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OPERATING AND IMPLEMENTING A MUON DETECTOR USING ARDUINO NANO

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Abstract
The muon detector is designed to be a hand-held, low-cost educational tool that enables students to construct their own detectors, study ionizing radiation from cosmic rays, and analyze real measurements. Before construction, the interaction of muons with matter, the role of the BC-408 plastic scintillator, the conversion of photons to an electric pulse in a silicon photomultiplier (SiPM), and on-board signal processing using custom PCBs and an Arduino Nano are reviewed. Performance is evaluated through altitude-dependent muon flux, angular-distribution measurements using coincidence techniques, dead-time studies with β (Sr-90) and γ (Co-60) sources, β-attenuation in aluminium, and radiation-mapping in a protection laboratory. Results confirm the detector's effectiveness and versatility for classroom and outreach use.
Keywords — Muon detector; Arduino Nano; cosmic rays; scintillator; silicon photomultiplier; radiation monitoring

1 INTRODUCTION

The earth planet is continuously receiving a flux of different high-speed particles called primary cosmic rays, coming from the universe due to the solar wind [1]. The primary cosmic rays consist mostly of 70% of protons and 5% of He nuclei with a little contribution of heavy nuclides such as Fe [2]. The charged pions (π ±), kaons (K ±) and other particles are produced due the collision of primary cosmic rays with the nitrogen (N_2), oxygen (O_2) molecules and other air molecules in the upper of earth's atmosphere. These charged pions will decay via weak force within ten billionths of seconds into charged high speed muon (μ±) particles which are representing the secondary cosmic ray [3].
Muon is an elementary particle and classified as a lepton that does not compose of quarks or other particles. Muon has a negative charge (-μ) (if decaying from -π) and positive charge(+μ) (if decaying from +π) with spin ½ [4]. The charged muon (-μ) is unstable particle and similar to electron but much larger mass about 206 times mass of electron and half-life of 2.2×10^{-6}s and traveling with speed close to speed of light 0.98c [2]. The uniqueness of its large mass, decaying half-life and speed traveling allow for muon to penetrate approximately 15 km through the earth's atmosphere and reaches the surface of earth, that because of the special relativity of Einstein is applied [3].
The muon detector is designed to be portable, small size and educational tool for students. The principle of detecting muon particles is: when charged muon particles pass through the organic plastic scintillator, their energy is absorbed and re-emitted in form of electromagnetic waves (photons). A silicon photomultiplier (SiPM) coupled to a plastic scintillator detects these photons. A single photon can generate an electric measurable signal in the SiPM. This signal is amplified and sent to Arduino Nano for detection. Finally, measurements and data of counts rate of muon particles are presented on OLED screen.
Muon plays a vital role in different fields. However, existing detectors like CMS (Compact Muon Solenoid) detector in CERN are massive and require specialists [3]. Implementing a small, inexpensive detector provides students with hands-on experience to build their own detectors, explore ionizing radiation from cosmic rays, and analyze measurements. [3]
In this paper, we aim to implement and operate a muon detector to measure muon particles (100keV-5MeV) as an educational tool. The detector is small, portable and low cost (~$100). Key objectives: Understand and implement electronic circuits; Use BC-408 plastic scintillator; Investigate SiPM principles; Program Arduino

Nano; Extend detection to beta/gamma radiation; Implement power bank circuit; Add microSD data logging; Implement coincidence detection with two detectors.

2 Theory

Muons lose energy passing through matter by ionizing atoms/molecules via electromagnetic force. Energy loss is described by Bethe Bloch formula (-dE/dx), measured in MeV cm²/g. Muons are non-destructive due to large mass, short half-life, and relativistic speed. After slowing down, muons enter atomic orbits until decay or nuclear capture.

BC-408 plastic scintillator ($5\times5\times1$ cm³) absorbs particle energy and re-emits photons. Composed of primary fluorescing agent (emits UV) and secondary agent (shifts to visible light) [5]. Works with 100keV-5MeV particles, light output efficiency 64%, refractive index 1.58, density 1.023 g/cm³ [6]. Silicon Photomultipliers (SiPM) Contains microcells with reverse-biased P-N junctions. Photons create electron-hole pairs in depletion region, producing current proportional to photon intensity/energy. Operates at +29.5V to minimize dark current [7]. Handles signal processing and data acquisition. Contains four circuits: Arduino interface, DC-DC booster (5V→29.5V), non-inverting amplifier (20× gain), and peak detector (holds voltage for measurement) [8].

Filters DC bias voltage with capacitors/resistors. Features pull-down resistor to maintain ground. Connects to main PCB via 6-pin connector (HV, GD, SNG). Converts analog signals to digital, performs measurements. Microcontroller controls processes, analog pins (A0-A7) for measurement, digital pins (D2-D13) for peripherals. Updates every 5.8μs via USB.

Key parameters: Dead time (τ) - time between detectable events, calculated via paired sources method. Threshold voltage (50mV) - minimum detection level to avoid noise [8].

Beta particles: Ionize/excite atoms, lose energy through interactions. Gamma rays: Three interactions - photoelectric effect (electron ejection), Compton scattering (energy transfer), pair production (electron-positron creation). Beta particles attenuate exponentially through materials. Quantified by: Linear attenuation coefficient (μ), Half-value thickness ($x_{1/2}$), Mass attenuation coefficient ($\mu m = \mu/\rho$) [8].

Gas-filled detector ionized by radiation. Electric field accelerates ions/electrons, creating measurable current pulse [8]. Uses two detectors to identify true muon events. Records simultaneous detections within time window (typically μs). Master detector controls slave, reducing background noise [9].

3 METHODOLOGY

3.1 Detector implementation

Polished and drilled with four holes for SiPM mounting. Wrapped in aluminum foil for photon reflection and black tape for light isolation. Components soldered on both sides of main/SiPM PCBs. Resistors/capacitors (0.08×0.05 inches) placed on bottom; larger components on top. SiPM soldered on top surface of its PCB.

Optical gel applied between SiPM and scintillator to match refractive indices. Components mounted with screws and taped together. Connected 6-pin connector between SiPM and main PCBs. Verified +29.5V bias voltage. Assembled in plastic enclosure with OLED and USB.

Confirmed +29.6V at HV-GD pins using multimeter. Two codes implemented: OLED display and microSD logging. Six-pin circuit connected to detector. Records: event number, time (ms), ADC value, SiPM voltage (mV), dead time (ms), temperature (°C).

3.2 The muon angular distribution measurement.

In this experiment, the count rate of muon particles was measured at different angles by using the coincidence detection of two detectors. The two detectors are placed on the woody object as shown in figure (1). At the left side of that woody object, there is a protractor. Five minutes is used for each measurement. The two detectors are connected by 3.5 mm female audio jack located at the back of muon detectors. And the reset bottom is pressed in upper detector then lower detector within 10 ms to 2000 ms. As a result, the coincident mode will be running, and the upper detector will operate as master detector and the lower as slave detector. The measurement was only taken from the slave detector. The power cable will only connect to master detector, which it will provide power to slave detector.

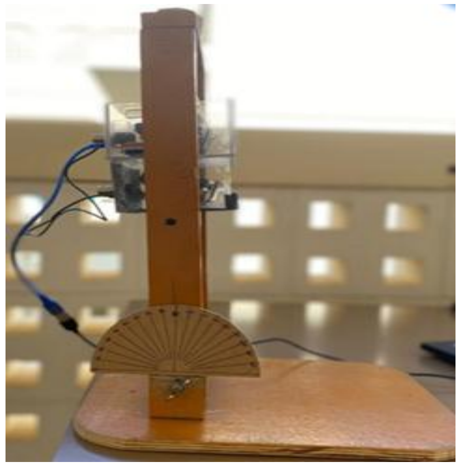

Figure1: The left side of two muon detectors connected in coincident mode for detectors.

3.3 Measuring the dead time for beta and gamma sources by muon detector.
The dead time for beta and gamma radiation is measured by using the method of paired sources. The paired sources method basically is measuring the counts rate of the two sources individually, then taking the count rate measurement of two sources together as shown in figure (23) [9]. Each source placed at the half centred as shown in figure(2). The sources were used are Sr-90 which is beta source and Co-60 which is gamma source. Finally, using the equation 2 to calculate the dead time.

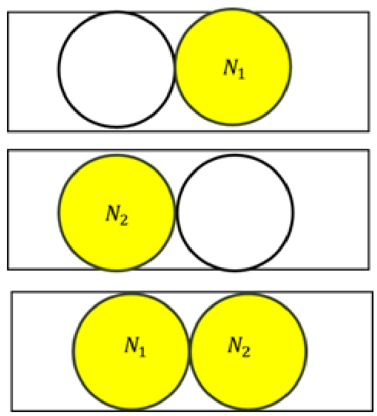

Figure 2: The method of paired sources to measure dead time for muon detector.

3.4 The absorption of beta particles experiment
In this experiment, the beta source (Sr-90) is used to calculate the attenuation coefficient of Al absorber and to detect the count rate of bēta particles when pass different mass thickness (mg/cm^2) of aluminum (Al) absorber by muon detector. Firstly, the count rate of Sr-90 was measured without absorber, and the count rate of BG radiation was measured. Then, taking the count rates for each mass thickness of Al. Moreover, ten mins is used to measure each count rate. After plotting the graph of counts rate of Sr-90 versus mass thickness (mg/cm^2) of Al, finding the half value thickness (x1) by taking the half count rate without absorber. Then, drawing a 2 straight line in y-axis that cross the carve and dropping a straight line to mass thickness on the x-axis where that is half value thickness located. Finally, using the equations 3 and 4 to calculate the linear attenuation coefficient.
3.5 Monitoring the radiation in the Radiation Protection Lab by using muon detector.
The process of monitoring radiation is used to detect the existence of any radiation in specific areas from radioactive sources. Firstly, the dimension of Radiation Protection Lab is 10.67 m ×5 m. So it divided into three axis, Where the x-axis is the length of lab, the y-axis is the width of lab and the z-axis is the height of the detector to take the measurement of count rate of radiation.

In addition, for each measurement of count rate of radiation was measured for each 1m within 1 min as shown in figure (3). Taking ten points on x-axis and each point is divided into five points in y-axis.

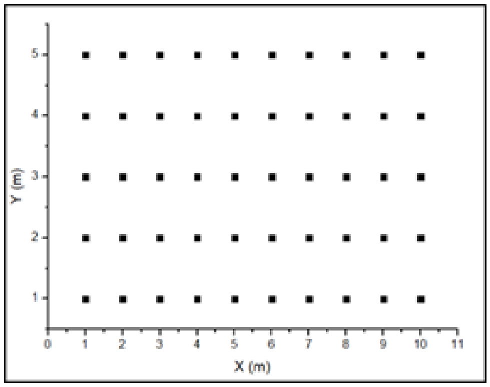

Figure 3: The dimension of the radiation protection lab.

4 RESULTS AND DISCUSSION

4.1 The muon angular distribution measurement.

The counts of muon particles are measured with variation of known angles. The figure (4) shows the behavior of increasing the zenith angle of two detectors in coincidence system. Which the zero-angle degree represents the vertical. As, the zenith angle of two detectors increased, the smaller number of muon particles are detected. That is reasonable, as the muon particles travel downward vertically to earth's surface. However, there is increasing at angles 400 and 600 . That's because, when two independent events are passing through the master detector and slave detector at same time, so the system will count it as coincidence event [3]. Finally, the low amount of muon particles at different angular distribution confirming that the muon particles travelling vertically.

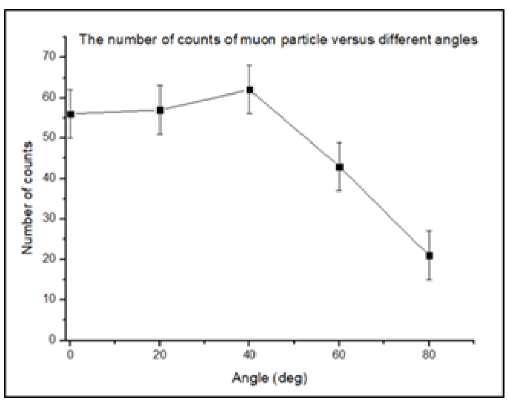

Figure 4: The measured counts number of muon particles at different angular distribution.

4.2 Measuring the dead time for beta and gamma sources by muon detector.

The dead time of muon detector was calculated for beta source and gamma source. The calculated dead time for gamma source is 265 ± 2 µs. The calculated dead time for beta source is 238.6 ± 0.5 µs
The dead time for beta source is 238.6 ± 0.5 µs which less than dead time for gamma source is 265 ± 2 µs. The difference is due to the natural of interaction of beta particle and gamma radiation with detection materials as mentioned previous. where, the beta source has short interaction range, and the gamma radiation has long interaction range. So, the short interaction range lead to small dead time. Finally, we can conclude that the muon detector is more efficient for beta radiation more than gamma radiation.

4.3 The absorption of beta particles experiment.

In this experiment, the BG radiation is 298 /s for 10 min and the counts of beta source (Sr-90) when no absorber used is 13729 ± 1268 /s. All the measurements is corrected from BG as shown in Figure (5).

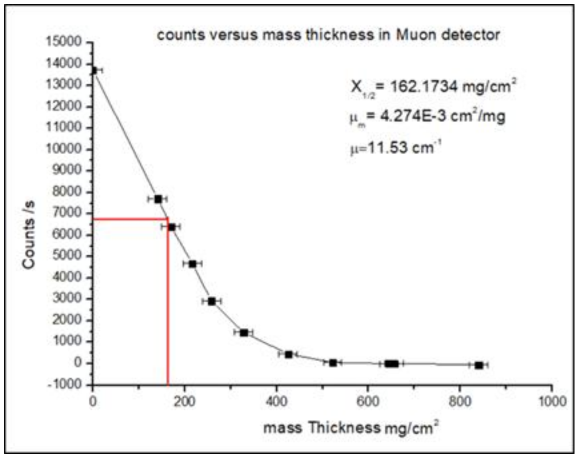

Figure (5): The counts rate versus different mass thickness of Al absorber for Sr-90 source in muon detector.

The half thickness of Al absorber is determined from the graph as shown infigure(5) where it occur at the half of the original counts of Sr-90 and equal to 126 ± 20 mg/cm^2. The mass attenuation coefficient is calculated and found equal to (4 ± 7) × 10^{-3}cm^2/mg . Then the linear attenuation coefficient is 12 ± 4 cm^{-1}. In addition, As the mass thickness of absorber increased, the more counts number of beta particles are absorbed as predicted in theory section. That is because the beta particles interact with the absorber's atom and will lose energy.

At the same condition, the experiment of absorption of the beta particles was done by GM tube. To compare the values measured in both detectors and to investigate the difference between these two detectors.

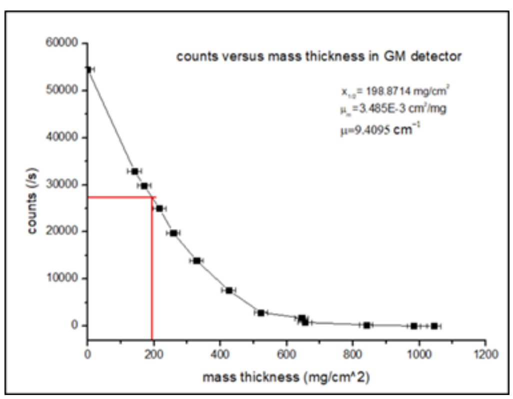

Figure (6): The counts rate versus different mass thickness of Al absorber for Sr-90 source in GM detector.

The half thickness of Al absorber is determined from the graph as shown in figure (6) where it occurs at the half of the original counts of Sr-90 and equal to 199 ± 20 mg/cm2. The mass attenuation coefficient is calculated and found equal to (3.5 ± 0.2) × 10^{-3} cm^2/mg . Then the linear attenuation coefficient is 9 ± 1 cm^{-1}. The linear attenuation coefficient of Al absorber was found 12 ± 4 cm^{-1} by muon detector and 9 ± 1 cm^{-1} by GM detector. In fact, it expected to find different values for linear attenuation coefficient of Al absorber from different detectors. So, the value on muon detector is larger than in GM detector and that's due to some reasons. Firstly, The linear attenuation coefficient is dependent on the atomic number (Z) of detection materials, where in muon detector the solid plastic scintillator and in GM tube is gas (Ar). Also, the principle of working muon detector is differ from GM detector as discussed in theory section. Finally, these two detectors are made from different arguments and thicknesses.

4.6 Monitoring the radiation in surface area of radiation protection lab by using muon detector.

The monitoringof the background (BG) radiation was 16 /s inside the radiation protection lab. So, all counts were corrected for all measurements from BG radiation. The figure (7) below shows the radiation distribution in the laboratory and the amount of radiation is classified by different colors. Where the deep blue color presents the less amount of radiation and red color presents the highest counts of radiation. At (1m, 4m) point there is high counts of radiation (orange color), And that there was a student who did experiment using a radioactive source (Cs-137). Also, in the middle area of lab in 6m and 7m in x dimension along y dimension, there is increasing in counts of radiation. In fact, there are no radioactive sources there, but it could be the contamination of the radioactive sources in this place and objects like tables. Also, at the 10 m in x dimension, there is high counts of radiation and that because of the lead box which used to keep the radioactive sources inside it. The more interesting area oh high counts at the 3m and 4m in x dimension with the 5m in y dimension. Where there are only computers. The computers produce electromagnetic radiation especially radio waves due to its electronics circuits and components in different frequencies, these will contribute to increase the counting radiation on the lab [11].

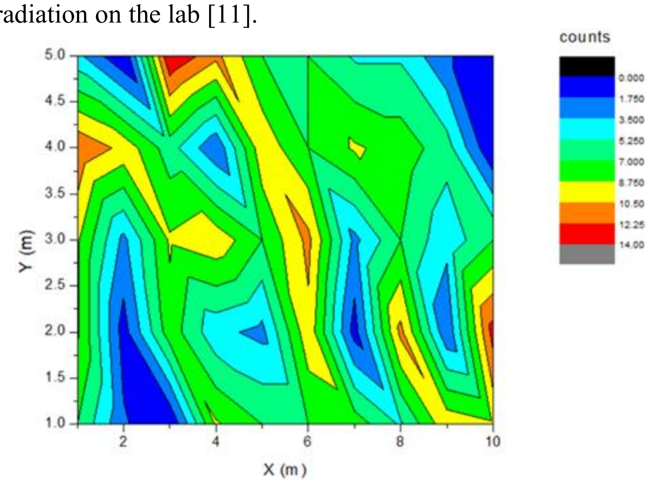

Figure 7: The radiation distribution in the radiation protection lab detected by muon detector.

5. CONCLUSION

The project successfully developed a portable, low-cost muon detector using an Arduino Nano and SiPM coupled with a plastic scintillator. The detector effectively measured cosmic muon flux variations with altitude and angle, and extended detection to beta and gamma radiation. Dead time and attenuation experiments validated detector performance and efficiency. Radiation monitoring in a laboratory environment demonstrated practical applications. This detector serves as a valuable educational tool, bridging theoretical physics and hands-on experimentation.

6. REFERENCES

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