists a gas-filled chamber, typically containing a low-pressure inert gas, and a central wire electrode running along the chamber's axis. The detector applies a high voltage between its outer casing (anode) and the central wire electrode (cathode), thereby creating an electric field within the gas-filled chamber. When ionizing radiation enters the detector, it interacts with the gas atoms, leading to the formation of ion pairs positively charged ions and free electrons. These free electrons, accelerated by the electric field, travel towards the central wire, inducing additional ionization events through collisions with other gas atoms. This cumulative effect, known as an electron avalanche, generates a detectable electrical pulse. This signal is then amplified and processed by the detector's electronics.

Requirements

No other tools or instruments are needed.

Carrying out the experiment

The experiment involves two data-taking phases: one with rock sample and one without. Begin by placing the GM detector on the desk and powering on the system. The GM detector will immediately initiate measurements and record data every minute during acquisition. Background counts, essential for calibration, should be obtained in the absence of samples, specifically with the GM tube window uncovered. It is advisable to conduct a background acquisition for a minimum of 2 hours. Upon completing the background measurement, place the rock sample in the middle of the open window of the GM detector. Start the new acquisition maintaining the same acquisition time to facilitate straightforward background subtraction.



Experimental setup.

Results

The student is provided with an opportunity to familiarize themselves with the presence of radioactivity within a given rock sample through a straightforward measurement technique. This involves a comparative analysis of the detected counts using a GM (Geiger-Muller) detector, both in the presence and absence of the rock sample. The comparison between the counts with and without the rock sample serves as a means of assessing the radioactivity associated with the specific geological material. An increase in detected counts when the rock sample is present suggests the emission of ionizing radiation from the sample. This increase is indicative of the radioactive properties of the rock, as certain minerals within the sample may naturally emit alpha, beta, or gamma particles, contributing to the overall ionization observed by the GM detector.

CPM Max	37.0
CPM Min	11.0
CPM Mean	22.0
σ_{STAT}	0.1
STD	4.5
Live Time [m]	197

Environmental background

CPM Max	37.0
CPM Min	15.0
CPM Mean	27.2
σ_{STAT}	1.3
STD	5.9
Live Time [m]	197

Rhyolite Rock



SP5660 - ROCKYRAD

Difficulty



Execution Time



Purpose of the experiment

The objective of the experiment is to analyze and compare the detected counts originating from rocks of different origins.

Fundamentals

The radioactivity of rocks varies significantly depending on their geological origin, with different types of rocks contributing distinctively to the overall radiation background. The composition of the Earth's crust contains various radioactive elements, and the concentration of these elements in rocks can vary based on factors such as the rock type and the geological processes that formed them.

Granitic rocks, for example, often exhibit higher concentrations of radioactive elements such as uranium, thorium, and potassium. These rocks contribute to elevated levels of ionizing radiation due to the decay of these

radioactive isotopes. On the other hand, sedimentary rocks like limestone may have lower concentrations of these radioactive elements, resulting in comparatively lower radioactivity.

The different contributions of rocks to radioactivity are crucial in understanding natural background radiation and its variations across geological regions. This knowledge not only has implications for scientific studies but also plays a role in applications such as radiological assessments, mineral exploration, and environmental monitoring. Additionally, it underscores the importance of considering the geological context when interpreting measurements from radiation detection experiments, as the types of rocks present can influence the observed radiation levels.

Requirements

No other tools or instruments are needed.

Carrying out the experiment

The experiment involves several data-taking sessions, depending on the number of rocks under investigation. Begin by placing the GM detector on the desk and powering on the system. The GM detector will immediately initiate measurements and record data every minute during acquisition. Background counts, essential for calibration, should be obtained in the absence of samples, specifically with the GM tube window uncovered. It is advisable to conduct an acquisition for a minimum of 2 hours.

Upon completing the background measurement, place the first rock sample in the middle of the open window of the GM detector. Start the new acquisition, maintaining the same acquisition time to facilitate straightforward background subtraction. Repeat the procedure by using the other rock samples.



Experimental setup.

Results

The primary aim of this experiment is to investigate the variations in ionizing radiation levels exhibited by several geological samples. Furthermore, it not only serves as a practical application of radiation detection principles but also encourages participants to apply scientific methods in data analysis and interpretation. The experiment opens avenues for discussions on the geological factors influencing radioactivity, contributing to a broader understanding of the complex interplay between rocks and ionizing radiation.

	Background	Leucitic Tephrite	Granite	Porphyry	Trachyte
Max	37.0	47.0	40.0	40.0	33.0
Min	11.0	20.0	15.0	15.0	15.0
Mean	22.0	33.6	25.4	25.4	24.8
σ_{STAT}	0.1	0.4	0.9	0.9	0.9
STD	4.5	5.6	5.4	5.4	4.6
Live Time [m]	197	197	121	35	28

CPM Comparison: Analyzing experimental results obtained with various rock samples.

INVERSE SQUARE LAW: GAMMA RAYS

SG6165H

Difficulty



Execution Time



SP5660 - ROCKYRAD



Purpose of the experiment

The fundamental objective of this nuclear physics educational experiment is to provide students with a practical understanding of how the intensity of gamma radiation changes proportionally to the square of the distance from a rock sample.

Fundamentals

The Inverse Square Law, governing the behaviour of gamma radiation, asserts that the intensity of gamma rays is inversely proportional to the square of the distance from the radiation source.

In the context of gamma rays, which arise from nuclear transitions, their electromagnetic nature becomes paramount. These high-energy photons exhibit a unique ability to penetrate matter, making them invaluable in various applications from medical imaging to industrial

processes. The Inverse Square Law articulates how the intensity diminishes rapidly as one moves away from the source, emphasizing the significance of distance in influencing the impact of gamma radiation. Mathematically, this can be expressed as: $I = I_0/r^2$, where I is the intensity of radiation at a distance r from the source and I_0 is the initial intensity of radiation at the source.

In the context of this experiment, a GM (Geiger-Muller) counter is utilized to measure the intensity of gamma radiation at varying distances from the gamma ray source. The GM counter is a radiation detector that produces an electrical pulse when ionizing radiation interacts with its gas-filled chamber. By measuring the number of pulses, we can infer the intensity of the gamma radiation.

Requirements

No other tools or instruments are needed.

Carrying out the experiment

Begin by placing the GM detector on the desk and powering on the system. The GM detector will immediately initiate measurements and record data every minute during acquisition. Background counts, essential for calibration, should be obtained in the absence of samples, specifically with the GM tube window uncovered.

Upon completing the background measurement, place a rock sample at the first know distance from the middle of the open window of the GM detector, and start the acquisition.

Systematically increase the sample distance from the GM detector and record the corresponding CPM values.

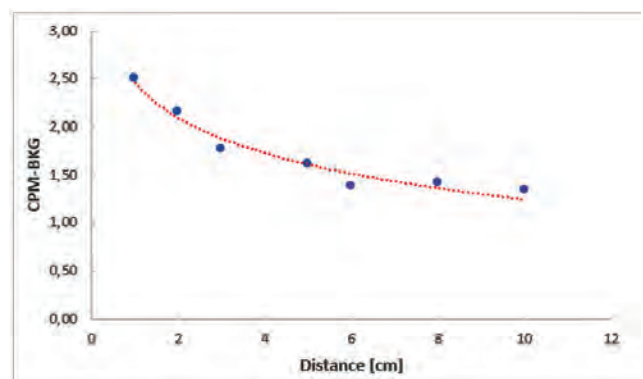
Repeat the measurements for multiple distances.



Experimental setup.

Results

Analyzing the collected data allows the students to determine whether the intensity of gamma radiation follows the expected Inverse Square Law relationship. This experiment provides valuable hands-on experience in nuclear physics and reinforces fundamental concepts related to the behaviour of gamma radiation.



Graph of the net CPM as a function of the distance.



SP5660 - ROCKYRAD

Difficulty



Execution Time



Purpose of the experiment

The experiment aims to investigate the variation of dose equivalent rate with altitude during an aircraft flight. The measurements allow the user to observe the increase in cosmic radiation exposure as the atmospheric shielding decreases.

Fundamentals

Cosmic radiation originates from high-energy particles arriving from outer space and from the Sun. When these primary particles interact with the Earth's atmosphere, they generate secondary radiation fields composed of neutrons, photons, electrons, muons, and other particles.

The atmosphere acts as a natural shield, reducing radiation levels at ground level. As altitude increases, the thickness of the protective atmospheric layer decreases, leading to higher dose equivalent rates. Commercial aircraft typically cruise at altitudes between 9 and 12 km, where radiation levels can be several times higher than those measured at sea level. For this reason, flight crews are considered occupationally exposed workers in many radiological protection regulations.

Requirements

Access to flight altitude data (GPS or aircraft information system), and a commercial flight route.

Carrying out the experiment

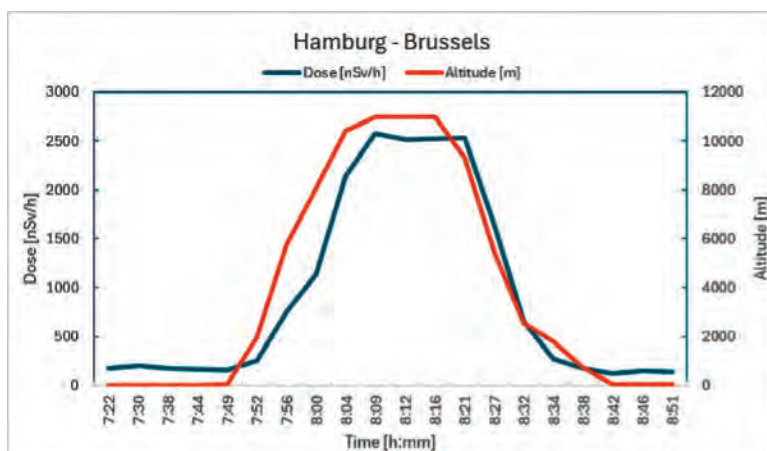
Before boarding, start the detector and record the ambient dose equivalent rate at ground level. Continue the acquisition throughout the flight, ensuring that both radiation measurements and altitude data are recorded at regular intervals. Measurements should cover the main flight phases: takeoff, climb, cruise, descent, and landing. To improve statistical significance, data averaging over several minutes may be applied. After the flight, correlate the measured dose equivalent rate with the corresponding altitude values.



Experimental setup.

Results

The user can easily observe the dependence of ambient dose equivalent rate on altitude by comparing measurements collected during the various flight phases. The results typically show a gradual increase during ascent, reaching maximum values at cruising altitude, followed by a decrease during descent. Depending on flight altitude and geomagnetic latitude, dose equivalent rates at cruise altitude may be several times higher than those measured at ground level. The data clearly confirm the strong dependence of cosmic radiation exposure on altitude, even during a short commercial flight such as Hamburg–Brussels.



Equivalent rate (blue, nSv/h) and aircraft altitude (orange, m) as a function of time during a short commercial flight (Hamburg–Brussels).

C. Particle Physics

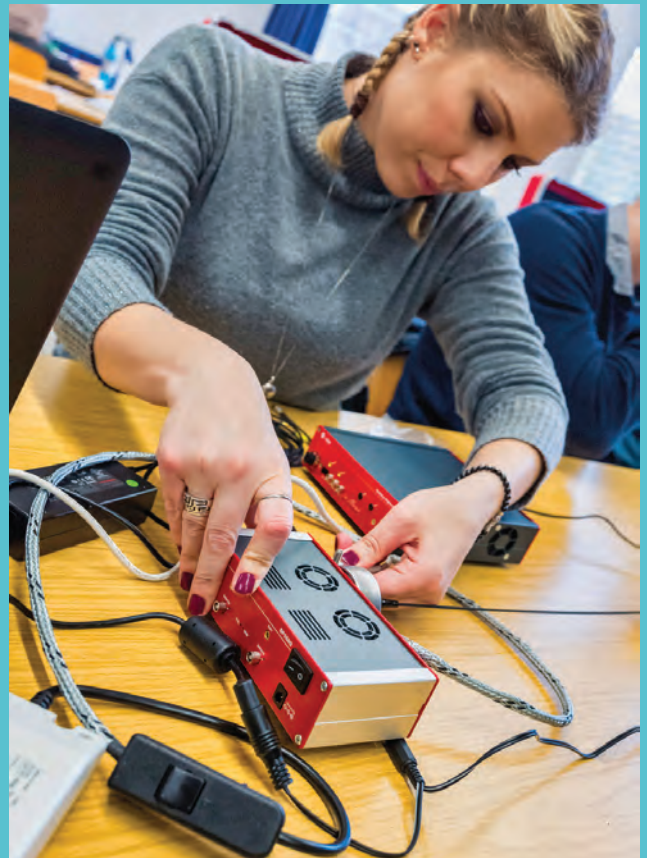
C.1 Cosmic Rays

Cosmic rays, first discovered by Victor Hess in 1912, are high-energy particles continuously reaching the Earth from space. They consist of primary cosmic rays, mainly composed of protons and atomic nuclei, which originate from astrophysical sources, and secondary cosmic rays, produced through interactions between primary particles and the Earth's atmosphere.

These atmospheric interactions generate a complex cascade of secondary particles, including pions, kaons, muons, neutrinos, electrons, and photons. Among these particles, muons represent one of the most accessible components for educational experiments, allowing students to investigate fundamental concepts of particle physics and cosmic radiation.

The experiments presented in this section introduce students to the detection and characterization of cosmic rays using the Educational Beta Kit and the Cosmic Hunter system. Through these activities, students can explore cosmic radiation measurements, particle detection techniques, and the properties of the radiation continuously present in our environment.

For both experimental setups, a dedicated mechanical structure is also available to build a cosmic telescope, enabling measurements of the azimuthal variation of the cosmic-ray flux.





SP5620CH - COSMIC HUNTER

Difficulty



Execution Time

**Purpose of the experiment**

Statistical properties of the cosmic rays.

Fundamentals

The event number in a given time interval is one of the most interesting points in many Physics phenomena. This number is often affected by statistical fluctuations around an average value determined by the type of phenomenon. Multiple factors may cause fluctuations and influence the measurement result. Thus, the exact value is not always the same (as in the case of particles that decay may derive from space or from a radioactive source).

The most important goal in the experimental approach is to understand which values can occur in a series

of measurements as well as their probability, i.e. the probability distribution. The Poisson distribution describes with good approximation events coming from radioactive phenomena or from counting cosmic rays. This distribution expresses the probability of a given number of events occurring in a fixed interval of time or space, and can be expressed as:

$$P_{\mu}(n) = \frac{\mu^n}{n!} \cdot e^{-\mu}$$

where μ is the average number of events in a fixed interval and n is the number of events.

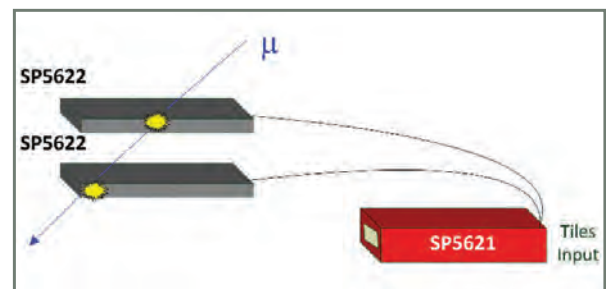
Requirements

No other tools or instruments are needed.

Carrying out the experiment

Connect the cable connector from each SP5622 Detection System to the input located on the rear panel of the SP5621 module. Power on the SP5621 module and start acquisition via the START button on the front panel. When a charged particle crosses the black tile its energy is converted into scintillation light. The photons produced are detected by the photosensor and converted into an electrical signal. The number of counts for each scintillator is available via the SP5621 display. Note that spurious electrical signals will likely also be detected by the photosensor, thus producing noise. Coincidence between two SP5622 will greatly reduce the number of spurious events. However, the statistical fluctuations cannot be totally removed. Select the scintillators coincidence via the related button on the front

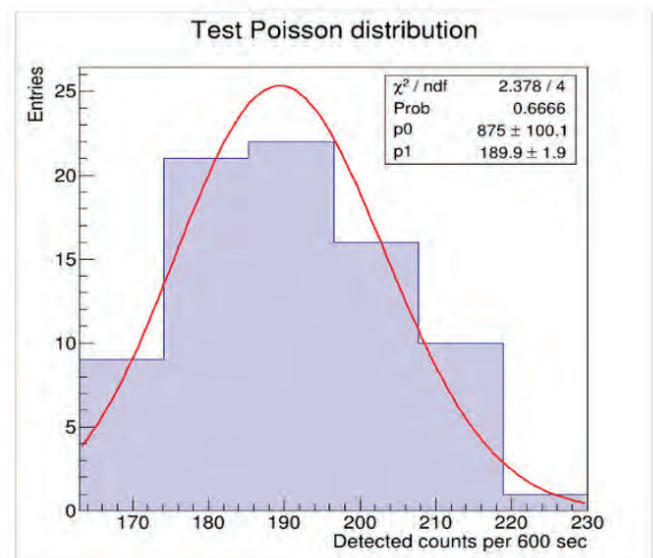
panel, then select the integration time of the measurement. Before starting acquisition choose the system geometry. Be sure to keep this geometry constant for the duration of the experiment. Take and record more data to obtain statistical significance.



Experimental setup block diagram.

Results

The Poisson distribution of cosmic rays can be experimentally verified via data analysis and the treatment of their statistical uncertainty.



Poissonian distribution of cosmic rays [Fit: $y = p_0 \times (p_1^x / x!) \times e^{-p_1}$].

Difficulty



Execution Time



SP5600D - EDUCATIONAL BETA KIT



Purpose of the experiment

Cosmic rays detection by using a system composed of a plastic scintillating tile directly coupled to a Silicon Photomultiplier detector.

Fundamentals

The muons, produced by the decay of pions and kaons generated by the hadronic interaction of the primary cosmic rays with atmospheric nuclei, are the most cosmic rays at sea level.

Cosmic muons are charged particles, produced

high in the atmosphere (typically 15 km) with highest penetration capability in matter. Their mass (~ 200 times the electron mass), the absence of strong interactions and their long lifetime ($\tau \sim 2,2 \times 10^{-6}$ s), allow muons to cross the atmosphere and reach the Earth's surface.

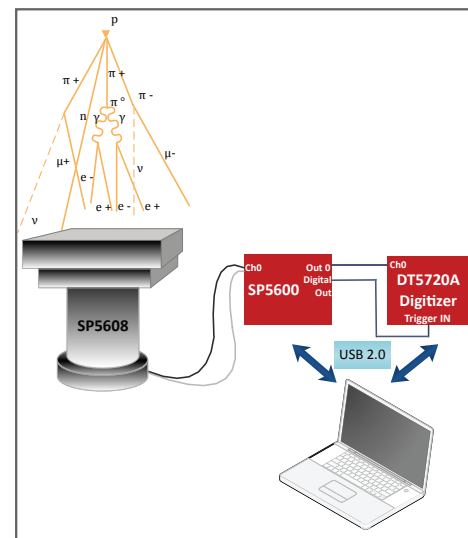
The muon average energy at sea level is around 4 GeV.

Requirements

No other tools or instruments are needed.

Carrying out the experiment

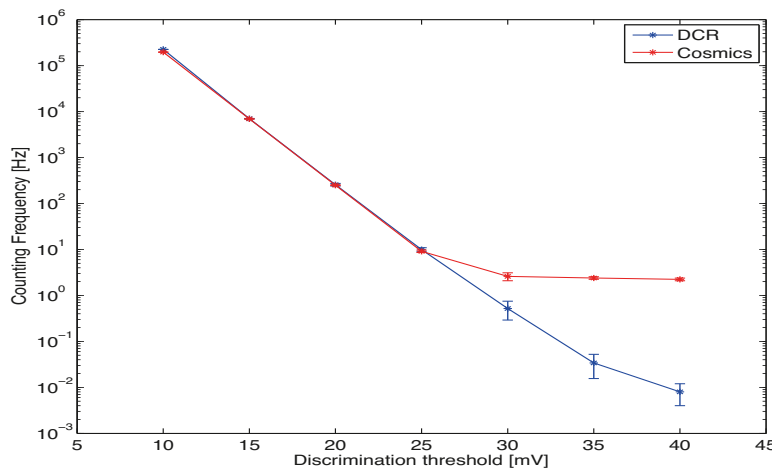
Open the SP5608 and remove the plastic scintillating tile. Close the SP5608 and connect its power cable and its MCX cable to one channel of the SP5600. Connect the two outputs of the chosen channel to DT5720A: the analog output to the channel 0 and the digital output to "trigger IN" of the digitizer. Use the default software values or optimize the parameters to evaluate the noise contribution of the sensor, called Dark Count Rate (DCR). Measure the DCR as a function of the discrimination threshold in mV. Because of the DCR, the system has to be made sensitive to the cosmic ray flux relying on the acquisition time of the sensor signal. Switch off the power supply, open the SP5608 top, spread the optical grease on the SiPM and insert the scintillating tile. Close the support top, switch ON the power supply and restore the previous configuration parameters. Measure the counting rate scanning the values of the threshold.



Experimental setup block diagram.

Results

The cut-off threshold has a key role in the cosmic ray detection and it shall be set to reduce the random coincidence rate below the Hertz level and measure the cosmic rate.



Signal frequency as a function of discriminator threshold. The red line represents the cosmic contribution, the black one the noise.



SP5600D - EDUCATIONAL BETA KIT

Difficulty



Execution Time

**Purpose of the experiment**

Measurement of the muon vertical flux on a plastic scintillating tile. Estimation of the detection efficiency of the system by comparison between the expected rate and the measured one.

Fundamentals

Muons lose about 2 GeV to ionization before reaching the ground with average energy around 4 GeV. The production spectrum, energy loss in the atmosphere and decay of

the muons are convoluted in their energy and angular distribution. The integral intensity of vertical muons is:

$$I_V \approx 82 \text{ m}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$$

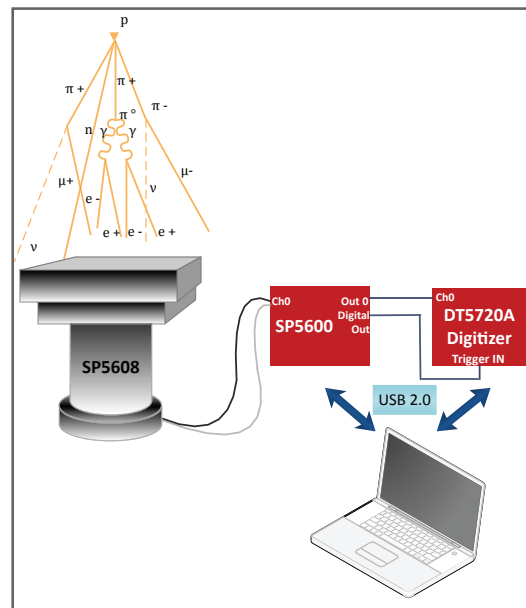
and their flux for horizontal detectors is $\approx 1 \text{ cm}^{-2} \text{ min}^{-1}$ at energies higher than 1 GeV at sea level, as known in literature².

Requirements

No other tools or instruments are needed.

Carrying out the experiment

Open the SP5608 and remove the plastic scintillating tile. Close the SP5608 and connect its power cable and its MCX cable to one channel of the SP5600. Connect the two outputs of the chosen channel to DT5720A: the analog output to the channel 0 and the digital output to "trigger IN" of the digitizer. Use the default software values or optimize the operating voltage of the sensor to reach a higher photon detection efficiency (PDE). The first measurement step is the evaluation of the noise (Dark Count Rate) as a function of the discriminator threshold. Because of the DCR, the system has to be made sensitive to the cosmic ray flux relying on the acquisition time of the sensor signal. The thresholds shall be set to reduce the random coincidence rate below the Hertz level. Switch off the power supply, open the SP5608 top, spread the optical grease on the SiPM and insert the scintillating tile. Close the support top, switch ON the power supply and reset the previous configuration parameters. Measure the muons counting rate and estimate the cosmic flux.

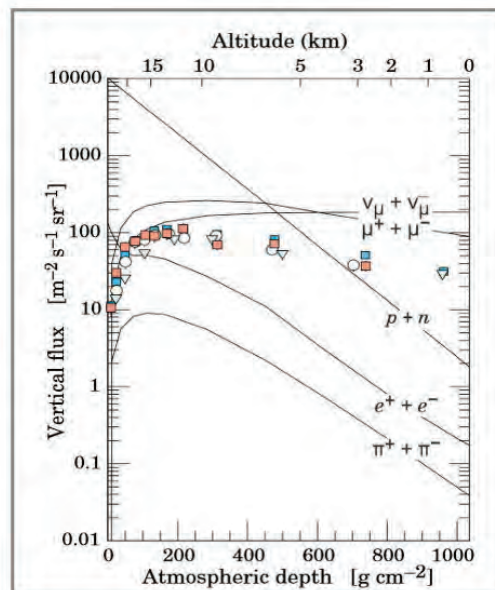


Experimental setup block diagram.

Results

The expected rate of muons across the scintillating tile is very low, requiring a fine tuning of the system in order to achieve a significant reduction of the random count rate and enhance the system sensitivity.

Considering the zenith dependence of flux ($I(\theta) = I_V \cos^2 \theta$) and the integration over the solid angle, the expected cosmic rate due to the geometry system can be estimated and the detection efficiency can be evaluated.



Cosmic vertical flux as a function of altitude and atmospheric depth².

² K.A. Olive et al. (Particle Data Group), Chin. Phys. C, 38, 090001 (2014).

Difficulty



Execution Time



SP5620CH - COSMIC HUNTER



Purpose of the experiment

To understand the potential for accidental counts coming from double tile coincidence.

Fundamentals

Once the geometry of the detectors has been defined and coincidence is confirmed it becomes important to estimate the number of random coincidences. Random coincidences derive from simultaneous or nearly-simultaneous pulses caused by accidental discharges (i.e. noise), and not by particles with a trajectory within the volume determined by the solid angle of the geometry. The probability that a particle crosses the detector is a function of the surface of the tile itself and of the average

rate. Therefore, the probability of a random coincidence is proportional to the pulse duration.

An evaluation of random coincidence contribution [R_{random}] can be obtained by a simple theoretical calculation:

$$R_{\text{random}} = 2 \cdot R_A \cdot R_C \cdot \tau$$

Where τ is the pulse duration (700 ns), and R_A and R_C are the event rate of each scintillating tile.

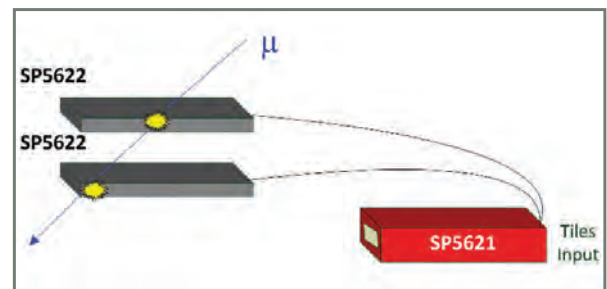
Requirements

No other tools or instruments are needed.

Carrying out the experiment

Connect the cable connectors of the two SP5622 to the tile inputs located on the rear panel of the SP5621 module. Power on the SP5621 module and start the acquisition via the front panel START button. When a charged particle crosses the black tile it's energy is converted into scintillation light. The photons which are produced are detected by the photosensor and converted into an electrical signal. The number of counts for each scintillator may be viewed via the SP5621 display. Select the scintillators coincidence via the related button on the front panel, then select the integration time of the measurement.

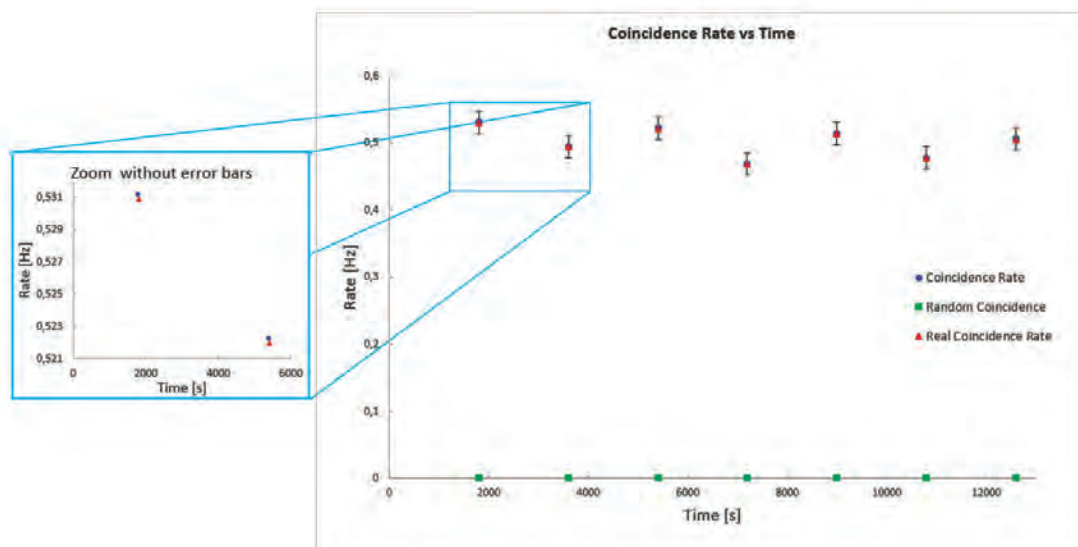
Before starting acquisition choose the system geometry. Be sure to keep this geometry constant for the duration of the experiment. Take and record more data to obtain statistical significance.



Experimental setup block diagram.

Results

Double tile coincidence plays a key role in a great many Physics experiments. The random coincidence rate allows you to evaluate the data quality via estimation of the Signal to Background ratio [SBR].



Trend of the Count Rate and Random Rate as a function of the time. The plot on the left side is an enlargement of the main plot and underlines the deviation between the measured coincidence rate and the real one, obtained via the random rate subtraction.



SP5620CH - COSMIC HUNTER

Difficulty



Execution Time

**Purpose of the experiment**

The goal of the experiment is the evaluation of the detection efficiency of the scintillating tiles that make up the system.

Fundamentals

Detection efficiency is the probability that a particle is detected after crossing the sensitive volume of the detector. Detection efficiency is dependent upon the incidence angle, the cross-section through which the particle interacts with the scintillator, and on its physical dimensions. The efficiency of a detector can change depending upon the bias voltage applied and upon the particle type and energy. The efficiency (ϵ) is defined experimentally as the ratio between the number of detected particles (N_0) and the number of particles incident upon the detector surface (N):

$$\epsilon = \frac{N_0}{N}$$

The number of the particles detected in coincidence between additional detectors can be expressed as the product between the impinging particles and the efficiency of each detector. The following expressions can be assumed for the double and triple coincidences:

$$N_{AC} = \epsilon_A \cdot \epsilon_C \cdot N_0 \quad \text{and} \quad N_{ABC} = \epsilon_A \cdot \epsilon_B \cdot \epsilon_C \cdot N_0$$

Thus, the detection efficiency of the scintillating tile positioned in the middle can be expressed as:

$$\epsilon_B = \frac{N_{ABC}}{N_{AC}}$$

Requirements

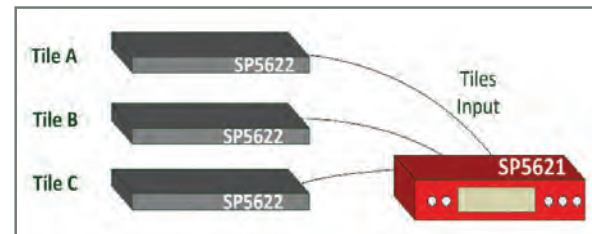
- SP5622 - Detection System
- DT1081A - Four-Fold Programmable Logic Unit (Discriminator, Coincidence and Scaler modules in one solution)
- Cable Adapter

Carrying out the experiment

Connect the cable connectors of the three SP5622 to the tile inputs located on the rear panel of the SP5621 module. Power on the SP5621 module and start the acquisition via the front panel START button. When a charged particle crosses the black tile its energy is converted into scintillation light. The photons which are produced are detected by the photosensor and converted into an electrical signal. The number of counts for each scintillator may be viewed via the SP5621 display. Select triple scintillator coincidence mode via the related button on the front panel, then select the integration time of the measurement. Arrange the geometry of the detectors as depicted in the diagram above. Be sure to keep this geometry for the duration of the experiment. This system configuration allows the user to test the efficiency

of the central scintillating tile. Connect the signal outputs of the three scintillating tiles to an external apparatus in order to identify double and triple counts at the same time, which correspond to the same cosmic ray.

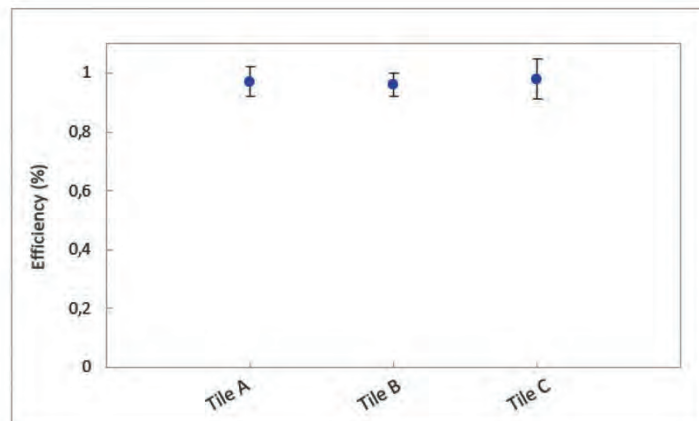
To estimate the detection efficiency of the upper and lower scintillating tiles change the detector positions and repeat the measurement.



Experimental setup block diagram.

Results

The efficiency value for each detector should be very close to one another.



Detection efficiency of the three scintillating tiles – SP5622.

COSMIC FLUX AS A FUNCTION OF THE ALTITUDE

SG6215D

Difficulty



Execution Time



SP5620CH - COSMIC HUNTER



Purpose of the experiment

The measurement of cosmic ray flux as a function of altitude. The goal of this experiment is analyse muon rate behaviour by performing measurements at different altitude levels. For example, one may perform such measurements on different floors of a building, at different elevations of a hill, or even by using a hot-air balloon.

Fundamentals

The origin of cosmic radiation represents one of the most fascinating Physics discoveries of the 20th century. The first evidence of natural and non-terrestrial ionizing radiation in the atmosphere was observed in the early 1900s and subsequently studied via different typology of electroscopes by several scientists: from the Jesuit monk Theodor Wulf to the Italian physicist Domenico Pacini, to the Austrian-American physicist Victor Hess (Nobel Prize in 1936).

The measurement of the cosmic ray flux as a function of

the altitude played a key role in the comprehension of the nature of both primary and secondary cosmic rays. The Earth's atmosphere acts as a filter by absorbing most of the secondary particles produced by the interaction of the primary ones with the external layers of the atmosphere itself. Muons and Pions are the most have the greatest penetrating capability and can reach the Earth's surface. For that reason they constitute the hard component of the secondary cosmic radiation. The soft component consists mainly of gamma, positrons, and electrons that are easily absorbed by the Earth's atmosphere. Initially, the flux of the secondary cosmic rays as a function of the altitude endures a slight decrease due to the loss of the contribution of natural radioactivity from the terrestrial crust. However, evident increase in the flow of revealed particles is then observed.

Requirements

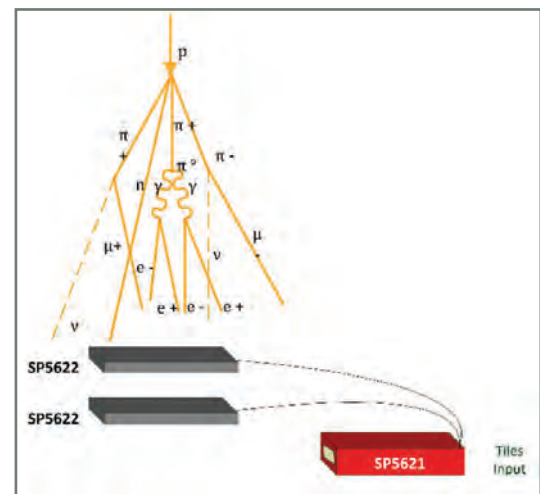
No other tools or instruments are needed.

Carrying out the experiment

Connect the cable connectors of the two SP5622 to the tile inputs located on the rear panel of the SP5621 module. Power on the SP5621 module and start the acquisition via the front panel START button. When a charged particle crosses the black tile it's energy is converted into scintillation light. The photons which are produced are detected by the photosensor and converted into an electrical signal. The number of counts for each scintillator may be viewed via the SP5621 display. Select double scintillators coincidence mode via the related button on the front panel, and then select measurement integration time. Because the acquisition of events takes place only in the presence of the coincidence, all such events coming from a cosmic particle that crosses only one scintillating tile will automatically be discarded.

Before starting acquisition choose the system geometry. Be sure to keep this geometry constant even at different

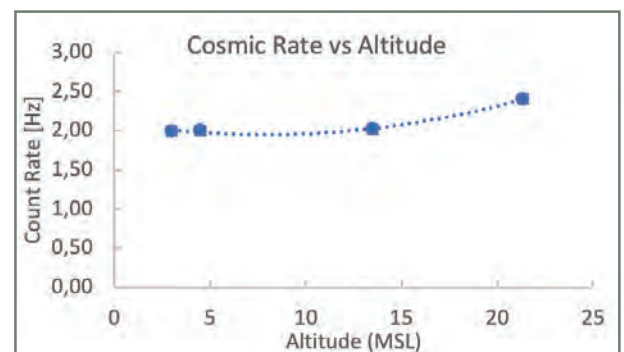
altitude levels. Take and record more data to obtain statistical significance.



Experimental setup block diagram.

Results

This experiment is a simple way to identify and prove the non-terrestrial origin of cosmic radiation. For better comprehension of the cosmic flux behaviour as a function of the altitude the user may cover the floor with lead bricks.



Cosmic flux as a function of altitude.



Purpose of the experiment

Measurement of the zenith dependence of the cosmic ray flux as a function of altitude. The goal of the experiment is to analyse zenith dependence by performing a series of measurements at different zenith angle values.

Fundamentals

Most muons are produced in the upper atmosphere, typically 15km above the surface of the earth. Muons typically lose about 2 GeV to ionization before reaching the ground. The average energy of muons on the ground is around 4 GeV. When their decay ($E_\mu > 100 / \cos\theta$ GeV) and the curvature of the Earth (for $\theta > 70^\circ$) can be disregarded the flux of cosmic muons can be expressed as follows:

$$\frac{dN_\mu}{dS dt dE_\mu d\Omega} = 0.14 E_\mu^{-2.7} \left\{ \frac{1}{1 + \frac{1.1 E_\mu \cos\theta}{115 \text{ GeV}}} + \frac{0.054}{1 + \frac{1.1 E_\mu \cos\theta}{850 \text{ GeV}}} \right\} [\text{cm}^2 \text{s GeV sr}]^{-1}$$

Where θ is the zenith angle, and the two terms in the brackets indicate the contribution of the charged pions and kaons. For $E_\mu \sim 3$ GeV, the angular distribution of muons is proportional to $\cos^2\theta$ at sea level. The intensity of cosmic muons is only determined by the angular dependence of the zenith on their energy spectrum and their energy. As first approximation, the dependence of the muon flow from ϕ is considered negligible, which is in fact less than 10% (*).

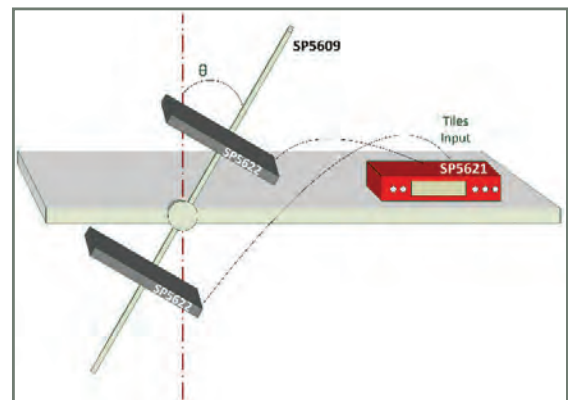
Requirements

SP5609 – Telescope Mechanics or a similar structure.

Carrying out the experiment

Set up the SP5609 on a desk or table and assemble the two SP5622 on the vertical arm. Connect the cable connectors of the two SP5622 to the tile inputs located on the rear panel of the SP5621 module. Power on the SP5621 module and start the acquisition via the front panel START button. When a charged particle crosses the black tile it's energy is converted into scintillation light. The photons which are produced are detected by the photosensor and converted into an electrical signal. The number of counts for each scintillator may be viewed via the SP5621 display. Select double scintillators coincidence mode via the related button on the front panel, and then select measurement integration time. Because the acquisition of events takes place only in the presence of the coincidence, all such events coming from a cosmic particle that crosses only one scintillating tile will automatically be discarded. Determine the solid angle of the muon telescope by fixing the distance

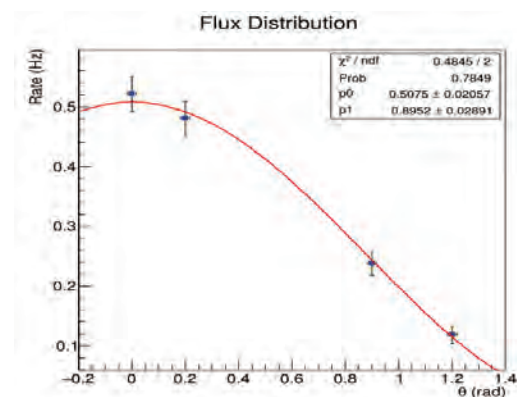
of the two scintillating tiles. Be sure to keep this orientation for the duration of the acquisition. Perform the cosmic flux measurement at the first zenith angle value, then rotate the structure to change the angle value and acquire new measurements.



Experimental setup block diagram.

Results

The following plot shows the result obtained by positioning the two detectors at 20 cm distance. The count rate was measured at four values of the zenith angle, $\theta = [0, 10^\circ, 50^\circ, 70^\circ]$, to verify the $\cos^2(\theta)$ theoretical trend of the muons flux.



Zenith angle dependence of the muons flux [Fit: $y = p0 * \cos^2(p1 * x)$].

(*) A. A. Ivanov et al., JETP letters, V69 N4 (1999) 288.

Difficulty



Execution Time



SP5620CH - COSMIC HUNTER



Purpose of the experiment

Detection of the cosmic showers by using the coincidence of three scintillating tiles located adjacent to one another on a flat surface.

Fundamentals

Cosmic ray showers are cascades generated by cosmic rays interacting with the atmosphere. They were originally discovered by chance during the application of coincidence counters for the study of the cosmic rays. In some of these experiments coincident events were detected when the detectors were not assembled in telescopic structure, but rather were organized near one another on a flat surface.

The intuition of this new physical phenomenon was formulated by Bruno Rossi in 1934 and is considered to be the first evidence of the existence of extended

atmospheric showers. The Italian physicist was the first to deduce that the multiplicative processes made by the cosmic rays produced in the atmosphere are identical to those observed in dense materials such as lead. Several groups of scientists studied this phenomenon. In particular, Auger and Maze undertook a campaign of systematic studies of these showers and even managed to measure coincident events between detectors as far apart as 300 meters! Auger and collaborators discovered the Extensive Atmospheric Showers [EAS] of very high energy, i.e. the energy of the primary particles at the origin of these events is around 10^{16} eV.

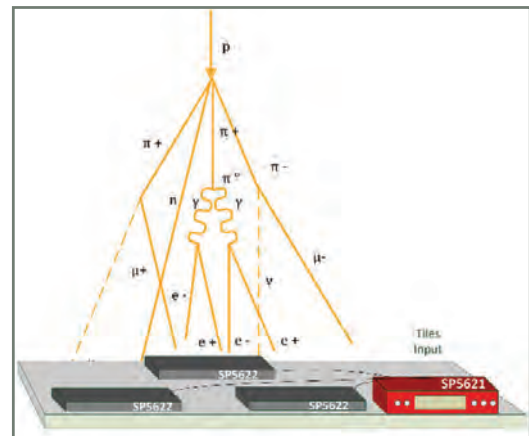
Requirements

Additional SP5622 - Detection System is needed.

Carrying out the experiment

Connect the cable connectors of the three SP5622 to the tile inputs located on the rear panel of the SP5621 module. Arrange the tiles on a flat surface some distance apart from one another. Power on the SP5621 module and start the acquisition via the front panel START button. When a charged particle crosses the black tile it's energy is converted into scintillation light. The photons which are produced are detected by the photosensor and converted into an electrical signal. The number of counts for each scintillator may be viewed via the SP5621 display. Select triple scintillator coincidence mode via the related button on the front panel, then select the integration time of the measurement. Because event acquisition will only take place only in the presence of the coincidence, all those events coming from a cosmic particle that crosses only one scintillating tile will be automatically discarded.

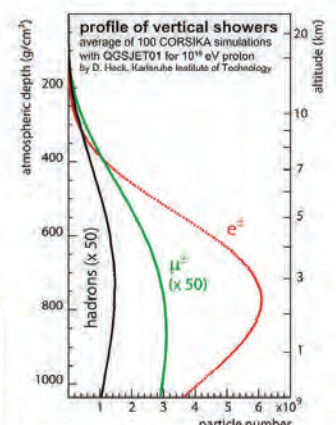
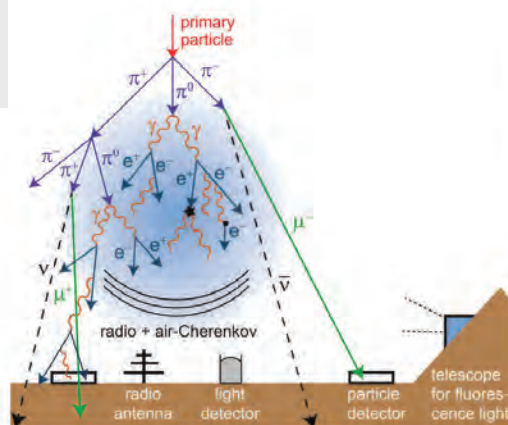
An extended geometry can be realized simply by using additional Cosmic Hunter. Additionally, it could be interesting to observe Air Showers as a function of the altitude.



Experimental setup block diagram.

Results

Observation of the cosmic shower phenomenon.



Scheme of an air shower detected by several detectors and its vertical profile (Ref. Frank G.Schröder, Radio detection of cosmic-ray air showers and high energy neutrinos, 2017, <https://doi.org/10.1016/j.pnpnp.2016.12.002>).



SP5620CH - COSMIC HUNTER

Difficulty



Execution Time

**Purpose of the experiment**

To estimate the contribution of environmental radiation during the detection of the cosmic radiation.

Fundamentals

Natural radiation is composed of two components: Environmental (primarily derived from soil, but also water, air and food) and Cosmic radiation. Gamma rays coming from soil will have mean energy lower than 2 MeV and will descend from the decay chains of three natural radioactive elements: Potassium [^{40}K], Thorium [^{232}Th] and Uranium [^{238}U]. However, there is a not null

probability that a soil-derived gamma interacts with the scintillating tile and deposits 1MeV of energy. This potential could cause confusion or inaccuracies in cosmic rays counting measurement. However, the high threshold of the electronics and the low probability of this phenomenon, when compared to the cosmic ray high detection probability, should typically avoid this inconvenient situation.

Requirements

No other tools or instruments are needed.

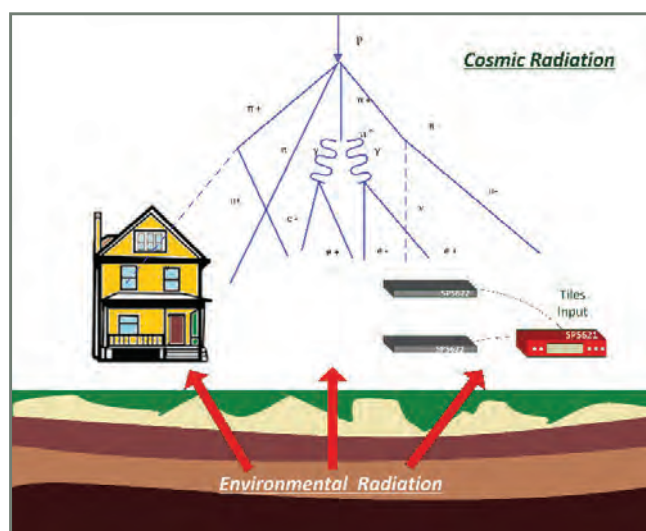
Carrying out the experiment

Connect the cable connectors of the two SP5622 to the tile inputs located on the rear panel of the SP5621 module. Power on the SP5621 module and start the acquisition via the front panel START button. When a charged particle crosses the black tile it's energy is converted into scintillation light. The photons which are produced are detected by the photosensor and converted into an electrical signal. The number of counts for each scintillator may be viewed via the SP5621 display. Select double scintillators coincidence mode via the related button on the front panel, and then select measurement integration time.

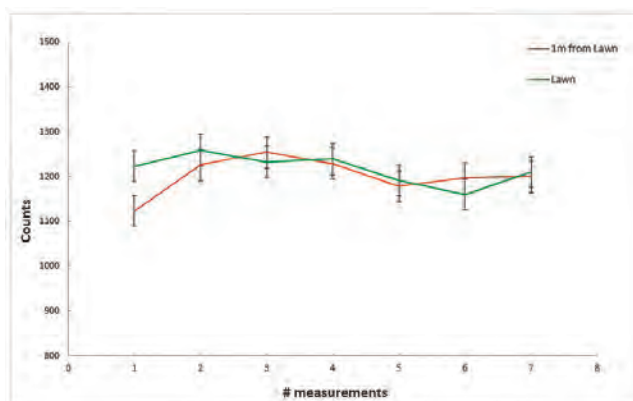
Before beginning acquisition the geometry of the system must be determined. Be sure to keep this geometry for the duration of the experiment. To get acquainted with environmental radiation detected by the Cosmic Hunter place the system over bare soil and record data. Once complete, place the detectors a few meters above bare soil and place an iron or lead shield between the soil and the tiles. Acquire the data again with identical tile geometry and compare the results.

Results

Students may become acquainted with the presence of natural radioactivity by identifying environmental and cosmic contributions via simple comparison of the counting measurements at different heights.



Experimental setup block diagram.



Comparison between the count rates of the measurements acquired on soil and again 1 meter above soil. The comparison plot demonstrates that the parameter settings (Bias Voltage and Threshold) are such that cosmic ray detection is not affected by environmental radiation.

Difficulty



Execution Time



SP5620CH - COSMIC HUNTER



Purpose of the experiment

The main goal of this experiment is verify the absorption of the cosmic rays passing through solid matter and understand related observations about the material which has been traversed by the cosmic rays.

Fundamentals

Before reaching the ground cosmic muons lose energy by ionization and through processes such as bremsstrahlung, creation of pairs ($e^+ e^-$), and nuclear interactions. If a detector is located within a building or below the earth's surface the detected muon flux decreases in relation to the thickness of the crossed rock/material. The expression of the average energy lost by a muon through matter is:

$$\frac{dE}{dx} = k(E) + b_b(E)E + b_p(E)E + b_nE$$

where the $b_b(E)$, $b_p(E)$ and b_n are proportionally connected to the losses due to bremsstrahlung, to pairs creation,

and to the nuclear interactions respectively. Interesting applications which explore the absorption of cosmic rays are represented by muon radiography and tomography. Muon radiography and tomography are based on the measurement of the absorption undergone by high energy muons when they cross solid objects. Good measurement techniques can provide precise maps of the average density of the object under investigation. These methods are used in several fields, from the geophysical application (volcanoes, caves, etc.) to the control of illicit traffic of radioactive materials, and much more. Typically, the average energy loss is about $1.7 \text{ MeV g}^{-1}\text{cm}^2$, therefore in the case of 1 Km of crossed rock whose density is equal to 2 g cm^{-3} , the muons lose about 0.5 TeV.

Requirements

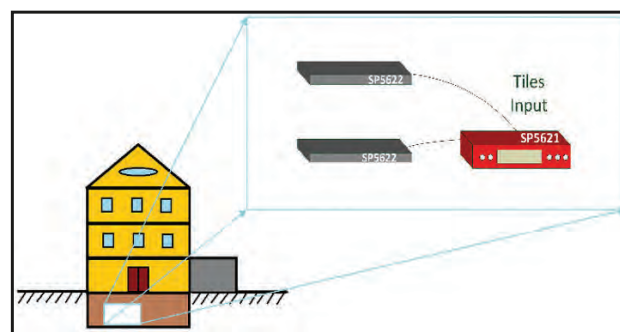
No other tools are needed.

Carrying out the experiment

Connect the cable connectors of the two SP5622 to the tile inputs located on the rear panel of the SP5621 module. Power on the SP5621 module and start the acquisition via the front panel START button. When a charged particle crosses the black tile it's energy is converted into scintillation light. The photons which are produced are detected by the photosensor and converted into an electrical signal. The number of counts for each scintillator may be viewed via the SP5621 display. Select double scintillators coincidence mode via the related button on the front panel, and then select measurement integration time.

Before beginning acquisition the geometry of the tile must be determined. Be sure to keep this geometry for the duration

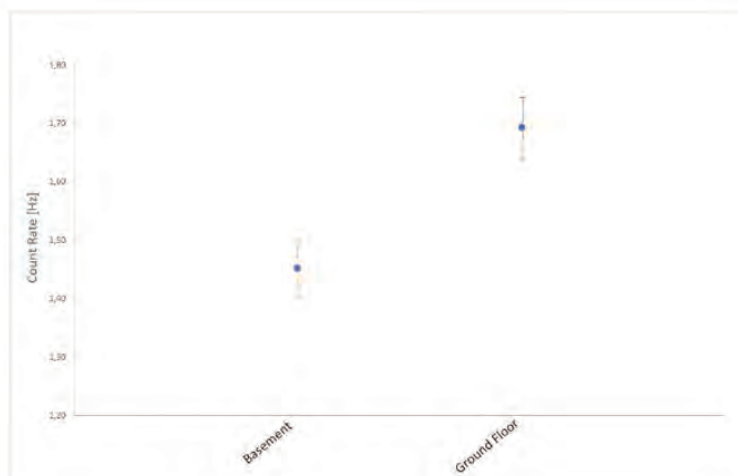
of the experiment. Acquire data in a cave or solid structure. Then repeat acquisition, keeping the tiles in an identical geometric orientation, outside of the structure or cave.



Experimental setup block diagram.

Results

Students can estimate absorption extent by comparing the results of the measurements performed underground or inside a cave to measurements performed outdoors and without any solid obstructions. Additionally, if the thickness of the overburden material or structure is known then some hypothesis about the average density of the material can be determined.



An example of absorption measurement has been performed in the basement of a building. As shown in the plot, the counting rate in thebasement is reduced by 14%.



SP5620CH - COSMIC HUNTER

Difficulty



Execution Time

**Purpose of the experiment**

Observation of cosmic flux variation due to solar activity.

Fundamentals

The intensity of the cosmic rays observed at the surface of the Earth is influenced and modulated by geomagnetic effects, by the location where the measurement takes place, and by the solar activity. There is a strong connection between the Sun and its effects on the Earth. The most visible effect relates to sunlight. But another effect relates to cosmic rays. Cosmic rays can be divided into two types: galactic cosmic rays and extragalactic cosmic rays (high-energy particles originating outside the solar system), and solar energetic particles (high-energy particles emitted by

Solar activity). The solar wind which is continuously produced by the Sun is not constant due to changes in solar activity. The unsteady nature of the solar wind is responsible for the flux variations of incoming cosmic rays observed at the top of the Earth's atmosphere. Multiple studies have shown that the sunspot cycle is not correlated with cosmic rays detected. This is caused by the solar magnetic field being stronger at the solar maximum which lets fewer cosmic rays penetrate into the Earth's atmosphere. Hence, cosmic rays are at a minimum when solar activity is at a maximum.

Requirements

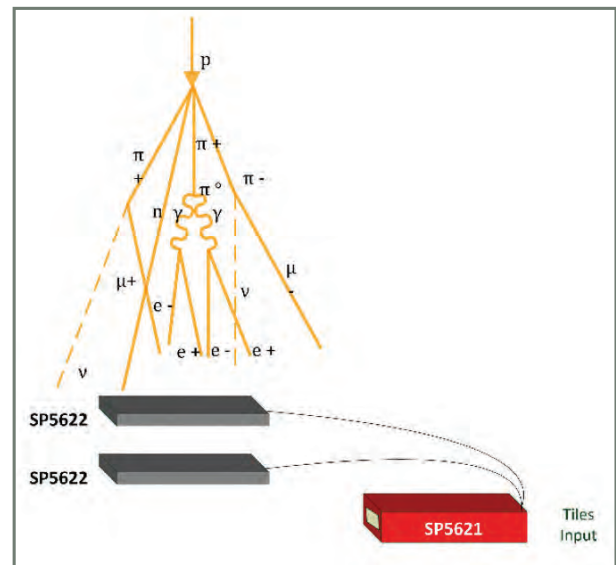
No other tools or instruments are needed.

Carrying out the experiment

Connect the cable connectors of the two SP5622 to the tile inputs located on the rear panel of the SP5621 module. Power on the SP5621 module and start the acquisition via the front panel START button. When a charged particle crosses the black tile it's energy is converted into scintillation light. The photons which are produced are detected by the photosensor and converted into an electrical signal. The number of counts for each scintillator may be viewed via the SP5621 display. Select double scintillators coincidence mode via the related button on the front panel, and then select measurement integration time. Because the acquisition of events takes place only in the presence of the coincidence, all such events coming from a cosmic particle that crosses only one scintillating tile will automatically be discarded.

Determine the system geometry and keep this geometry constant the duration of the measurement. Try to collect as much data as possible, over the period of days or even weeks, in order to perform and understand several

theoretical considerations about the night-day trend, the solar wind, etc.

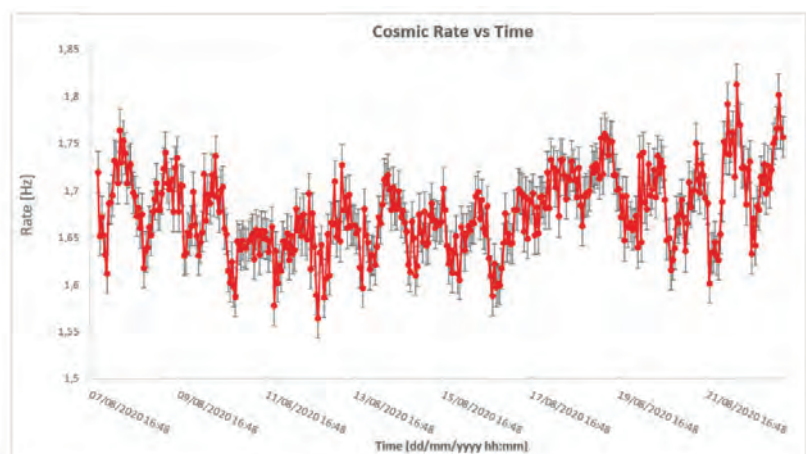


Experimental setup block diagram.

Results

This experiment leads the students to an intriguing and critical analysis of acquired data. Collected data can be compared to data from several websites which are designed allow the user to monitor the solar activity in real-time [*]. When comparing such data it is possible to find correlations between the trend of the cosmic rays detected by the system and the solar activity itself, the solar wind speed, the geomagnetic field, etc.

[*] <http://cosmicrays oulu.fi/links.html>



The typical cosmic rate night /day trend can be sometimes modified due to solar activity changes.

C. Particle Physics

C.2 Photons

Elementary particles can be classified into two main families: fermions, which include matter and antimatter particles such as quarks, antiquarks, electrons, and positrons, and bosons, which act as carriers of the fundamental interactions between particles.

The photon is the elementary particle associated with the electromagnetic interaction. It is a massless, electrically neutral boson with integer spin, obeying Bose–Einstein statistics. Photons are the fundamental constituents of light and play a central role in many physical processes involving the emission, propagation, and detection of light.

The experiments presented in this section introduce students to the fundamental properties of photons and to the principles of light detection. Using the CAEN Educational Photon Kit, students can explore photon detection techniques and gain practical experience with the measurement and analysis of light signals.





SP5600E - EDUCATIONAL PHOTON KIT

Difficulty



Execution Time

**Purpose of the experiment**

Exploring the quantum nature of light thanks to bunches of photons emitted in a few nanoseconds by an ultra-fast LED and sensed by a state-of-the-art detector, a Silicon Photomultiplier (SiPM).

Fundamentals

In the XVII century the concept of wave-particle duality was developed, starting from the wave nature of light postulated by Huygens to the Einstein Photoelectric Effect, which postulates light quanta existence.

A basic principle of quantum mechanics is complementarity: each quantum-mechanical object has both wave-like and particle-like properties. With this approach the photon is

at the same time wave and particle, but they can never be observed simultaneously in the same experiment, not even if the uncertainty principle is successfully bypassed

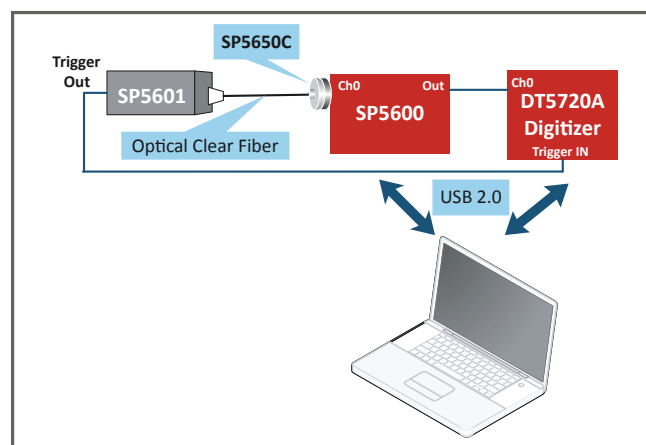
Requirements

No other tools or instruments are needed.

Carrying out the experiment

Plug in the SP5650A into one channel of SP5600 and connect the analog output to DT5720A channel 0. Remove the protection cover of the SP5601 and SP5650A, spread the optical grease on both ends of the optical fiber and connect them. Use internal trigger mode on SP5601 and connect its trigger output on the DT5720A trigger IN. Connect via USB the modules to PC and power ON the devices. Use the default software values or optimize the parameters to acquire the light spectrum.

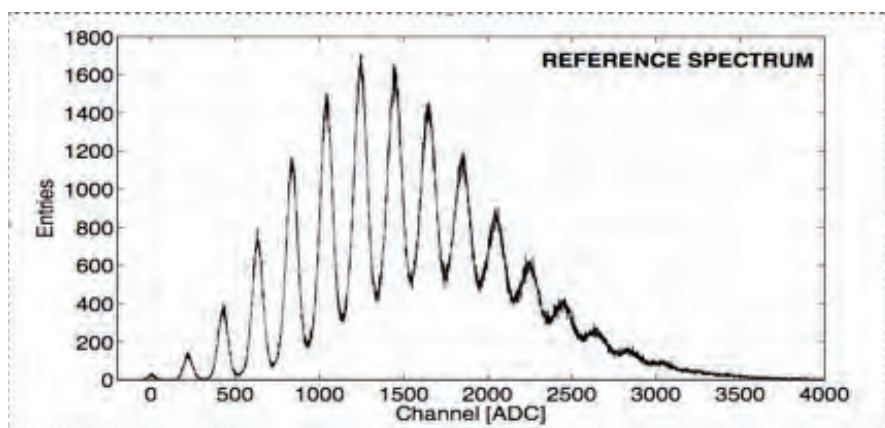
In the spectrum of the SiPM response to a light pulse, every entry corresponds to the digitized released charge, measured integrating the electrical current spike during a predefined time interval. The peaks correspond to different number of cells fired at the same time by incoming photons.



Experimental setup block diagram.

Results

This detector can count the number of impacting photons, shot by shot, allowing to observe how the light is composed by photons. Moreover the SiPM measures the light intensity simply by the number of fired cells.



Spectrum of the photons emitted by a LED Driver and detected by a Silicon Photomultiplier.

Difficulty



Execution Time



SP5600E - EDUCATIONAL PHOTON KIT



Purpose of the experiment

Statistical properties of the light pulses emitted by a LED driver.

Fundamentals

Spontaneous emission of light results from random decays of excited atoms and it is expected to be Poissonian. SiPM can count the number of impacting photons, shot by shot, opening up the possibility to apply basic skills in probability and statistics while playing with light quanta displaying the spectrum of the SiPM response to a high statistics of pulses. The spectrum is composed by a series of peaks, each ones correspond to different number of cells fired at the same time. Each peak is well separated and occurs with a probability linked at first order to the light intensity fluctuations. In SiPM the homogeneity of the response is quite high, however, since fired cells are randomly distributed in the detector sensitive area residual differences in the gain become evident broadening the peak.

A key point in the analysis technique was the estimation of

the area underneath every peak, essential to reconstruct the probability density function of the emitted number of photons per pulse. An easy procedure is to consider each peak as a gaussian, so spectra recorded in response to photons impacting on the sensor can be seen as a superposition of Gaussians, each corresponding to a well defined number of fired cells. A binned Gaussian distribution of N_{pk} events may be written as:

$$y_i = y_{\max} e^{-\frac{(x_i - x_0)^2}{2\sigma^2}}$$

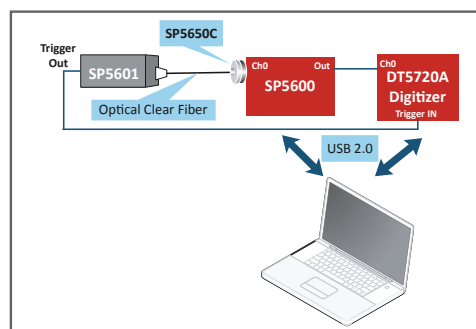
where y_i is the number of events in the bin centred on x_i and $y_{\max}$ is the peak value, measured in x_0 . Since $y_{\max} = N_{pk}/(\sigma\sqrt{2\pi})$, knowing the content of the bin centred in x_0 and estimating σ leads to N_{pk} . The standard deviation can also be calculated in a simple way by the Full Width at Half Maximum (FWHM), obtained searching for the position of the bins with a content equals to $y_{\max}/2$ and presuming that $FWHM = 2.355\sigma$.

Requirements

No other tools or instruments are needed.

Carrying out the experiment

Plug in the SP5650A into one channel of SP5600 and connect the analog output to DT5720A channel 0. Remove the protection cover of the SP5601 and SP5650A, spread the optical grease on both ends of the optical fiber and connect them. Use internal trigger mode on SP5601 and connect its trigger output on the DT5720A trigger IN. Connect via USB the modules to PC and power ON the devices. Use the default software values or optimize the parameters to perform the experiment.

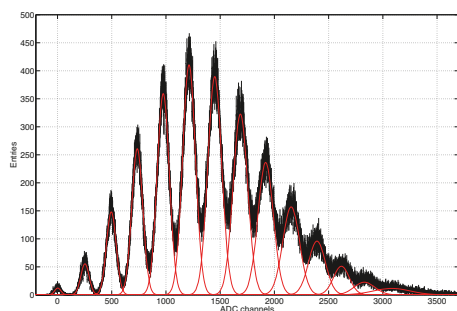


Experimental setup block diagram.

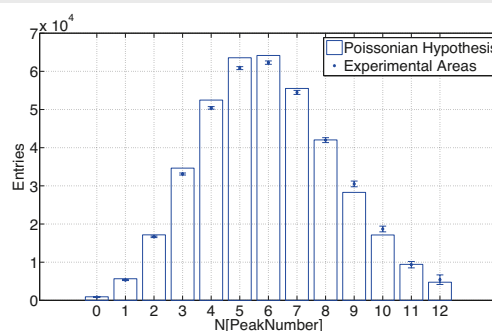
Results

The probability density function of the emitted number of photons per pulse can be estimated by the evaluation of the area underneath every peak.

Two different hypothesis can be investigated to evaluate the statistical model and mean number of photoelectrons: Model Independent (the mean photon number is nothing but the mean) and Poissonian hypothesis (mean value obtained by presuming a pure Poissonian behaviour and by referring to the probability $P(0)$ of having no fired cell when the expected average value).



Photocurrent spectrum probing a LED source measured with a Hamamatsu SiPM. The Individual Gaussians are shown in red.



Data from the light spectrum compared to a simple Poissonian.

D. Pulse Processing

D.1 Open FPGA Experiments



Field-Programmable Gate Arrays (FPGAs) are a key technology in modern scientific instrumentation, providing the high processing speed, parallel execution, and deterministic behavior required by data acquisition, digital signal processing, and real-time control systems.

Traditionally, FPGA development has been confined to specialists with expertise in Hardware Description Languages (HDLs), such as VHDL and Verilog. While these languages provide complete control over the hardware, they also require a significant learning effort and a deep understanding of digital design, making FPGA programming inaccessible to most students approaching the subject for the first time.

The experiments presented in this section offer a different educational approach. Rather than focusing on the syntax of HDL programming, they introduce the fundamental concepts of digital logic, signal processing, and hardware implementation through a series of progressive laboratory activities. Students are encouraged to reason in terms of logical functions, data flow, and parallel processing that are essential concepts that underpin FPGA design.

To support this learning process, the experiments are based on the SCI-Compiler development environment. SCI-Compiler adopts a graphical block-diagram methodology that automatically generates the FPGA firmware from the designed application. This approach significantly lowers the entry barrier to FPGA development, allowing students with little or no experience in VHDL or Verilog to design and implement real FPGA applications. By removing the complexity of traditional HDL coding, students can focus on understanding the logical structure of the system while gaining practical experience with one of the most powerful technologies used in modern instrumentation.

LED BLINKING DEMO ON DT1260 WITH SCI-COMPILER

SG6301F

SP5650 - OPEN FPGA KIT

Difficulty



Execution Time



Purpose of the experiment

This experiment shows two ways to blink an LED on the DT1260 with Sci-Compiler: a counter-comparator design and a PWM-based design. The aim is to compare implementation effort and timing control while obtaining the same visual result.

Fundamentals

Digital systems often use periodic signals to control timing and sequencing operations. A blinking LED is a simple way to visualize a square-wave signal generated by a digital circuit.

The frequency of the blinking corresponds to the signal

period, while the proportion of time the LED stays on defines the duty cycle. In digital hardware, such timing can be created either by manually counting clock cycles or by using a built-in Pulse-Width Modulation (PWM) generator.

This experiment demonstrates how essential concepts in digital electronics, such as timing control, signal generation, and logic synchronization, can be implemented and observed in practice.

Requirements

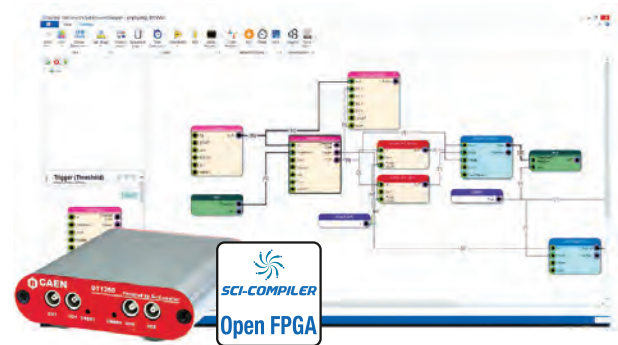
No other tool is needed.

Carrying out the experiment

Activate your Sci-Compiler license and set up the software installation. Plug the USB Dongle in your PC and launch Sci-Compiler. Create a project for your DT1260 unit: press New Project.

- Counter Method: Use a Chrono block to count clock cycles; two GREATER comparators set/reset an SR Flip-Flop. Drive LED_0 with FF output; optionally drive LED_1 with the inverted signal.
- PWM Method: Use a Pulse Generator (PWM). Set PERIOD and WIDTH constants; connect the PULSE output to LED_1.

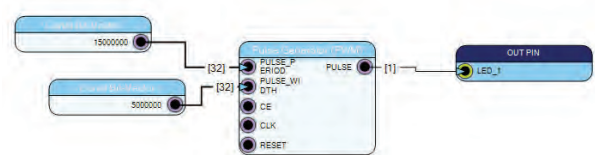
Run & Observe: Build, program the DT1260, and verify blink frequency/duty by changing constants.



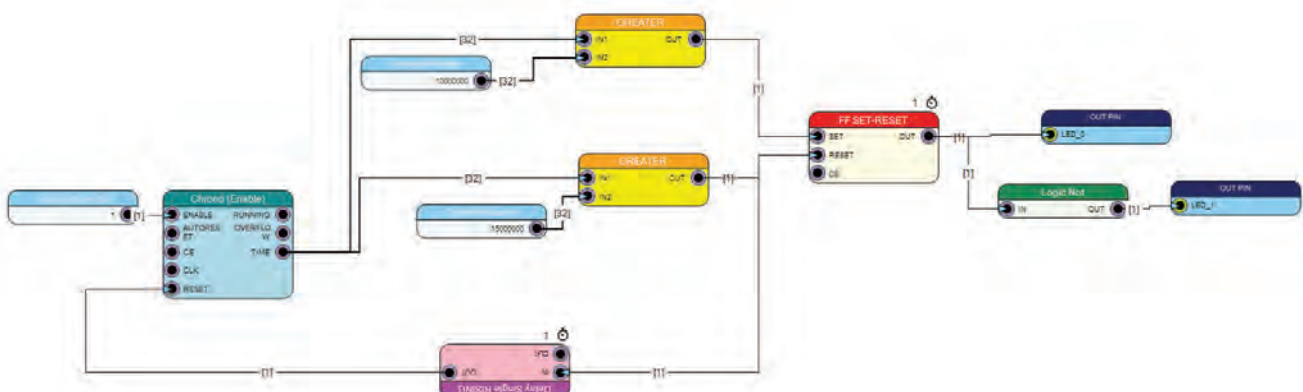
Experimental setup block diagram.

Results

Both approaches produce a stable blink. The counter method offers granular control over timing sequences; the PWM method minimizes design effort. Adjusting the constants directly sets blink frequency and duty cycle.



Integrated Pulse Generator (PWM) Approach.



Low-Level Counter Approach.



Difficulty



Execution Time



SP5650 - OPEN FPGA KIT

Purpose of the experiment

This application demonstrates how to integrate and operate the Oscilloscope block in a Sci-Compiler FPGA design on the DT1260 board, to visualize analog and digital signals in real time.

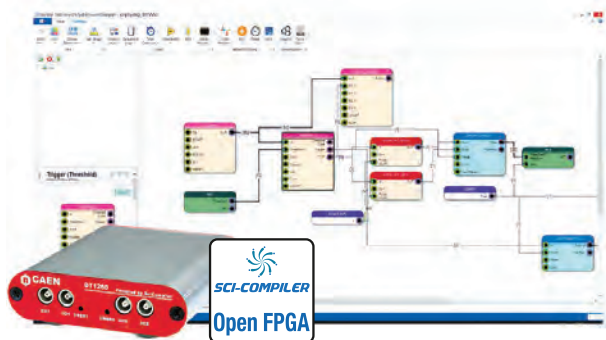
Fundamentals

An oscilloscope captures and displays signal waveforms, enabling time-domain observation of amplitude versus time. Analog input signals (after ADC conversion) and

internal digital signals inside the FPGA can be sampled and visualized through a memory-mapped interface. Triggering functions (edge detection, thresholds, pre/post trigger) stabilize the display of periodic or transient signals. A block, called "Oscilloscope", connects FPGA logic with external visualization tools for debugging and signal validation.

Requirements

No other tool is needed.



Experimental setup block diagram.

Carrying out the experiment

Activate your Sci-Compiler license and set up the software installation. Plug the USB Dongle in your PC and launch Sci-Compiler. Create a project for your DT1260 unit: press New Project.

Add the Oscilloscope block to the design and connect analog (A0) and digital (D0–D3) inputs.

Configure channels, buffer size, and enable capture.

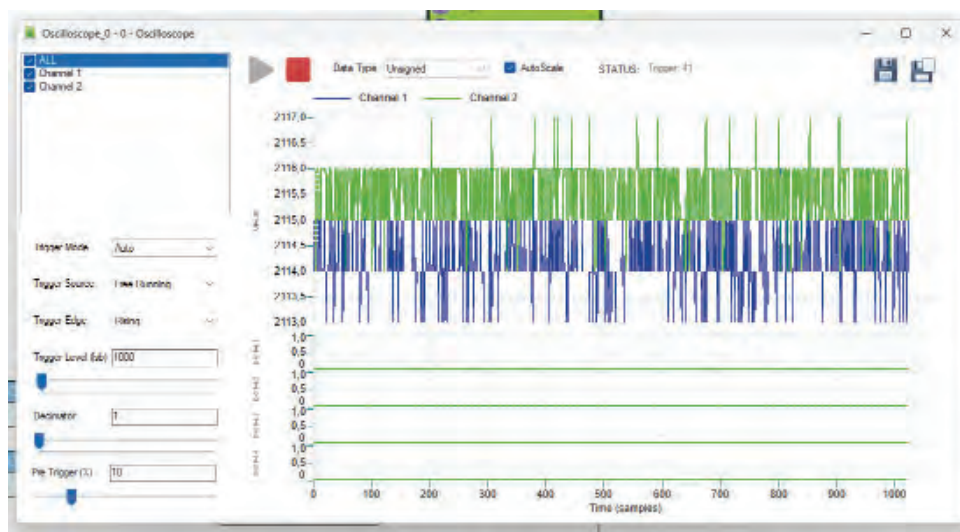
Assign memory addresses automatically, build the project, and program the DT1260.

Feed a test signal (e.g. PWM) to an input, open Oscilloscope_0 from the Resource Explorer, and set trigger source, mode, and level.

Start acquisition and adjust trigger settings to stabilize the displayed waveform.

Results

The Oscilloscope block provides real-time observation of FPGA-generated signals without external equipment. By adjusting trigger parameters, students can stabilize periodic waveforms or capture transient events, improving signal debugging, timing verification, and system validation.



Oscilloscope Screen.

THRESHOLD DISCRIMINATOR WITH EVENT COUNTER

SG6303F**SP5650 - OPEN FPGA KIT****Difficulty****Execution Time**

Purpose of the experiment

Demonstrate how to implement a threshold discriminator and count events exceeding that threshold using logic blocks on the DT1260 with Sci-Compiler. The goal is to convert an analog or digital input into a binary “event” signal and record how many such events occur over time.

Fundamentals

A threshold discriminator outputs a logic high when its input signal crosses a predetermined level. This

mechanism enables digital detection of analog signal excursions. An event counter then increments each time a discriminator output transitions (i.e., detects a “hit”). These functions are fundamental in instrumentation and particle detection systems, where counting the number of threshold crossings (or pulses) is essential. Synchronization with FPGA clocking ensures reliable digital sampling and avoids metastability.

Requirements

No other tool is needed.

Carrying out the experiment

Activate your Sci-Compiler license and set up the software installation. Plug the USB Dongle in your PC and launch Sci-Compiler. Create a project for your DT1260 unit: press New Project.

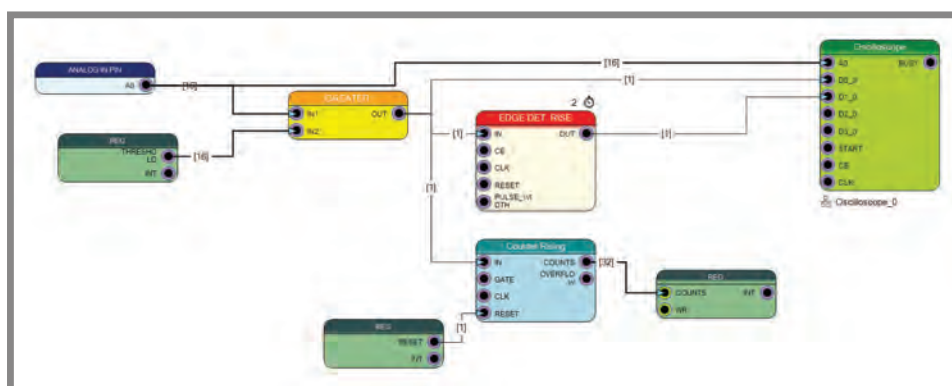
First, the FPGA firmware is created with the following functional blocks: an analog comparator that compares the input signal with the programmable threshold, a register to control the threshold value, a counter that increments when the signal crosses the threshold, a reset register to clear the counter when needed. After compiling the design and programming the DT1260 board, the system can be tested using the DT4800 connected to the DT1260 analog input. The integrated oscilloscope tool in Sci-Compiler can be used to observe both the analog waveform and the digital discriminator output.



Experimental setup block diagram.

Results

The implemented system generates a digital pulse each time the input signal crosses the programmed threshold and increments the event counter accordingly. By combining the Comparator, Edge Detector, Counter, and memory-mapped registers, the firmware implements a configurable threshold discriminator capable of counting how many times the incoming analog signal exceeds the selected level. By adjusting the threshold value, students can observe how the number of detected events changes. This illustrates the fundamental principle of signal discrimination and event counting, which is widely used in detector readout systems for radiation and particle physics experiments.



Counter with register schematic.

USING PYTHON TO ACCESS THE THRESHOLD DISCRIMINATOR REGISTERS



Difficulty



Execution Time



SP5650 - OPEN FPGA KIT

Purpose of the experiment

The purpose of this experiment is to demonstrate how a Python application can interact with FPGA firmware to configure and monitor a digital system. Students learn how to access memory-mapped registers in order to control the threshold discriminator and read the event counter implemented in the previous experiment.

Fundamentals

In FPGA-based data acquisition systems, configuration parameters and status information are often exposed through memory-mapped registers. These registers allow external software to configure firmware parameters and read measurement results. In this experiment, a Python

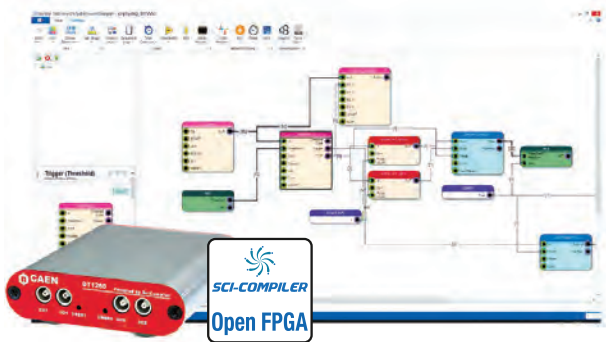
program communicates with the FPGA firmware to:

- set the threshold value of the discriminator,
- reset the event counter,
- read the number of detected events.

This approach reflects how many real detector systems are controlled, where software running on a computer manages configuration and data acquisition from programmable hardware.

Requirements

Python environment.



Experimental setup block diagram.

Carrying out the experiment

A Python script is used to communicate with the FPGA firmware and access the relevant registers.

The script performs the following operations:

- establishes the connection with the DT1260 board,
- writes a threshold value to the discriminator register,
- resets the event counter,
- periodically reads the counter value.

By running the script while a signal is applied to the input, students can observe how the counter increases as events are detected.

Results

The Python application successfully accesses the registers controlling the threshold discriminator and event counter implemented in the FPGA firmware. This experiment demonstrates how software applications can interact with programmable hardware, enabling flexible control and monitoring of data acquisition systems.

```

Registering DT1260 endpoints
SCIDK_Lib library loaded correctly ...
Threshold set to 2300
Threshold read back: 2300
Counter has been reset.
COUNTS = 0
COUNTS = 65
COUNTS = 130
COUNTS = 195
□
  
```

Expected output.

SP5650 - OPEN FPGA KIT

Difficulty



Execution Time

**Purpose of the experiment**

The aim of this experiment is to demonstrate how a Python application can be used to acquire and visualize waveforms in real time from an FPGA-based system.

Fundamentals

In many detector readout systems, it is important not only to detect events but also to observe and analyze the full waveform produced by the detector. The shape of a pulse can provide valuable information about the signal amplitude, timing characteristics, noise conditions, and overall system performance. In digital data acquisition systems, the analog signal is first sampled by an Analog-to-Digital Converter (ADC). The resulting sequence of samples represents the waveform in the time domain and can be processed or transmitted to a computer for

visualization and analysis. Modern FPGA-based systems often include dedicated waveform buffers, where a set of consecutive samples is stored. These samples can then be transferred to a PC through a communication interface and displayed using software tools.

In this experiment, waveform data generated by the FPGA firmware are acquired by a Python application and plotted in real time using a graphical visualization library. This allows users to observe the signal evolution sample by sample and better understand how the detector and the readout electronics behave during operation.

Requirements

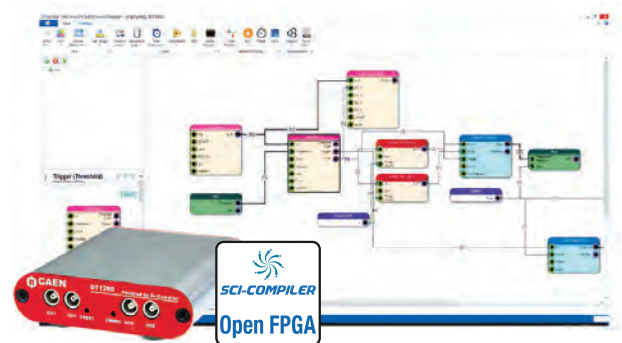
Python environment and Matplotlib for plotting.

Carrying out the experiment

A Python program is used to connect to the hardware and read waveform data generated by the FPGA firmware. The program performs the following steps:

- establishes communication with the board,
- requests waveform samples from the firmware buffer,
- converts the acquired data into a format suitable for visualization,
- displays the waveform using a real-time plotting interface.

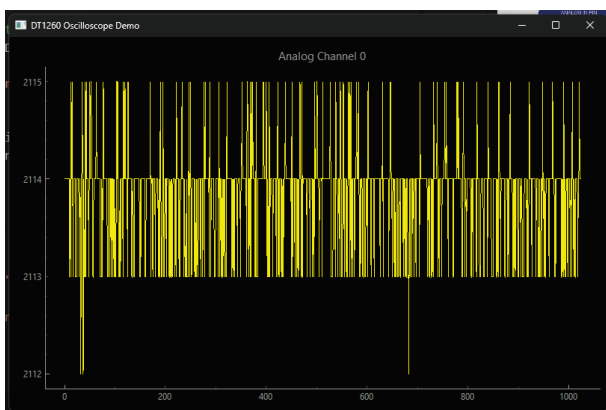
As signals are applied to the input, the acquired samples are continuously updated in the graphical display.



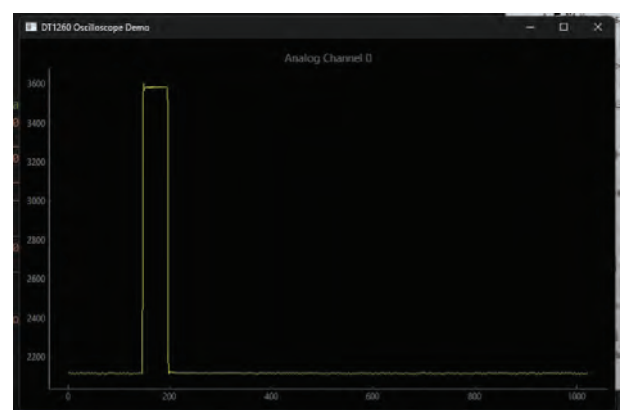
Experimental setup

Results

The system acquires waveform samples from the hardware and displays them in real time. Students can observe the shape and amplitude of the signal and how the waveform changes with different input conditions. This experiment demonstrates how software tools can be used to visualize detector signals in digital readout systems.



Plot Windows.



Triggered signal.



Difficulty



Execution Time



SP5650 - OPEN FPGA KIT

Purpose of the experiment

The aim of this experiment is to perform a threshold scan to study how the number of detected events varies as a function of the discriminator threshold.

Fundamentals

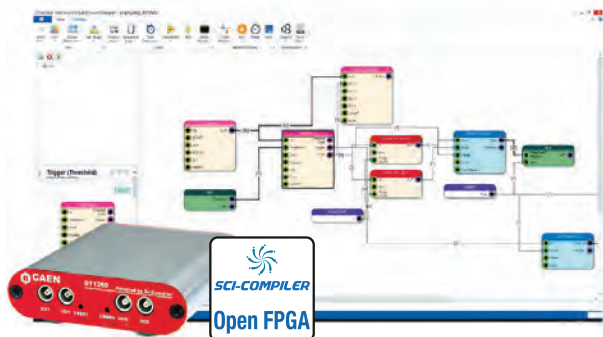
In detector readout systems, the threshold level of a discriminator determines which signals are accepted as valid events. Signals with amplitudes above the threshold generate a trigger, while smaller signals are rejected as noise. By gradually changing the threshold

and measuring the corresponding event rate, it is possible to characterize the signal distribution and understand the relationship between pulse amplitude and detection probability.

This procedure, known as a threshold scan, is commonly used to evaluate detector performance, noise levels, and signal amplitude distributions.

Requirements

Python environment and Matplotlib for plotting.



Experimental setup.

Carrying out the experiment

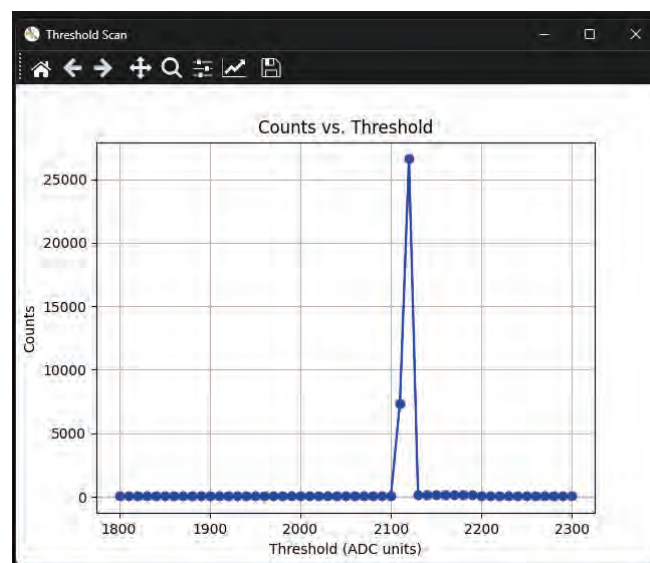
A Python script is used to automate the measurement process. The program performs the following operations:

- sets a threshold value through the corresponding register,
- resets the event counter,
- waits for a fixed acquisition time,
- reads the number of detected events.

This procedure is repeated for multiple threshold values. The collected data are then stored and plotted to visualize how the event count depends on the threshold.

Results

The measurement produces a curve showing the number of detected events as a function of the threshold value. Students can observe that increasing the threshold reduces the number of detected events, since only larger pulses exceed the discrimination level. This curve provides a simple way to visualize the signal amplitude distribution and evaluate the discriminator setting.



Plot of the counts vs threshold.

FPGA-BASED DWELL TIME FOR PRECISE EVENT COUNTING

SG6307F

SP5650 - OPEN FPGA KIT

Difficulty



Execution Time



Purpose of the experiment

The aim of this experiment is to demonstrate how event counting can be performed within a fixed time interval (dwell time) using FPGA logic. Students learn how to implement a timing-controlled acquisition that counts the number of detected events during a defined measurement period.

Fundamentals

In many measurement systems, event counting must be performed over a well-defined time interval to determine quantities such as event rate or signal intensity. This time

interval, often called dwell time, defines the duration of the counting window. During this period, incoming events are accumulated by a counter. At the end of the interval, the counter value represents the number of detected events.

Implementing the dwell time directly in the FPGA ensures precise timing control, since the measurement interval is generated by the hardware clock rather than by software timing.

Requirements

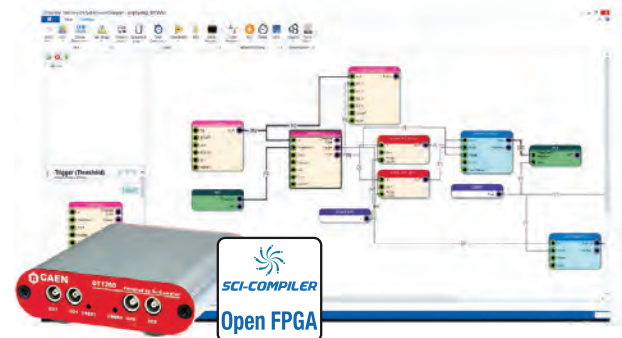
Python environment.

Carrying out the experiment

A firmware design is implemented including:

- an event counter that increments when a signal crosses the threshold,
- a timer block that defines the dwell time,
- registers used to control and monitor the acquisition.

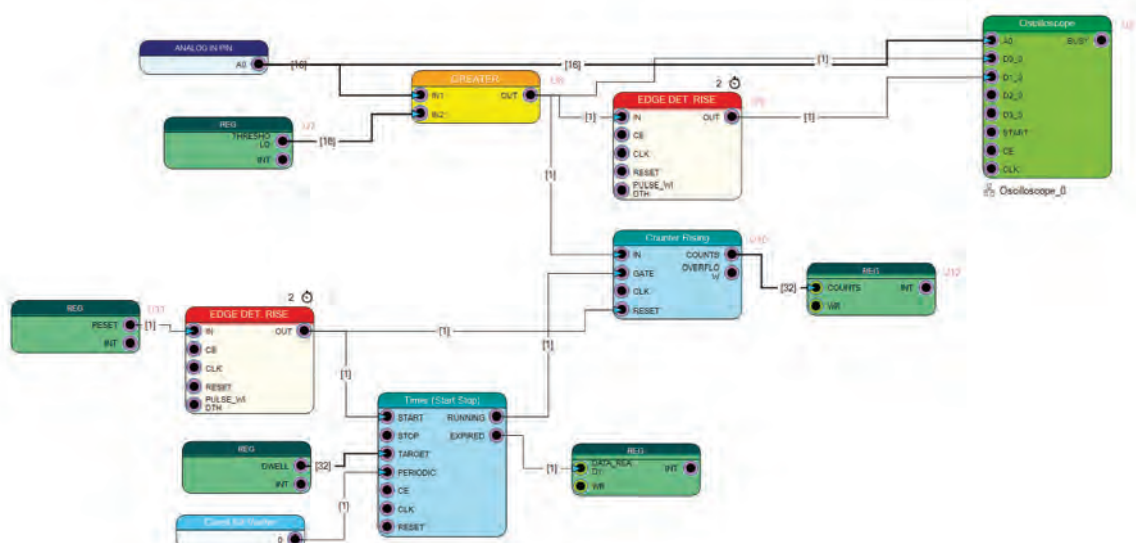
After programming the DT1260 board, a signal source generates pulses at the input. The FPGA counts the events occurring during each dwell time interval. The results can then be read by the control software.



Experimental setup block diagram.

Results

The system counts the number of detected events within a fixed dwell time interval. By adjusting the dwell time or the input signal rate, students can observe how the number of counted events changes. This experiment illustrates how precise timing control implemented in FPGA hardware enables accurate event rate measurements in digital data acquisition systems.



Design with hardware DWELL .



Difficulty



Execution Time



SP5650 - OPEN FPGA KIT

Purpose of the experiment

The aim of this experiment is to demonstrate how digital electronics can be used to measure timing properties of detector signals, specifically Time-of-Flight (ToF) and Time-over-Threshold (ToT). Students implement FPGA logic capable of measuring the time difference between signals and the duration of pulses crossing a threshold.

Fundamentals

In many detector systems, timing information plays a crucial role in identifying events and reconstructing physical processes. Time-of-Flight (ToF) measurements determine the time difference between two signals, often corresponding to the arrival of a particle at two different

detectors. This information can be used to estimate particle velocity or interaction position. Time-over-Threshold (ToT) measures how long a signal remains above a predefined threshold. Since the duration of this interval is related to the pulse amplitude, ToT can provide a simple estimate of signal strength. In digital readout systems, these quantities can be measured by detecting the leading and trailing edges of threshold crossings and counting clock cycles between them.

Requirements

Python environment.

Carrying out the experiment

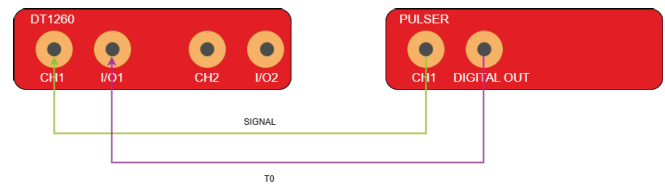
Activate your Sci-Compiler license and set up the software installation. Plug the USB Dongle in your PC and launch Sci-Compiler. Create a project for your DT1260 unit: press New Project.

A firmware design is implemented including:

- a threshold discriminator to detect signal crossings,
- logic to identify the leading and trailing edges of pulses,
- counters or timers used to measure time intervals.

Input signals are provided to the board using a pulse generator. The FPGA measures the time difference

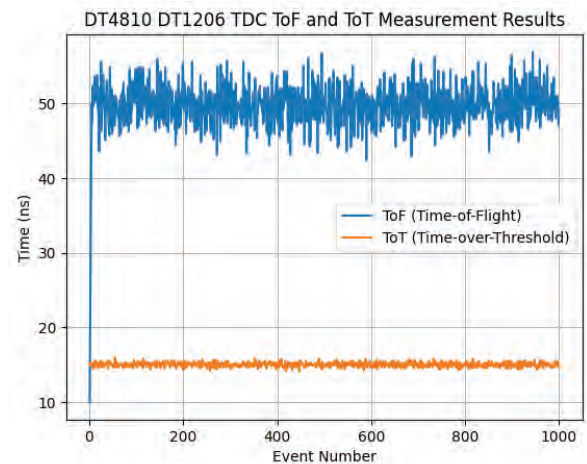
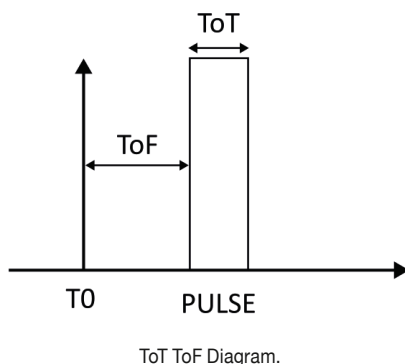
between signals for ToF and the pulse duration above threshold for ToT. The measured values are then made available to the control software.



Experimental setup block diagram.

Results

The system successfully measures both the time difference between signals (ToF) and the duration of pulses above the threshold (ToT). By changing the timing or width of the input pulses, students can observe how the measured values vary. This experiment demonstrates how FPGA-based timing measurements can be used to extract temporal information from detector signals in digital readout systems.



Experimental Results.

SP5650 - OPEN FPGA KIT

Difficulty



Execution Time



Purpose of the experiment

The aim of this experiment is to show how a Python program can read and display two histograms produced by the FPGA firmware: the Time-over-Threshold (ToT) spectrum and the Time-of-Flight (ToF) spectrum. Students learn how software can be used to collect, visualize, and compare timing-related measurements from the same acquisition system.

Fundamentals

In digital readout systems, measured quantities such as ToT and ToF can be accumulated into spectra, where each bin stores the number of events corresponding to a given measured value. A ToT spectrum shows how long

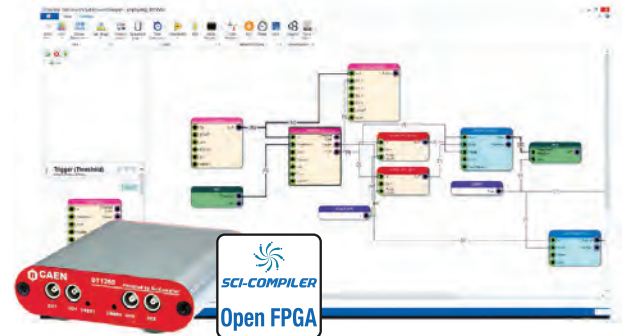
signals remain above threshold, while a ToF spectrum shows the time delay between a reference signal and the detected event. Plotting these two histograms helps users study both pulse timing and pulse-related amplitude information in a simple visual form. In this lab, the firmware inherited from ID.6308 includes two histogram blocks, one for ToT and one for ToF, and both can be read from Python and plotted side by side.

Requirements

Python environment and Matplotlib for plotting.

Carrying out the experiment

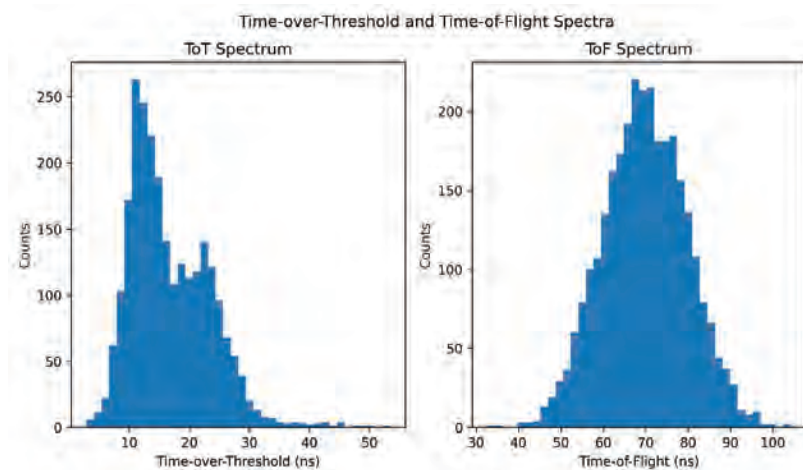
A Python script connects to the DT1260, configures the two spectrum components, resets their memories, and starts data accumulation. After a fixed acquisition time, the program reads both histograms from the FPGA memory and plots them in two side-by-side graphs: one for ToT and one for ToF. This allows students to visualize the distribution of the measured values directly from software.



Experimental setup block diagram.

Results

The experiment produces two spectra displayed side by side: a ToT histogram and a ToF histogram. The ToT spectrum shows the distribution of pulse durations above threshold, while the ToF spectrum shows the distribution of time delays between the reference and the detected signal. By observing the position and shape of the peaks, students can evaluate the timing behaviour of the system and relate the two measurements to the characteristics of the input pulses.



Example ToT and ToF spectra obtained with the DT1260/DT4810 setup. Each bin represents the number of events measured within a given time interval.



Difficulty



Execution Time



SP5650 - OPEN FPGA KIT

Purpose of the experiment

The aim of this experiment is to demonstrate how event-by-event data can be recorded using a list data buffer implemented in FPGA firmware. Students learn how to store and read structured event data including timestamps and Time-over-Threshold (ToT) values for each detected signal.

Fundamentals

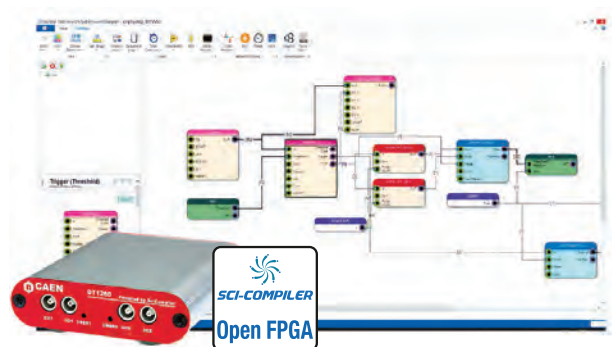
In many detector readout systems, measurements are not only accumulated into histograms but also recorded event by event. This approach, often called list mode acquisition, stores the relevant parameters of each detected event in a sequential data structure.

Typical event parameters include the timestamp, which identifies when the event occurred, and quantities such as Time-over-Threshold (ToT), which provide information about the signal duration above the discrimination threshold.

These values are collected into a list data buffer inside the FPGA. Each entry in the buffer corresponds to a single detected event and contains the associated measurement parameters. The buffer can then be read by the control software for further analysis or visualization.

Requirements

Python environment.



Experimental setup block diagram.

Carrying out the experiment

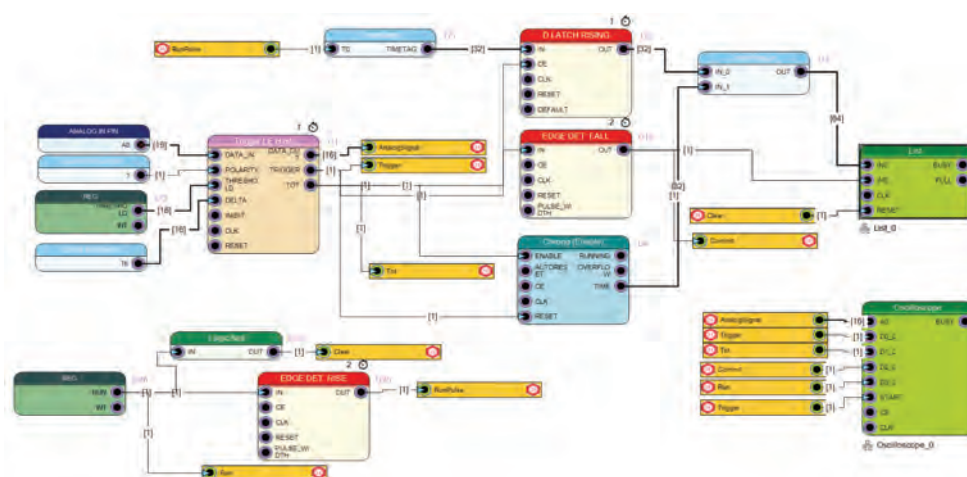
A firmware design is implemented including:

- a threshold discriminator to detect signal events,
- logic to measure the Time-over-Threshold (ToT),
- a timestamp counter driven by the FPGA clock,
- a list data buffer used to store event data sequentially.

During operation, each detected event generates a record containing the timestamp and ToT value. These records are stored in the list buffer and periodically read by a Python program for inspection and analysis.

Results

The system produces a sequence of event records containing timestamps and ToT measurements. By reading the list data buffer, students can observe how each event is stored individually with its associated timing information. This experiment demonstrates how list mode acquisition allows detailed analysis of detector signals and provides a flexible alternative to histogram-based measurements in digital data acquisition systems.



Design Schematics.

PYTHON READOUT, DECODING, AND PLOTTING OF TOF AND TOT

SG6311F

SP5650 - OPEN FPGA KIT

Difficulty



Execution Time



Purpose of the experiment

The aim of this experiment is to demonstrate how event data acquired in list mode can be read, decoded, and analyzed using a Python application.

Fundamentals

In digital data acquisition systems, measurements can be stored as list data, where each event is recorded sequentially together with its associated parameters. These parameters may include quantities such as timestamps, ToF, and ToT, which describe the timing properties of detector signals.

Before the data can be analyzed, the raw event records must be decoded to extract the individual measurement values. Once decoded, these values can be processed or plotted to study their statistical distribution.

Using software tools such as Python, it is possible to automatically read the event buffer, decode the data structure, and generate plots that display the measured quantities.

Requirements

Python environment.

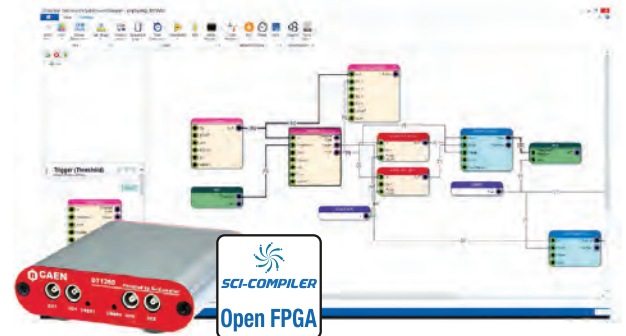
Carrying out the experiment

A Python script connects to the DT1260 and reads the list data buffer containing the recorded event data.

The script performs the following operations:

- retrieves the raw event data from the hardware buffer,
- decodes each event to extract timestamp, ToF, and ToT values,
- stores the decoded measurements in arrays for analysis,
- generates plots to visualize the distributions of ToF and ToT.

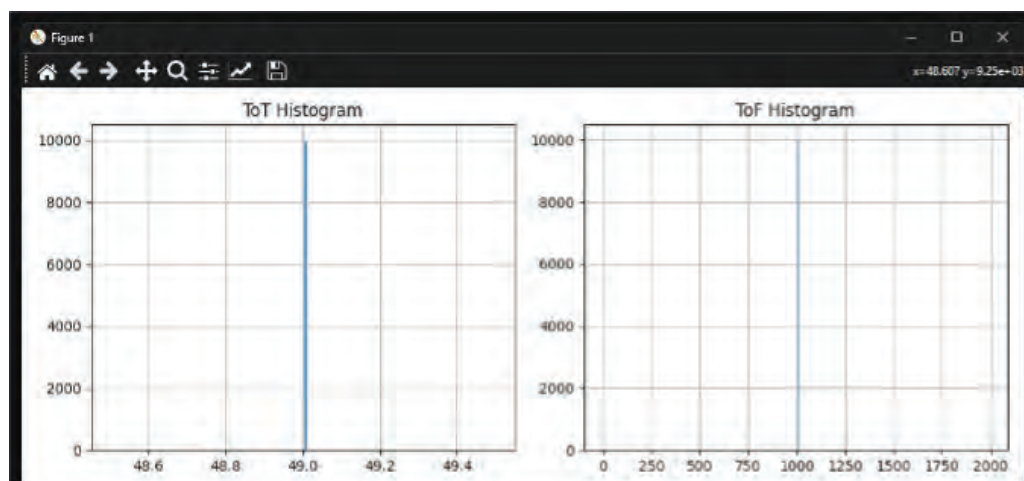
This process demonstrates how event data can be processed directly from the acquisition system using a software-based workflow.



Experimental setup block diagram.

Results

The decoded event data are displayed as histograms or scatter plots showing the distributions of ToF and ToT values. By analyzing these plots, students can observe the timing characteristics of the detected signals and verify the measurements performed by the FPGA firmware. This experiment illustrates how software-based data processing and visualization can be used to interpret list-mode acquisition data in digital detector readout systems.



Histograms.

LEADING EDGE WITH HYSTERESIS, DERIVATIVE, AND TRAPEZOIDAL TRIGGER COMPARISON



Difficulty



Execution Time



SP5650 - OPEN FPGA KIT

Purpose of the experiment

The aim of this experiment is to compare different trigger algorithms used to detect signal events in digital readout systems.

Fundamentals

In detector readout electronics, a trigger is used to determine when a valid signal event occurs. Different trigger algorithms can be implemented depending on the signal characteristics and noise conditions.

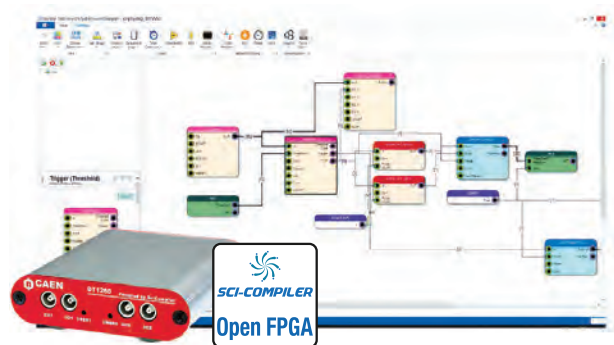
The Leading Edge trigger generates an event when the signal crosses a fixed threshold. Adding hysteresis introduces a second threshold for returning below the trigger level, helping to avoid false triggers caused by

noise fluctuations. A Derivative trigger operates on the derivative of the signal, detecting rapid changes in amplitude. This approach is useful for identifying the rising edge of pulses and improving timing precision.

A Trapezoidal trigger is based on digital filtering of the signal using a trapezoidal shaping algorithm. This method enhances the signal-to-noise ratio and can provide more stable triggering for signals with varying amplitude. By implementing and comparing these methods in FPGA firmware, students can study how different trigger strategies influence signal detection.

Requirements

Python environment.



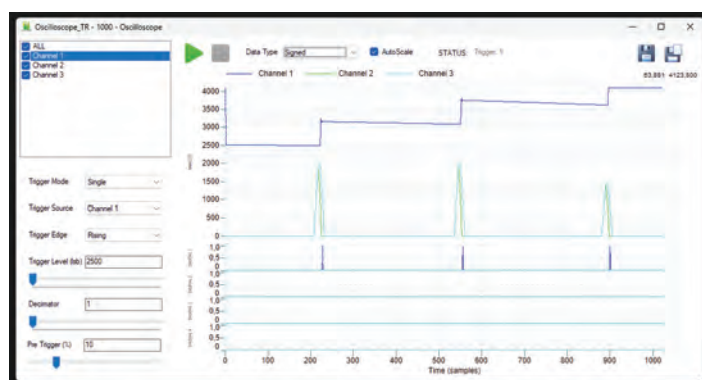
Experimental setup block diagram.

Carrying out the experiment

Activate your Sci-Compiler license and set up the software installation. Plug the USB Dongle in your PC and launch Sci-Compiler. Create a project for your DT1260 unit: press New Project. A firmware design is implemented including three parallel trigger paths: Leading Edge discriminator with hysteresis, Derivative-based trigger, Trapezoidal filter trigger.

The input signal is applied to the board and processed simultaneously by the three trigger algorithms. The resulting trigger signals can be monitored and compared using the acquisition software.

By adjusting parameters such as threshold values and filter settings, students can observe how each trigger method responds to the same input signal.



Example of Trapezoidal filter trigger operating in high rate regime.

Results

The experiment allows students to compare the behaviour of the three trigger techniques when processing identical input pulses. Differences can be observed in trigger timing, noise sensitivity, and stability. The Leading Edge trigger provides a simple and fast detection method, while the derivative trigger improves sensitivity to rapid signal changes. The trapezoidal trigger, thanks to digital filtering, offers more robust performance in the presence of noise. This comparison highlights how different trigger algorithms affect signal detection and timing accuracy in digital detector readout systems.

MEASURING SIGNAL AMPLITUDE VIA PEAK DETECTION

SG6313F

SP5650 - OPEN FPGA KIT

Difficulty



Execution Time



Purpose of the experiment

The aim of this experiment is to demonstrate how the amplitude of detector pulses can be measured using a peak detection algorithm implemented in FPGA firmware.

Fundamentals

In many radiation and particle detection systems, the pulse amplitude is proportional to the energy deposited in the detector. Measuring the maximum value of the signal therefore provides important information about the detected event. A common technique to determine this value is peak detection, where the system continuously monitors the incoming waveform and records the highest

sample value reached during the pulse. Once the pulse ends, this maximum value is stored as the amplitude measurement for that event. In digital readout systems, the signal is sampled by an Analog-to-Digital Converter (ADC) and processed by FPGA logic. The peak detection algorithm compares consecutive samples and keeps track of the highest value observed during the pulse window. This approach allows the system to measure pulse amplitudes in real time and store them for further analysis or histogram generation.

Requirements

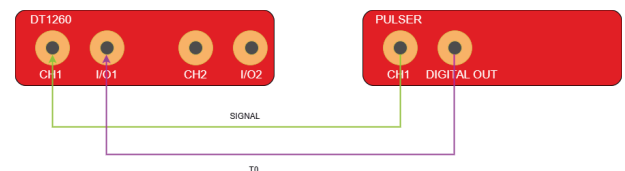
Python environment.

Carrying out the experiment

Activate your Sci-Compiler license and set up the software installation. Plug the USB Dongle in your PC and launch Sci-Compiler. Create a project for your DT1260 unit: press New Project. A firmware design is implemented including:

- a trigger block used to detect incoming pulses,
- a peak detection module that tracks the maximum sample value during the pulse,
- registers used to store and access the detected peak value

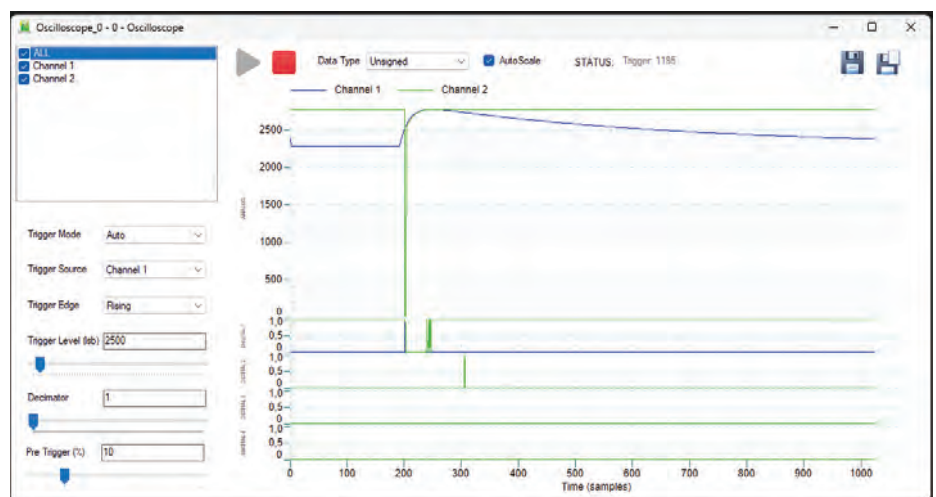
A signal generator is used to produce pulses with controlled amplitude. The FPGA processes the incoming waveform and records the peak value for each detected event. The results can then be read by the software application.



Experimental setup block diagram.

Results

The system detects and stores the maximum amplitude of each input pulse. Students learn how the peak value of a signal can be identified and recorded for each event, enabling digital amplitude measurements. By varying the input signal amplitude, the corresponding changes in the detected peak values can be observed.



Oscilloscope Signals.



Difficulty



Execution Time



SP5650 - OPEN FPGA KIT

Purpose of the experiment

The aim of this experiment is to demonstrate how the charge associated with a detector pulse can be measured using a digital integration algorithm implemented in FPGA firmware. Students learn how the area of a pulse can be computed to estimate the total charge generated by the detected signal.

Fundamentals

In many radiation and particle detection systems, the total charge collected from a pulse is proportional to the energy deposited in the detector. Instead of measuring only the peak amplitude, the signal can be analyzed by

integrating the waveform over a defined time window.

In digital readout systems, the analog signal is first sampled by an Analog-to-Digital Converter (ADC). The charge is then estimated by summing the digital samples corresponding to the pulse over the selected integration interval. This process is known as charge integration.

Implementing the integration directly in the FPGA allows the system to compute the pulse charge in real time for each detected event.

Requirements

Python environment.



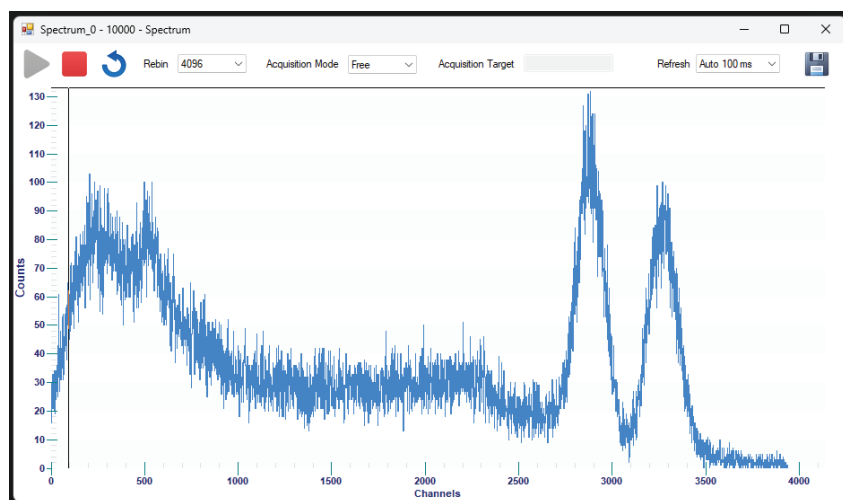
Experimental setup block diagram.

Carrying out the experiment

Activate your Sci-Compiler license and set up the software installation. Plug the USB Dongle in your PC and launch Sci-Compiler. Create a project for your DT1260 unit: press New Project. A firmware design is implemented including:

- a trigger block used to detect incoming pulses,
- an integration module that sums the samples of the waveform over a defined time window,
- registers used to store and read the computed charge value.

A signal generator provides pulses with controlled characteristics. The FPGA processes the incoming waveform and performs the charge integration for each detected event. The resulting values can then be accessed through the control software.



Energy Spectrum.

Results

The system computes the integrated charge of each detected pulse by summing the waveform samples within the integration window. Students learn how the pulse area can be used as a digital estimate of the signal charge.

By modifying the input signal amplitude or width, the corresponding changes in the measured charge values can be observed.

TRAPEZOIDAL FILTERING WITH A FULLY INTEGRATED MCA IP CORE

SG6315F

SP5650 - OPEN FPGA KIT

Difficulty



Execution Time



Purpose of the experiment

This experiment introduces digital pulse processing techniques used to perform energy measurements with detector signals. Students explore how a trapezoidal filter and a Multi-Channel Analyzer (MCA) implemented in FPGA firmware can process incoming pulses and build an energy spectrum.

Fundamentals

In many radiation detection systems, the energy deposited in a detector is estimated from the amplitude of the processed signal. Digital pulse processing techniques are commonly used to improve

measurement accuracy and reduce noise. A widely used method is trapezoidal filtering, which shapes the incoming pulse into a trapezoidal waveform. This digital filtering technique enhances the signal-to-noise ratio and produces a stable flat-top region from which the signal amplitude can be measured reliably. Once the pulse amplitude is determined, the measurement can be accumulated into a Multi-Channel Analyzer (MCA) histogram. Each detected event increments the bin corresponding to the measured amplitude, gradually forming an energy spectrum.

Requirements

Python environment.

Carrying out the experiment

Activate your Sci-Compiler license and set up the software installation. Plug the USB Dongle in your PC and launch Sci-Compiler. Create a project for your DT1260 unit: press New Project. A firmware design is implemented including:

- a trapezoidal filter used to shape the incoming signal,
- a measurement stage to determine the pulse amplitude from the filtered waveform,
- an MCA module that accumulates the measured values into a histogram.

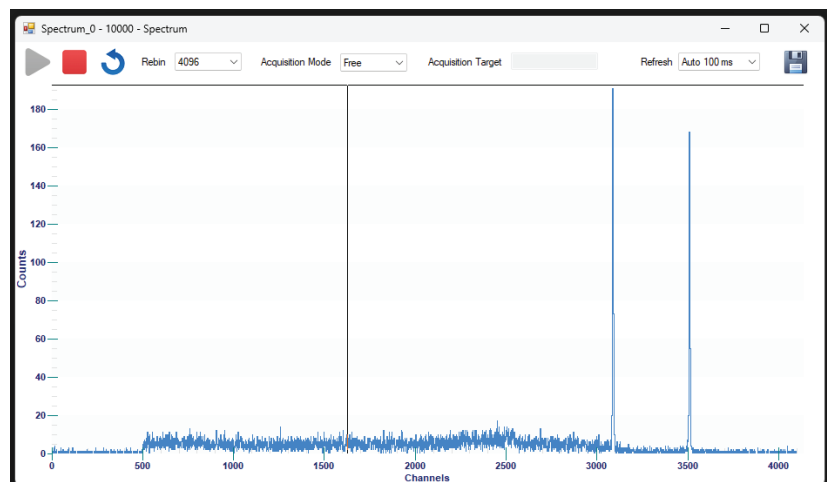
During operation, incoming pulses are processed by the trapezoidal filter, and their amplitudes are assigned to the corresponding MCA channels. The resulting spectrum can then be read and visualized through the control software.



Experimental setup block diagram.

Results

The system generates an energy spectrum by accumulating the processed pulse amplitudes into the MCA histogram. Students can observe how repeated measurements produce a distribution of events across the spectrum. This experiment shows how digital filtering and histogram accumulation enable spectroscopic measurements in FPGA-based detector readout systems.



Co-60 Spectrum.



Difficulty



Execution Time



SP5650 - OPEN FPGA KIT

Purpose of the experiment

This experiment introduces the concept of pulse shaping in detector readout electronics. Students explore how a CR-RC² shaping filter can be implemented in FPGA firmware to process detector signals and improve their suitability for amplitude measurements.

Fundamentals

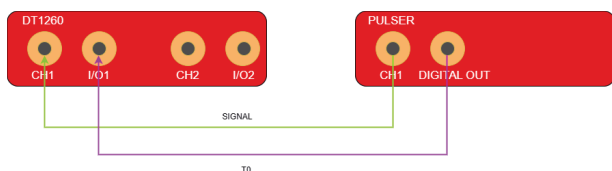
In radiation and particle detection systems, the signals produced by detectors often contain noise and long decay tails that can complicate amplitude measurements. To improve signal quality, the waveform is typically processed by a shaping amplifier.

A common shaping method is the CR-RC² filter, which combines a high-pass stage (CR) with two low-pass stages (RC²). This configuration differentiates the signal and then integrates it, producing a semi-Gaussian shaped pulse with improved signal-to-noise ratio and reduced baseline fluctuations.

Pulse shaping helps to stabilize the signal amplitude and makes it easier to perform accurate measurements in subsequent processing stages such as peak detection or spectroscopy.

Requirements

Python environment.



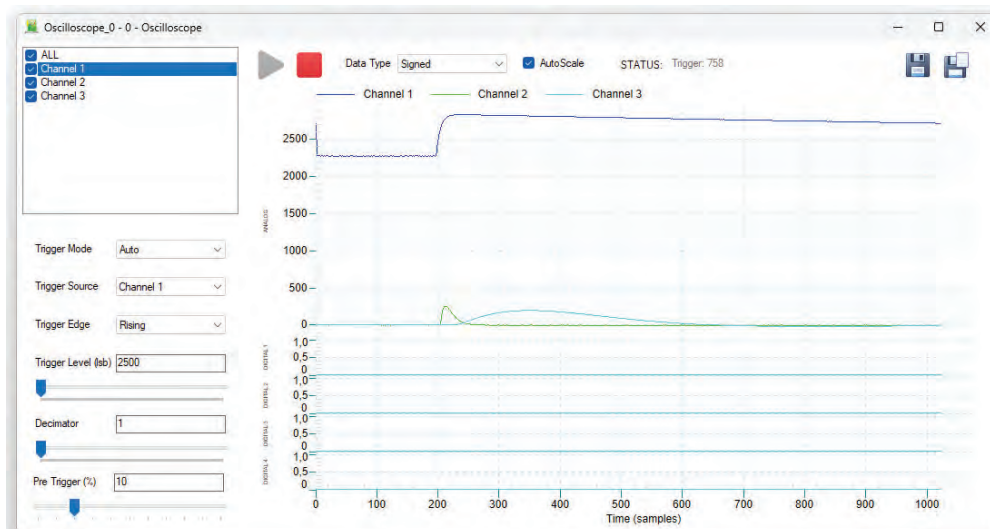
Experimental setup block diagram.

Carrying out the experiment

Activate your Sci-Compiler license and set up the software installation. Plug the USB Dongle in your PC and launch Sci-Compiler. Create a project for your DT1260 unit: press New Project. firmware design is implemented including a CR-RC² digital shaping filter that processes the incoming waveform samples. The input signal generated by the pulse source is fed into the shaping module. The filter transforms the original waveform into a shaped pulse with smoother characteristics and reduced noise influence. Students can observe and analyze the shaped waveform through the acquisition software.

Results

The CR-RC² filter produces a semi-Gaussian shaped pulse from the original detector signal. Students can observe how the shaping process smooths the waveform and reduces noise effects. This experiment demonstrates how digital pulse shaping techniques are used to improve signal quality and prepare detector signals for accurate amplitude and energy measurements.



Input signal (Blue), CR output signal (Green) and RC2 output signal (Cyan).

IMPLEMENTING A PULSE SHAPE DISCRIMINATOR (PSD) BASED ON AMPLITUDE VS. AREA RATIO

SG6317F

SP5650 - OPEN FPGA KIT

Difficulty



Execution Time



Purpose of the experiment

This experiment introduces the students to the concept of pulse shape discrimination (PSD), a technique used to distinguish different types of signals based on their shape.

Fundamentals

In some detectors, different types of radiation or particles produce pulses with different shapes, even when their amplitudes are similar. By analysing the shape of the pulse, it is possible to distinguish between different types of events. One common PSD technique is based on the

ratio between the pulse amplitude (peak value) and the pulse area (integrated charge). Since different signals may have different rise and decay times, this ratio can be used as a parameter to separate event populations. In digital readout systems, both amplitude and charge can be calculated from the sampled waveform. The FPGA can then compute the amplitude-to-area ratio for each event and use this value to perform event classification or generate PSD plots.

Requirements

Python environment.

Carrying out the experiment

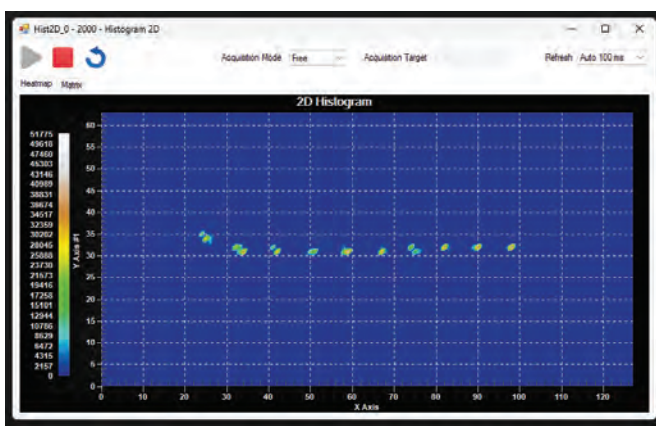
Create a project for your DT1260 unit: press New Project. A firmware design is implemented including: a trigger block to detect incoming pulses, a peak detection module to measure pulse amplitude, a charge integration module to measure pulse area, and a processing block that calculates the amplitude-to-area ratio. For each detected event, the FPGA computes the amplitude and the integrated charge and then evaluates their ratio. After compiling the design and programming the DT1260 board, the system can be tested using the DT4800 connected to the DT1260 analog input. The resulting values can be read and plotted using the control software.



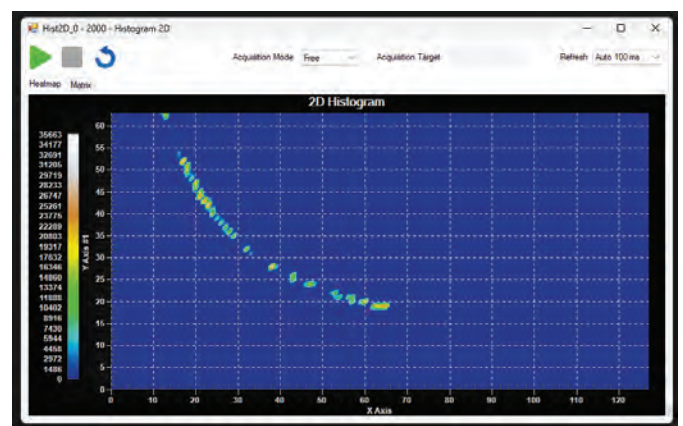
Experimental setup block diagram.

Results

This experiment demonstrates how pulse shape discrimination techniques can be implemented in FPGA-based readout systems to distinguish between different types of signals based on their waveform characteristics.



Histogram with Amplitude Variation.



Histogram with Tau Variation.

IMPLEMENTING A PULSE SHAPE DISCRIMINATOR (PSD) BASED ON RATIO BETWEEN AREAS



Difficulty



Execution Time



SP5650 - OPEN FPGA KIT

Purpose of the experiment

This experiment introduces a pulse shape discrimination (PSD) technique based on the ratio between two integration areas of the same pulse. Students learn how different pulse shapes can be distinguished by comparing the charge collected in two different time intervals of the signal.

Fundamentals

In some detectors, different types of events produce pulses with similar amplitudes but different temporal shapes, especially in the decay portion of the signal. Pulse shape discrimination techniques can be used to

distinguish these events by analysing how the signal evolves over time. A common PSD method consists of integrating the signal over two different time windows: a short gate and a long gate. The ratio between the charge collected in these two windows depends on the pulse shape and can be used to separate different types of events. In digital systems, this is implemented by computing two integrals of the waveform samples and calculating the ratio between the partial charge and the total charge.

Requirements

Python environment.



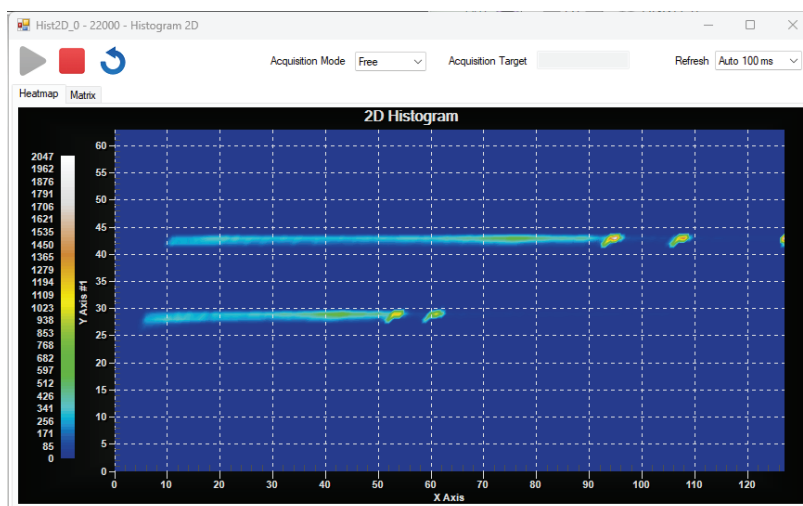
Experimental setup block diagram.

Carrying out the experiment

A firmware design is implemented including: a trigger block to detect incoming pulses, a short gate integrator, a long gate integrator, and a processing block that calculates the ratio between the two integrated charges. After compiling the design and programming the DT1260 board, the system can be tested using the DT4800 connected to the DT1260 analog input. For each detected pulse, the FPGA computes the charge collected in the short and long integration windows and then calculates their ratio. The results can be read and plotted using the control software.

Results

The system calculates the ratio between the short-gate charge and the long-gate charge for each detected pulse. By plotting these values, students can observe how pulses with different shapes produce different ratio values and form separate clusters. This experiment demonstrates how pulse shape discrimination based on charge integration can be used to distinguish between different types of detector signals in digital readout systems.



2D Histogram with 0.8us.

MULTICHANNEL READOUT USING THE ROUND ROBIN ARBITER

SG6319F

SP5650 - OPEN FPGA KIT

Difficulty



Execution Time



Purpose of the experiment

This experiment introduces the concept of multichannel data acquisition and shows how multiple input channels can be managed. Students learn how several channels can share the same processing and readout resources in a controlled and efficient way.

Fundamentals

In multichannel acquisition systems, several input channels may generate events simultaneously. Since the processing and readout resources are often shared, a method is required to decide which channel is processed at a given time. A common solution is the

Round Robin arbiter, which cyclically scans all channels and assigns processing time to each one in sequence. If a channel has data ready, it is served; otherwise, the system moves to the next channel. This method ensures fair access to shared resources and prevents any single channel from monopolizing the system. Round Robin arbitration is widely used in digital electronics and data acquisition systems to manage multiple data streams efficiently.

Requirements

Python environment.

Carrying out the experiment

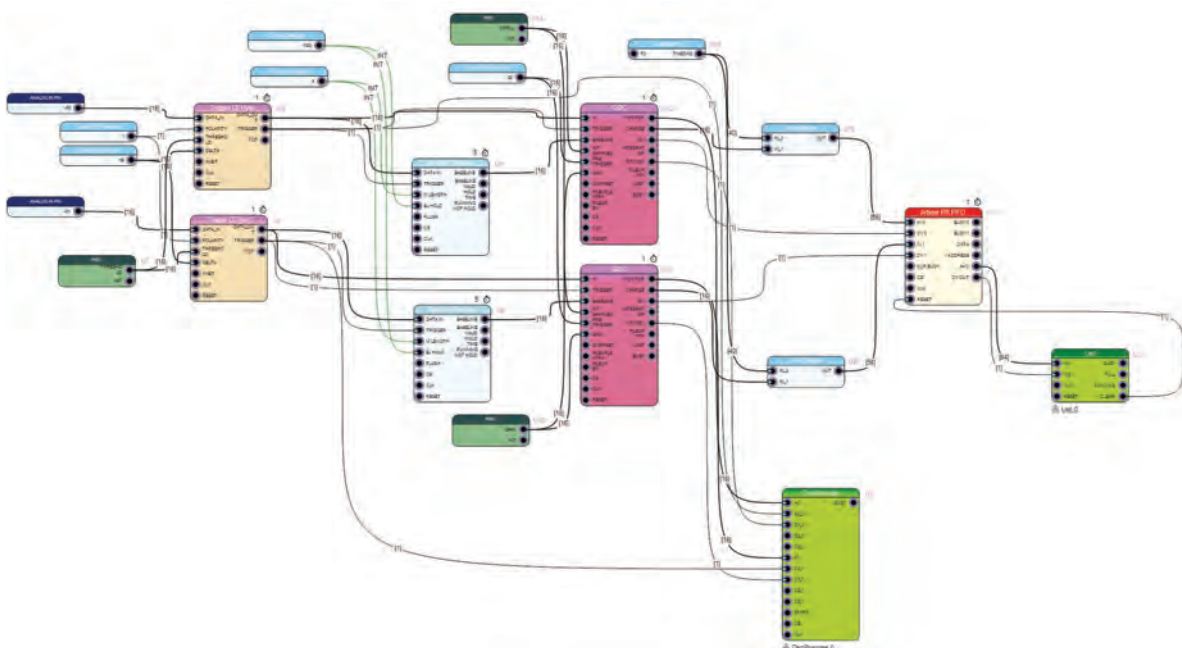
A firmware design is implemented including multiple input channels connected to a shared processing chain and readout interface. A Round Robin arbiter controls which channel is processed at each cycle. Input signals are applied to multiple channels, and the arbiter sequentially grants access to the processing and readout blocks. The acquired data are then transferred to the PC and monitored using the control software.



Experimental setup block diagram.

Results

This experiment demonstrates how the Round Robin arbitration method is used in multichannel data acquisition systems to manage shared resources efficiently and ensure fair channel access. Students can observe how the system handles multiple channels and how the arbitration logic distributes processing time among them.



Design Schematics.



Difficulty



Execution Time



SP5650 - OPEN FPGA KIT

Purpose of the experiment

This experiment introduces the concept of modular design in FPGA development using sub-designs. Students learn how complex multichannel systems can be built by replicating and connecting smaller functional blocks, making the design more scalable and easier to manage.

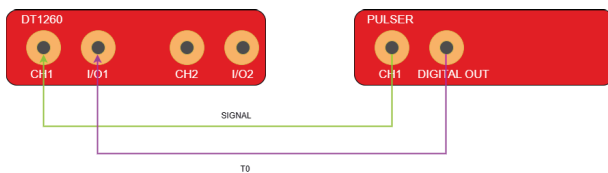
Fundamentals

In FPGA-based systems, complex designs are often created using a modular approach, where a functional block is designed once and then reused multiple times.

These reusable blocks are often called sub-designs. This approach is particularly useful in multichannel systems, where the same processing chain must be applied to several input channels. Instead of designing each channel separately, a single channel architecture can be implemented and then replicated multiple times. Using sub-designs improves design organization, simplifies debugging, and makes it easier to expand the system to a larger number of channels.

Requirements

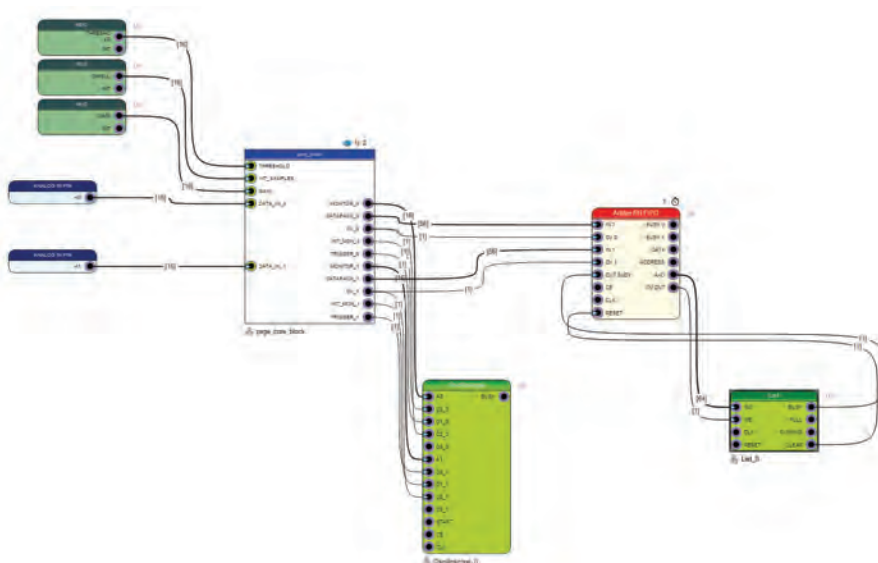
Python environment.



Experimental setup block diagram.

Carrying out the experiment

Create a new project for your DT1260 unit by clicking New Project. A firmware design is implemented starting from a single-channel processing chain, which includes the main signal processing blocks required for event detection and measurement. This single-channel architecture is then converted into a sub-design and instantiated multiple times to create a multichannel system. The outputs of the different channels are connected to shared resources such as memory buffers and readout interfaces. Input signals are provided to the board using a pulse generator connected to multiple channels. The FPGA processes the signals independently for each channel, and the measured data are then made available to the control software.



Top-level schematic with two sub-design channels.

Results

The system successfully implements a multichannel acquisition architecture using replicated sub-design blocks. Each channel processes its input signal independently while sharing common readout resources. This experiment demonstrates how modular FPGA design techniques allow scalable and efficient implementation of multichannel readout systems.



Purpose of the experiment

This experiment introduces the use of sub-block instances in FPGA design. Students learn how a functional block can be instantiated multiple times within a project, allowing efficient implementation of repetitive structures such as multichannel processing chains.

Fundamentals

In FPGA design, complex systems are often built using hierarchical and modular design techniques. Instead of creating large monolithic designs, smaller functional

blocks can be developed and reused multiple times. A sub-block instance is a copy of a functional block that operates independently but shares the same internal structure. This approach is useful when the same processing operation must be applied to multiple signals, such as in multichannel readout systems. Using sub-block instances improves design scalability, simplifies debugging, and reduces development time.

Requirements

Python environment.

Carrying out the experiment

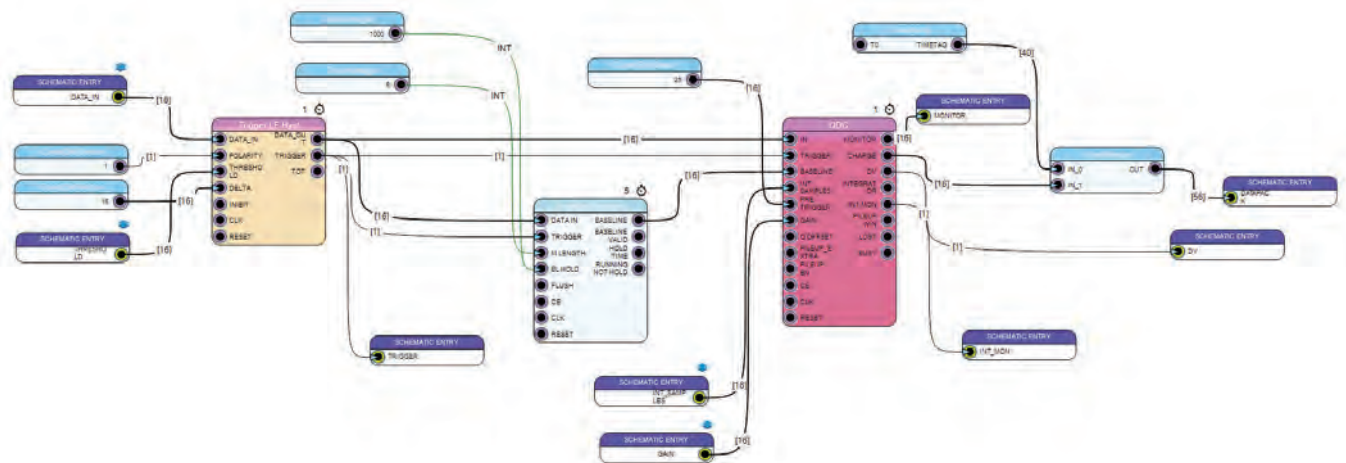
Activate your Sci-Compiler license and set up the software installation. Plug the USB dongle into your PC and launch Sci-Compiler. Create a new project for your DT1260 unit by clicking New Project. A firmware design is implemented by creating a functional processing block and then generating multiple instances of this block within the main design. Each instance processes its own input signal independently. The outputs of the different block instances are connected to shared resources such as memory buffers or readout modules. Input signals are provided to the board using a pulse generator connected to multiple inputs. The FPGA processes the signals through the different block instances, and the results are then made available to the control software.



Experimental setup block diagram.

Results

The system successfully processes multiple input signals using replicated sub-block instances. Each instance operates independently while sharing common readout resources. This experiment demonstrates how hierarchical design and block instantiation can be used to implement scalable multichannel systems in FPGA-based data acquisition applications.



Block diagram of the sub-design.



Difficulty



Execution Time



SP5650 - OPEN FPGA KIT

Purpose of the experiment

This experiment introduces how memory-mapped components can be used inside a sub-design to allow software control and monitoring of FPGA modules.

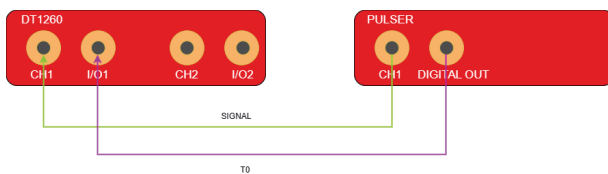
Fundamentals

In FPGA-based systems, many configuration parameters and measured values are accessed through memory-mapped registers. These registers allow software to write configuration values and read measurement results from the firmware. When using sub-designs or hierarchical blocks, memory-mapped components

can still be accessed from the top-level system. This allows each sub-block to contain its own configuration registers, counters, or memory buffers while remaining accessible to the control software. This approach is commonly used in complex systems where multiple processing blocks must be configured and monitored independently. Students learn how registers and memory blocks inside hierarchical designs can be accessed from software.

Requirements

Python environment.



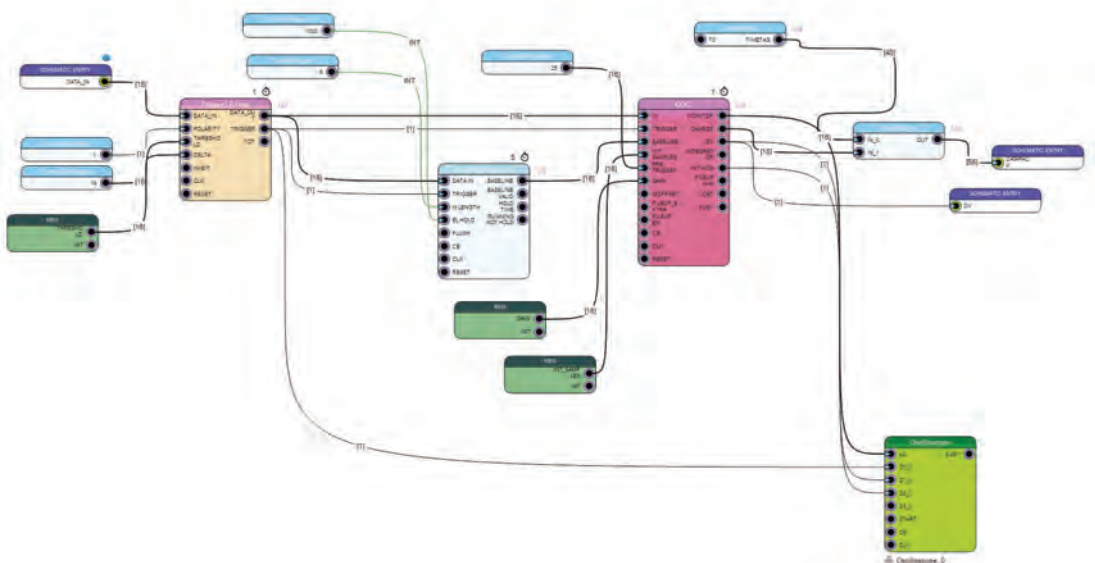
Experimental setup block diagram.

Carrying out the experiment

Create a new project for your DT1260 unit by clicking New Project. A firmware design is implemented including a sub-design containing memory-mapped components such as configuration registers, counters, or memory buffers. These components are connected to the main system bus so that they can be accessed from software. Input signals are provided to the board using a pulse generator. The firmware processes the signals, and the values stored in the memory-mapped components can be written or read through the control software.

Results

The system allows software to access and control memory-mapped registers and memory blocks located inside a sub-design. Students can configure parameters and read measurement data from hierarchical blocks within the FPGA design. This experiment demonstrates how memory-mapped components in sub-designs enable flexible configuration and monitoring of complex FPGA-based data acquisition systems.



Subdesign block diagram.

Products



The experiments presented throughout this handbook are performed using a range of instruments and modular kits selected to provide a comprehensive and effective laboratory experience.

Some of the systems have been specifically designed for educational purposes, while others are based on research-grade instrumentation routinely employed in scientific laboratories and integrated into educational kits. This combination allows students to become familiar with both dedicated teaching

tools and professional technologies used in modern experimental physics.

This section provides a brief overview of the main products used in the experimental setups. The modular organization of the kits allows the same instruments to be used across multiple experiments and application fields, providing a flexible platform for exploring a broad range of topics in physics and scientific instrumentation.

SP5700
EASYPET



2D image reconstruction in real-time to explore Nuclear Imaging World!

EasyPET is a simple, user-friendly and portable didactic PET system developed for high-level education, to explore the physical and technological principles of the conventional human PET scanners, using the same basic detectors of state-of-the-art systems.

- Positron Annihilation Detection
- Two-dimensional Reconstruction of Source
- Spatial Resolution

MORE INFO



CONTROL SOFTWARE



Easy PET
Control
Software

SP5701
EASYPET KIT



Explore PET Imaging and Gamma Spectroscopy through real-time detection and reconstruction!

The EasyPET Kit (SP5701) is a portable educational system designed to introduce students to the fundamental principles of Positron Emission Tomography (PET) imaging and nuclear detection techniques. The kit includes the EasyPET system (SP5700) and a dedicated multichannel analyzer, allowing students to perform both PET imaging experiments and gamma-ray spectroscopy measurements. The EasyPET Kit provides a complete educational platform for studying nuclear physics applications, combining imaging techniques, radiation detection, and data analysis within a flexible experimental environment.

- Nuclear Imaging
- Gamma spectroscopy
- Statistics

MORE INFO



CONTROL SOFTWARE



Easy PET
Control
Software

SP5600AN PREMIUM
EDUCATIONAL KIT



Advanced and compact solutions for Nuclear & Particle Physics experiments!

The CAEN Premium Educational kit is a modern, digital, and flexible platform developed by CAEN for teaching the fundamentals of Statistics & Nuclear, and Modern Physics.

The set-ups is based on Silicon Photomultipliers (SiPM) state-of-the-art sensors of light with single-photon sensitivity and unprecedented photon counting capability.

- Statistics
- γ and β Spectroscopy
- Cosmic rays
- Photon detection and light distribution

MORE INFO



CONTROL SOFTWARE



HERA
Handy Educational
Radiation
Application

SP5600EMU
EMULATION KIT



Create and Analyze a radioactive source!

This kit allows the user to perform a series of lab experiments without using a radioactive source and a detector, by simulating the signals produced by the interaction of particles with the detecting unit.

- Real Energy spectrum emulation (γ and β)
- Noise emulation
- Time distribution Emulation (Poissonian)
- Pulse processing: Height Analysis and Charge Integration

MORE INFO



CONTROL SOFTWARE

Emulation Control Software

SP5600C
EDUCATIONAL GAMMA KIT



A complete system for Gamma Spectroscopy study!

The Educational Gamma Kit (SP5600C) is a modular educational system designed to perform a wide range of gamma-ray spectroscopy experiments based on Silicon Photomultiplier (SiPM) technology. The kit includes the essential instrumentation required for gamma spectroscopy and represents a subset of the Premium Kit, focusing specifically on experiments related to gamma radiation detection and spectroscopy. Thanks to its modular architecture, it provides an effective introduction to gamma-ray measurements while maintaining compatibility with the broader CAEN educational platform.

- Statistics
- γ Spectroscopy

MORE INFO



CONTROL SOFTWARE



HERA
Handy Educational
Radiation
Application

SP5600E
EDUCATIONAL PHOTON KIT



From the Quantum Nature of Light to the SiPM Characterization!

The Educational Photon Kit (SP5600E) is a modular educational system designed to introduce students to the fundamental principles of photon detection and the operation of Silicon Photomultipliers (SiPMs). The kit includes the essential instrumentation required to investigate the properties of light and SiPM technology, and represents a subset of the Premium Kit dedicated to photon-related experiments. Its modular design provides an effective introduction to photon detection while maintaining full compatibility with the broader CAEN educational platform.

- Quantum World: Photons
- SiPM Characterization
- Photon Detection
- Light Statistics

MORE INFO



CONTROL SOFTWARE



HERA
Handy Educational
Radiation
Application

SP5650
OPEN FPGA KIT



**Programming with SCI-Compiler
like setup an experiment!**

The Open FPGA kit allows to perform a series of lab experiments without using a radioactive source and a detector, by simulating the signals produced by the interaction of particles with the detecting unit. Moreover, it is possible to configure the FPGA of the board in order to perform the most suitable signal processing for each specific application.

- Pulse Processing
- FPGA Programming
- Radiation simulation
- Statistics

MORE INFO



CONTROL SOFTWARE



SCI-Compiler
Open FPGA
development tool

SP5630EN
ENVIRONMENTAL KIT



**Discover the environment that
surrounds us!**

To increase the familiarity with Environmental Radioactivity Field, CAEN designed a dedicated educational kit, based on a Silicon Photomultipliers (SiPM) matrix coupled to a CsI Scintillator.

- Gamma Spectroscopy without radioactive source
- Radon measurement

MORE INFO



CONTROL SOFTWARE

i-Spector Digital Web
Interface

SP5630ENP
ENVIRONMENTAL KIT PLUS



**Experience the phenomena...
Explore the Physics...
Discover the essence!**

The Environmental Kit Plus (SP5630ENP) extends the Environmental Kit with advanced experiments on environmental gamma radioactivity, radiation interaction with matter, and detector characterization.

Students can study gamma-ray absorption through different materials and thicknesses, combining counting techniques with spectral analysis. The kit also supports the characterization of scintillating materials, improving understanding of gamma detection and detector response.

It provides an effective platform for advanced laboratory activities in radiation detection and gamma spectroscopy.

- Gamma Spectroscopy without radioactive source
- Passive Radon measurement
- Absorption measurements
- Comparison of different scintillating materials

MORE INFO



CONTROL SOFTWARE

i-Spector Digital Web
Interface

SP5620CH
COSMIC HUNTER



Portable detector for cosmic rays!

The Cosmic Hunter is a compact and portable educational detector designed to introduce students to the study of cosmic rays through hands-on experiments.

Based on Silicon Photomultiplier (SiPM) technology, it consists of a coincidence detection unit coupled with up to three plastic scintillating tiles. Thanks to its flexible geometry, it allows students to investigate cosmic-ray phenomena such as muon detection, flux measurements, and particle shower events in different experimental configurations.

The system can be operated directly without the need for dedicated software, making it simple and accessible for educational activities. A dedicated software application is also available for advanced data visualization, analysis, and experimental studies.

- Cosmic rays
- Statistics
- **No Needs SW interface**

MORE INFO



CONTROL SOFTWARE



Cosmic Hunter Control Software

SP5600D
EDUCATIONAL BETA KIT



From beta spectroscopy to cosmic rays detection!

The Educational Beta Kit is a modular educational system designed to perform experiments on beta radiation and cosmic rays using Silicon Photomultiplier (SiPM) technology.

The kit includes the essential instrumentation required to investigate beta-particle detection, beta spectroscopy, and the measurement of cosmic radiation. It represents a subset of the Premium Kit, focusing on experiments related to charged-particle detection while maintaining full compatibility with the broader CAEN educational platform.

- Cosmic Rays
- Beta spectroscopy
- Radiation-Matter Interaction
- Absorption coefficient measurements

MORE INFO



CONTROL SOFTWARE



HERA
Handy Educational
Radiation
Application

SP5640
GAMMAEDU



Just one tablet click to perform radioactive measurements outdoor!

The GammaEDU Backpack (SP5640) is a portable gamma radiation detection system designed to explore environmental radioactivity through measurements performed directly in the field.

Thanks to the high efficiency of its scintillation crystal, the system allows users to quickly detect and analyze gamma radiation from environmental sources. Its portable design makes it a valuable tool for performing measurements in different locations and for creating maps of environmental radioactivity, helping students investigate the spatial distribution of natural radiation background.

- Gamma spectroscopy
- Environmental radioactivity outdoor

MORE INFO



CONTROL SOFTWARE



GammaEDU APP
GammaEDU
Maps SW

SP5660
ROCKYRAD



Portable Geiger-Müller counter for nuclear radiation

Discover the fascinating world of rock radioactivity and then expand your horizon to detect the unseen radiation in our everyday surroundings.

- Statistics
- Gamma and Beta detection
- Dose Estimation

MORE INFO



CONTROL SOFTWARE



RockyRAD App

SPROCKS
RockyBOX



Expand your RockyRAD experiments with a wider range of rocks and minerals!

The SPROCKS RockyBox includes a curated collection of rocks and an UV lamp. The rock samples enrich the experimental possibilities offered by RockyRAD, allowing users to compare geological materials with different compositions and origins, and to observe how these differences may correlate with variations in detected radiation levels.

MORE INFO



SP5622B
DETECTION SYSTEM PLUS



Portable scintillating tile for cosmic rays detection!

The Detection System Plus, SP5622B, is a user-friendly system for cosmic-ray detection. It can be used as a didactic instrument or as an external trigger system for another experimental setup. The simple design makes it suitable for not only university-level physics labs, but also for high school level physics programs.

- Cosmic rays
- Veto System
- no need SW interface

MORE INFO



DT993

DESKTOP DUAL TIMER



One of the most useful modules ever made, today in a new and handy form.

The CAEN Model DT993 Dual Timer is a desktop module with two identical triggered pulse generators. It produces NIM/TTL or ECL pulses (selectable via an on-board switch) with widths ranging from 50 ns to 10 s. Output pulses are provided in both normal and negated forms. The timers can be re-triggered by the pulse end marker signal. Coarse width adjustment is done via a 9-position rotary switch, while fine adjustment is done either by a 15-turn dial handle (with lock) or an external voltage.

The trigger start can be initiated by an external signal (NIM, TTL, or ECL) or manually via a front panel switch. The module also has VETO and RESET inputs, with RESET available on a front panel switch. The DT993 features LEMO 00 connectors for NIM/TTL signals and male pin couples for ECL signals.

no need SW interface

MORE INFO



SP5609

TELESCOPE MECHANICS



The SP5609 Telescope Mechanics is an additional tool for an easy setup of components that need to be on the same axis from different angles. The SP5609 allows the construction of a Muon Telescope using either two SP5608 - Scintillating Tiles or two SP5622 - Detection Systems.

MORE INFO



SP5622

DETECTION SYSTEM



The Detection System consists of a plastic scintillator, a photodetector, and a small front-end electronic boards. The charged particles that pass through the unit deposit part of their energy inside the scintillators, producing a light signal. The light produced in the scintillator is then collected and converted into an electrical signal via a photosensor unit.

MORE INFO



SP5601 LED DRIVER



The SP5601 is an ultra-fast LED Driver with pulse width at ns level, tunable intensity and frequency, that provides a low-cost tool for the detector characterization. The LED pulse generation can be triggered by an internal oscillator or by an external pulser.

no need SW interface

MORE INFO



SP5650C SENSOR HOLDER WITH SIPM



The SP5650C is a sensor holder provided in the Educational Photon kit. The holder hosts a $1.3 \times 1.3 \text{ mm}^2$ Silicon Photo-Multipliers; moreover, a probe inside the holders senses temperature variations, thus allowing the user to compensate for possible gain instability. The SP5650C is made of a mechanical structure providing a FC fiber connector and a PCB where the SiPM is soldered. Bias voltage for the SiPM and temperature probe output are provided through a 10 pin female socket, while the analog output connector is MCX.

MORE INFO



SP5606 MINI-SPECTROMETER

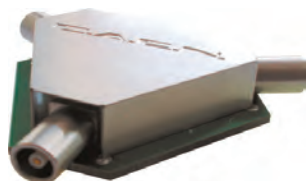


SP5606 is mini-spectrometer for gamma ray detection. The spectrometer is composed of a mechanical structure that houses a scintillating crystal, coupled to a dedicated SiPM. Three different crystals are available: CsI, LYSO and BGO. The spectrometer is equipped with a bottom support to allows an easy connection to the SP5600 via the splitter A315, to avoid saturation effects.

MORE INFO



A315
SPLITTER



The Mod. A315 splits one input on two output signals. All the connectors are LEMO female type. The splitter is adapted for 50 Ohm lines. The device is completely passive (no power supply is required); the amplitude on each output is one half of that on the input.

MORE INFO



SP5607
ABSORPTION TOOL



The Gamma absorption tool allows to perform gamma attenuation measurements. It is a modular tool and its design allows an easy connection to the SP5606 bottom support.

MORE INFO



SP5608
SCINTILLATING TILE



The SP5608 is a support with a embedded plastic scintillating tile, directly coupled to a SiPM . The tile, with a sensitive volume of $47 \times 47 \times 10 \text{ mm}^3$, is the ideal tool for tests with beta emitting isotopes and cosmic rays. The support structure allows to use the SP5608 stand-alone or to use two tile modules to build a cosmic telescope. A special source holder allows to perform beta attenuation measurements in a thin thickness material due to 2mm distance from the scintillating tile. It is provided by a paper and aluminum sheets

MORE INFO



Software

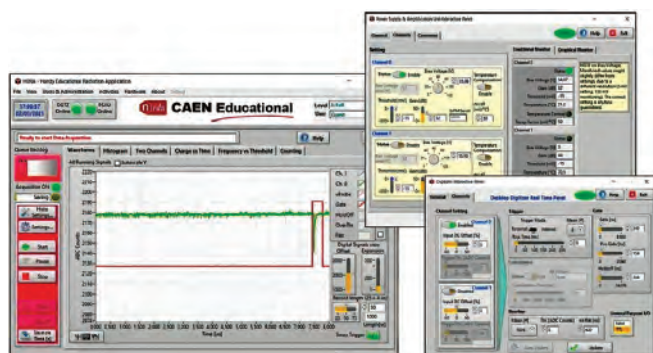


The instruments and kits presented in the previous section are supported by a range of software tools designed to configure experimental setups, control data acquisition, and support data visualization and analysis.

Depending on the system, these include desktop applications, web interfaces, and mobile tools, developed either specifically for educational use

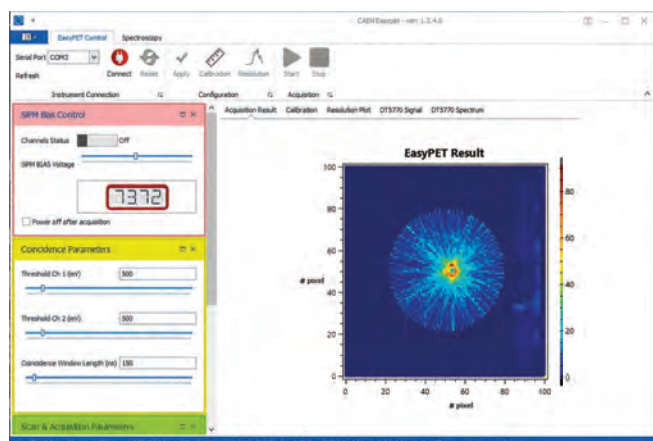
or derived from technologies used in scientific instrumentation.

Together, hardware and software form integrated and flexible experimental platforms, enabling students to carry out a wide range of laboratory activities while becoming familiar with the tools and workflows of modern experimental physics.

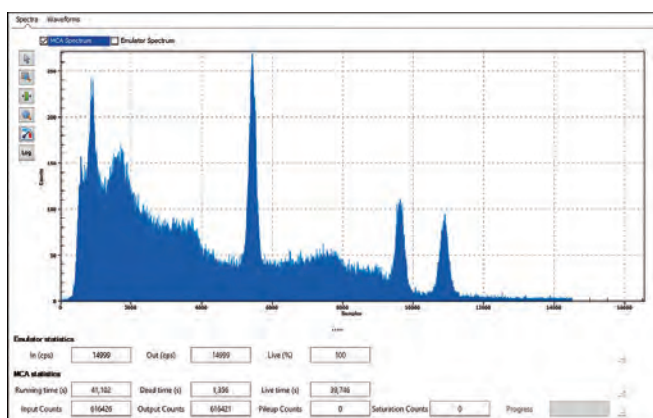


HERA (Handy Educational Radiation Application) is the software platform developed to support the CAEN Premium, Educational Gamma, Educational Beta, and Educational Photon Kits. It provides a simple and intuitive environment for configuring the experimental setups, acquiring data, and performing the laboratory activities described throughout this handbook.

Designed for both beginners and experienced users, HERA combines a user-friendly graphical interface with integrated documentation and guided experimental workflows.



EasyPET is controlled through a Graphic User Interface (GUI), developed in Visual Basic, which allows setting the acquisition parameters, performing the acquisition, visualizing the reconstructed image in real time during acquisition and recording the data for the offline analysis, performing calibration and spatial resolution measurements.

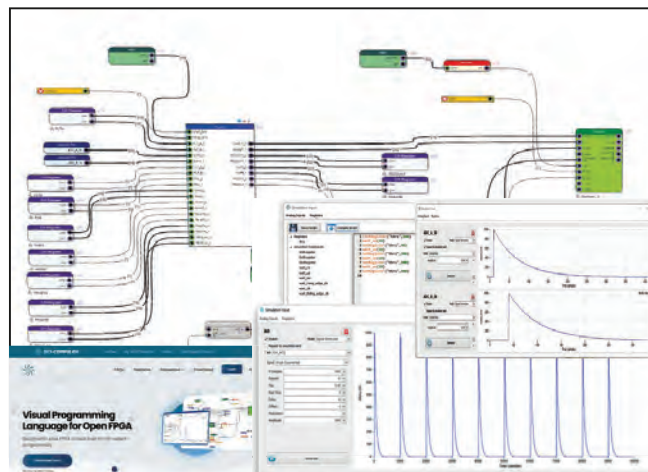


Software interface is particularly indicated for quickly setting the instruments. The GUI Interface enables the Emulator to generate an analog output: the user can set the analog output signal rate, the amplitude, the rise and fall time of the exponential shape, and the noise contributions. The GUI also allows to acquire the generated signal with an MCA. The user can set the features for the analog input signal, trigger with a single threshold or with a trapezoidal mode, use the charge integration or the trapezoidal as energy filter, control the baseline calculation and the pile-up rejection.

SCI COMPILER



SCI-Compiler is Windows based software designed to accelerate the firmware implementation for signal processing in scientific instrumentation. SCI-Compiler is an automatic code generator that, starting from a graphical block diagram, generates a VHDL piece of code that implements the required function. Moreover, SCI-Compiler is able to generate C libraries and drivers to be used in Windows, Linux and macOS for software implementation. SCI-Compiler uses a prebuilt library set containing macroblocks with complex function. Each macroblock could be imagined as a modular instrument (MCA, Oscilloscope, Digitizer, TDC) that the user could connect with each other.

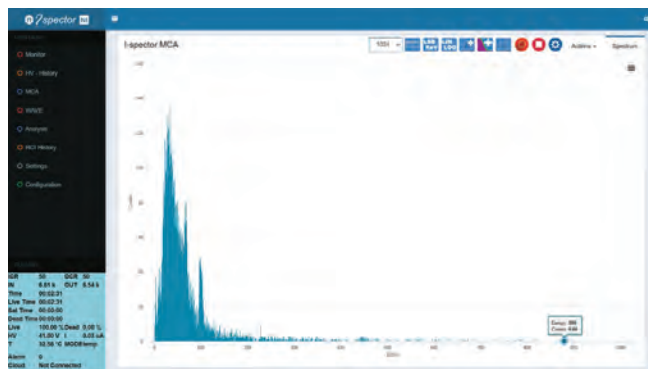


OS Compatibility

i-Spector Digital Web Interface

The i-Spector Digital Web Interface provides a simple and intuitive browser-based environment to control and monitor the detector without requiring any software installation.

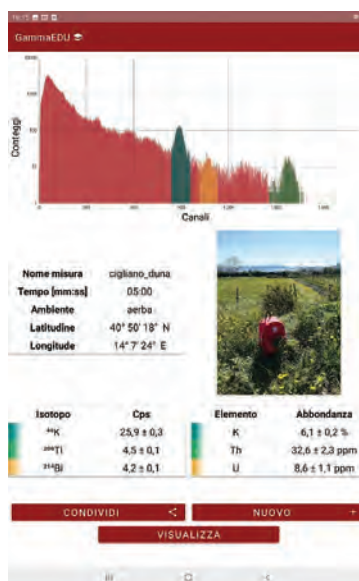
Through the interface, users can configure the module parameters, monitor the system status, visualize energy spectra in real time, perform basic online analysis, and download acquired data.



Android App GammaEDU

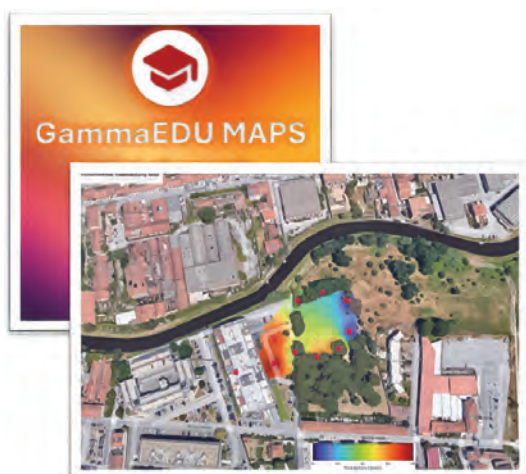


With the GammaEDU Android application users can acquire and analyze in real time a g-ray spectrum to get the K, U and Th abundances, keep note of the surrounding environment, take the GPS coordinates and shoot a picture of the on-going measurement. The data are saved in a kmz file ready to be visualized on Google Earth and shared on Google Drive for producing a radioactivity map of the area.



OS Compatibility

OS Compatibility



GammaEDU Maps

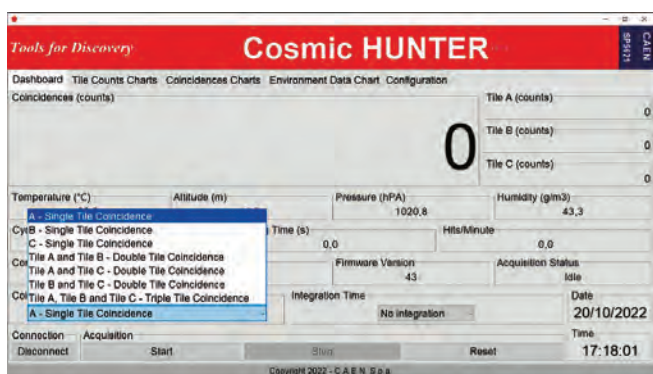


GammaEDU Maps, developed in Java, is an advanced software tool tailored for GammaEDU backpack users, researchers, educators and students who need to analyze and visualize collected environmental radioactivity data. Designed to seamlessly integrate with the GammaEDU app, GammaEDU Maps can process all file formats generated by GammaEDU, offering users flexibility in handling diverse data types for robust data extraction, interpolation, and mapping.

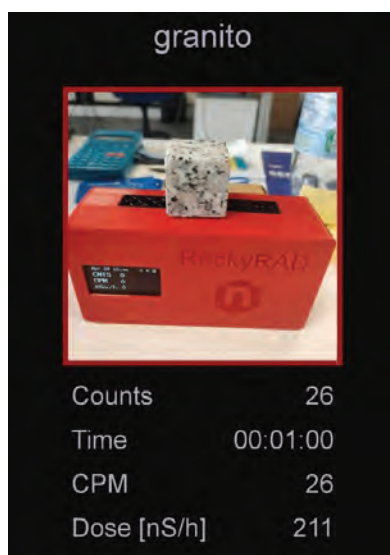
Cosmic Hunter Control Software



Cosmic Hunter can be managed through a Graphic User Interface (GUI), developed in Java, which allows setting the acquisition parameters, performing the acquisition, visualizing the data in real time during acquisition and recording the data for the offline analysis



OS Compatibility



RockyRAD APP



The RockyRAD App provides a simple interface to control the detector, record measurements, analyze data, and share results directly from an Android device.

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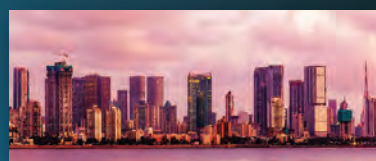
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