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Investigation of the Pulse Shape and Amplitude of 4He Gas Scintillations Produced by a 5.5 MeV Alpha Particle Source

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Abstract
Scintillation light is normally produced when ionizing particles such as alpha particles deposit their energy as they travel through a scintillating material, which can be solid, liquid or gaseous (e.g. 4He). In this project we compared scintillations produced in 4He gas by alpha particles (from the decay of ^{241}Am) to those produced in plastic scintillator by cosmic-ray muons. The properties of photomultiplier and Si photomultipliers as sensors of scintillation light were also compared. A Geant 4 simulation was done to measure the amount of energy deposited in the gas cell and a plastic scintillator. The mean energy deposited in the gas cell was found to be 4.3 MeV and that in the plastic scintillator produced by cosmic muons was found to be 4.76 MeV. The mean amplitude was 5 mV and 8 mV at a bias voltage of 73.5 V for both the gas cell and plastic scintillator, respectively.

Keywords: *Scintillation, photomultiplier tube, noble gas, cosmic muons, 4He*

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INTRODUCTION

Scintillation is a flash of light produced in a transparent material by the passage of charged particles such as an electron, an alpha particle, or an ion. High-energy photons may be detected by producing electrons either by photoelectric effect, Compton scattering or pair production, subsequently producing ionization and scintillation. Any material that emits flash of light when hit by energetic charged particle is known as *scintillator*. Scintillation detectors are therefore referred to any instrument capable of detecting the scintillation produced when energetic charged particle strike a scintillator. Scintillations were detected in early experiment with eyes using microscope [1].

Scintillation detection became popular around 1940s; during this period, the microscope was replaced by a photomultiplier tube (PMT). The first application of the PMT for scintillating counting was done by Curran and Baker (1944) [2]. They used zinc sulphide screen viewed by an RCA 1P21 PMT, connected through an appropriate circuit to an oscilloscope, to detect alpha particle of 2 MeV energy. They stated clearly the advantages of PMT over microscope with regard to sensitivity and resolving time. Since after this period, scintillation detectors became popular, accepted and a reliable instrument used in the detection of elementary particles in both nuclear and particle physics.

The suitability of a scintillation detector type is highly dependent on the user requirement. Scintillation detectors are designed with different scintillation materials, scintillation properties (like scintillation yield, rise time etc.), physical state (solid, liquids or gases) and chemical composition (organic or inorganic). No single scintillation detector has all the desired characteristics; however, selecting a detector type must therefore be based on the properties we are after. This project aimed at investigating the pulse shape and amplitude of 4He gas scintillations produced by a 5.5 MeV alpha particle source. The scintillations were observed in a gas cell with PMT and Avalanche photodiode (APD) coupled to it. The scintillations observed were compared to the ones recorded by the same APD coupled to a plastic scintillator using cosmic muons as the source. A Geant-4 simulation was also developed to calculate the energy loss by the different particles in the different detector materials. Later sections present some background information on some of the key components of the experiment, the experimental procedure, and a description of the Geant-4 simulation, followed by result and discussion.

BACKGROUND THEORY

Noble Gas Detectors

Noble gas detectors have for long been in use for particle detection. Development of noble gas detectors entered a new phase at the beginning of 1940s when Davidson and Larsh observed the appearance of electron conductivity in liquid argon that was initiated by the absorption of radiation in that medium [3]. In early 1950s, the research in using gas scintillation for detection of charged particles began when Grun and Schopper developed the first gas scintillation detector [2].

At the beginning of 1980s, it was recognized that the energy resolution of the noble liquid ionization detectors is much worse at low energies than predicted from ionization statistics, and researchers therefore turned their attention to the development of high-pressure gas detectors, which have better intrinsic resolution at low energies [3]. Most of the features that make noble gas scintillation detectors more preferable and acceptable as compared to many other types of scintillation detectors are summarized in Ref. [4] as:

- ✓ The scintillation response to energy deposited by ionizing particles is almost linear over a wide range of $\frac{dE}{dx}$ (energy loss per unit path length), which implies no quenching effects on signals from low energy particles.
- ✓ Fast response time.
- ✓ High flexibility, in terms of shaping and formation of the scintillation volume.
- ✓ The possibility of adjusting the stopping power by varying the gas pressure, which can allow selective detection efficiency for the particle under investigation.
- ✓ Transparency to their own radiation or scintillation light.
- ✓ High scintillation yield.
- ✓ High resistance to radiation damage.

Gas Cell

The gas cell is an aluminium container filled with He gas. It is designed to collect scintillation light caused by an energetic He particle moving through the gas. When ionizing particles traverse a gas volume, they lose their kinetic energy by electromagnetic interactions with the atomic electron, which results in the excitation and ionization of the atoms. After this interaction, a recombination and de-excitation process occur thereby emitting light photons. According to Sayres and Wu [5], the first successful observation of gas scintillation by using a PMT was reported by Eggler and Huddleston. Different gases have different optical spectra in the flash of light emitted during de-excitation and recombination, and due to the fact that PMTs have a photocathode which is only sensitive to a narrow range of wavelength, one must therefore be able to convert most of the photons of short wavelength to an appropriate range (visible region) detectable by the PMT using a wavelength shifter.

Avalanche Photodiode (APD)

An APD is a semiconductor-based photon detector. APDs are operated with a relatively high reverse voltage, ranging from tens to a hundred of volts. The minimum voltage (sometimes referred to as breakdown voltage) of an APD is the minimum reverse voltage which makes it conduct in reverse. APD have the potential to replace PMTs in applications due to their feature of high internal gain, fast timing and high photon detection efficiency in the visible region [6]. The basic structural elements in the design of an APD include the absorption region and the multiplication region.

In the absorption region, there is an electric field, which separates the electrons and the electron holes. The second region, known as the multiplication region, is designed to exhibit high electric field to produce internal gain by impact ionization. The APD used in this project was a 2x2 array of 3x3 mm pixels made by Hamamatsu and it was a reverse bias type. The signals from these four (4) pixels were coupled together to give the output displayed on the digital oscilloscope. Due to this coupling, the array was successfully operated as a single 6x6 mm APD. The APD was attached to a wall inside the gas cell and was operated at bias voltage from 70.5 V to 75.0 V.

Photomultiplier Tube

PMT is a vacuum tube consisting of an input window, a photocathode, focusing electrode, an electron multiplier and an anode usually sealed into an evacuated glass tube. The PMT used in the present work was a 51 mm diameter XP2262 model made by photonis [7]. The photomultiplier was attached to a synthetic-quartz viewing port on the He gas cell using optical grease. The window of this PMT was made up of lime glass, with bi-alkali photocathode material; it was a medium fast with about 12 stages of dynodes that provide a cascade multiplication of the excited electrons [8]. The voltage of PMT was chosen to be 1900 V, though still below the maximum voltage which was around 2050 V. PMT was connected to the channel four (4) of a TDS5054B digital oscilloscope, the signal from the PMT will trigger the digital oscilloscope. The pulse response of the APD was observed as the bias voltage was varied with a uniform increment of 0.5 V, starting from 70.5 V to 75.0 V. But as the bias voltage was increased to about 75.0 V, the signal was dominated by noise as shown in Figure 1.

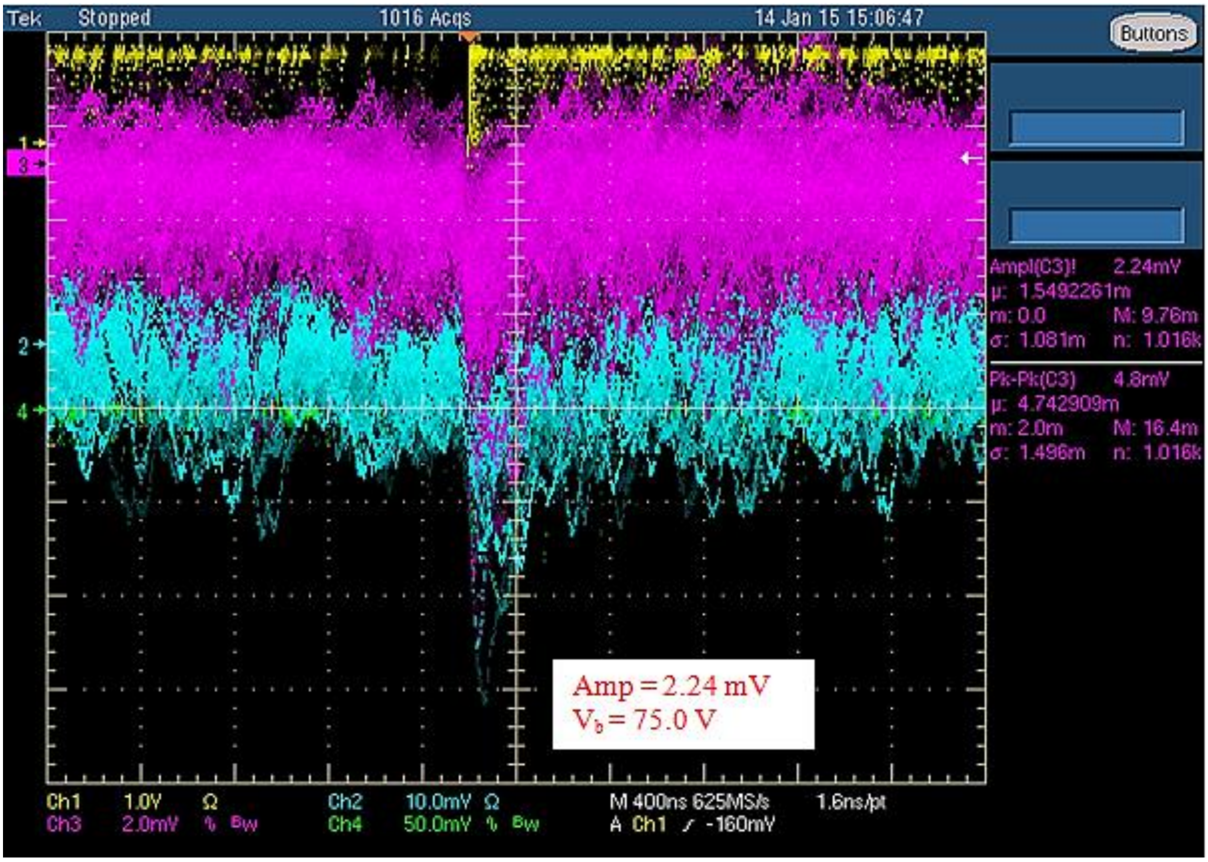


Fig. 1: *PMT Signal (Cyan) and APD Signal (Magenta) at the Breakdown Voltage (75.0 V).*

EXPERIMENTAL PROCEDURE

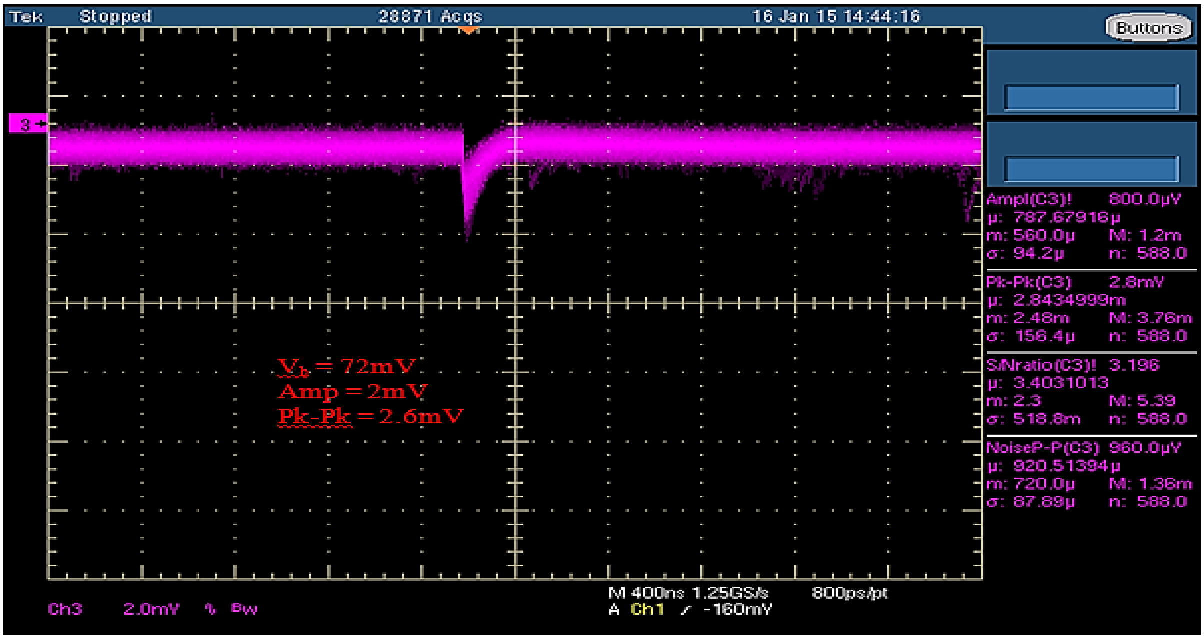
The apparatus used in this project include the gas cell, an APD, a PMT, digital oscilloscope, NINO discriminator, gas cylinders and voltage unit. The APD was coupled inside the gas cell facing the alpha particle source (Am-241). The PMT was connected to one of the four gas cell windows; the signal from this PMT was used to trigger the digital oscilloscope.

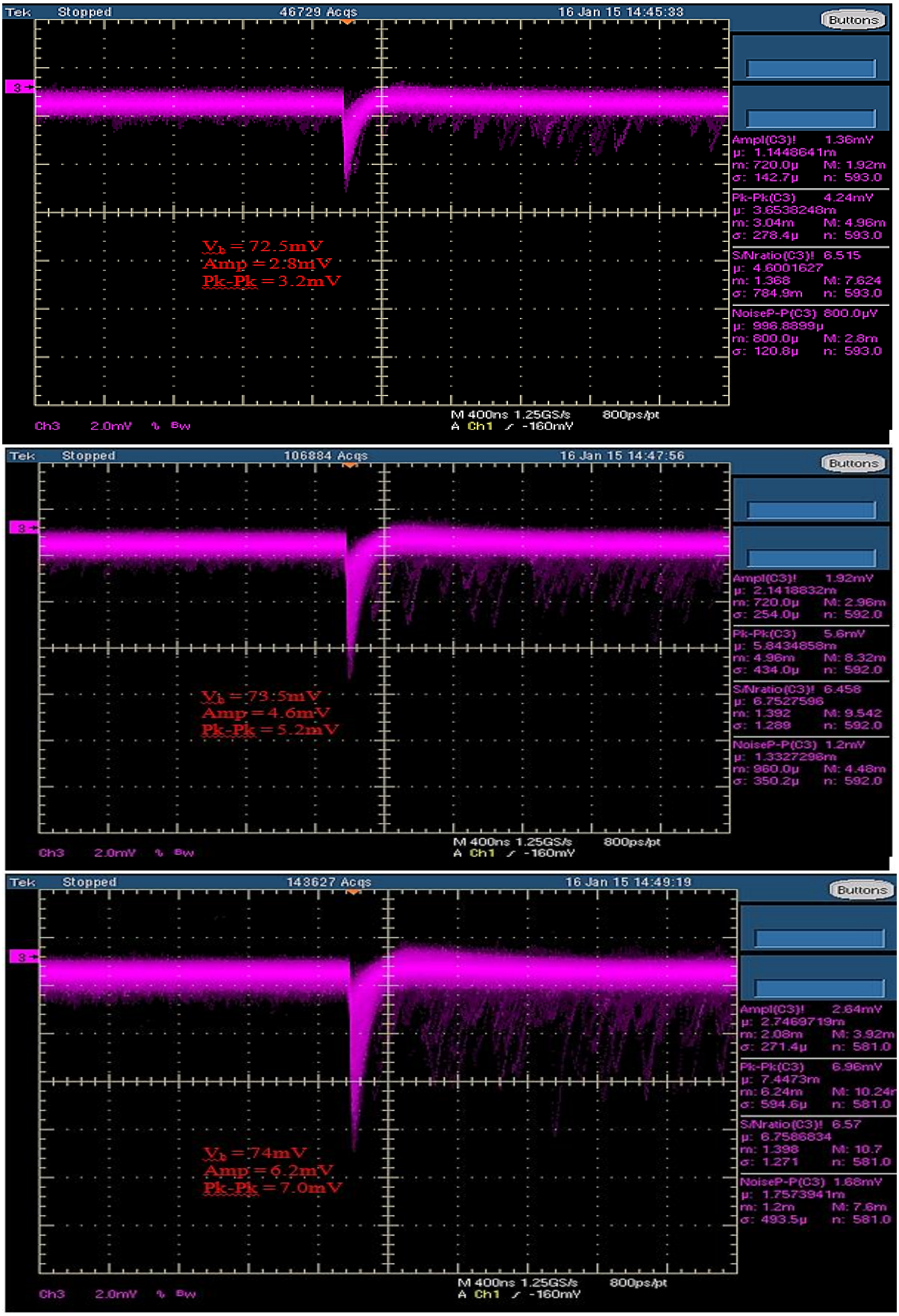
Scintillation Measurement from Gas Cell

The gas cell used in this project contained four 10 mm thick quartz windows; it was 72 mm in thickness. For the purpose of this project, the cell was filled with He gas to a pressure of 10 bar (1000000 Pa) with a mixture of nitrogen gas about 0.1% (approximately about 1000 ppm). The nitrogen serves as a wavelength shifter; it absorbs the UV spectrum from the He scintillation and re-emits it in the visible (blue, approximately 400 nm) region. Inside the cell, there was an alpha particle source (^{241}Am). ^{241}Am is an unstable nucleus which decays mainly by the emission of an alpha particle (4He nucleus) to leave ^{237}Np in one of several possible excited states. The mean energy of the produced alpha particles was around 5.5 MeV. These particles then deposited their energy as they travel through the 10 bar He gas pressure. During this journey, excited molecules are generated via ionization and recombination. The newly created excited molecules will then decay to stable ground state by emitting a flash of light in the decay process.

The scintillation photons emitted have energy less than the initial excited state and therefore cannot be re-absorbed by the helium target. Since most of the scintillation emission from all noble gas scintillators lies in the ultraviolent region, a wavelength shifter was used to convert most of or all of the emission spectrum to the visible region where the APD and the PMT is most sensitive. The scintillation light was collected by both the PMT and the APD. The PMT signals was used to trigger the digital oscilloscope and the APD pulse shape, pk-to-pk voltage and pulse height were then observed on the oscilloscope. The reverse bias voltage was varied with interval of 0.5 V, which accounts to ten different measurements. In each case, the pulse height, the noise (peak-to-peak) and the pulse shape were observed and saved on the digital oscilloscope TDS5054B made by Tektronix. No pulse was observed at a reverse voltage of 70.5 V and the peak-to-peak noise was around 1.28 mV. The pulse appeared when the voltage was increased to 71.0 V; both the pulse height and the peak-to-peak noise kept increasing as the reverse voltage was increased. APD began to draw a measurable current around 75.0 V, and the signal became dominated by noise as can be seen in Figure 2.

The APD gain increases with increasing reverse voltage in the normal operating range (70.5–75.0 V). At higher reverse voltage on the APD, the reverse voltage along the P-N junction of the APD decreases due to voltage drop caused by the series resistance component of the APD or circuit, therefore the APD gain drops [9]. The APD gain is also temperature dependent. The magnitude of vibration of the crystal lattice increases when the temperature increases. If the crystal lattice vibrates heavily, the chance that the carriers may collide with the lattice before getting to a more sufficient energy level also increases, which then makes impact ionization difficult to occur. This phenomenon makes the gain smaller at a point as the temperature increases. The temperature of the room where this project was done was kept constant (19 ºC) to avoid or minimize sudden drop of the APD gain due to temperature fluctuation.




Tek Stopped 46729 Acqs 16 Jan 15 14:45:33
Buttons
Ampl(C3)! 1.36mV
μ: 1.1448641m
m: 720.0μ M: 1.92m
σ: 142.7μ n: 593.0
Pk-Pk(C3) 4.24mV
μ: 3.6538248m
m: 3.04m M: 4.96m
σ: 278.4μ n: 593.0
S/Nratio(C3)! 6.515
μ: 4.6001627
m: 1.368 M: 7.624
σ: 784.9m n: 593.0
NoiseP-P(C3) 800.0μV
μ: 996.8899μ
m: 800.0μ M: 2.8m
σ: 120.8μ n: 593.0
Vb = 72.5mV
Amp = 2.8mV
Pk-Pk = 3.2mV
Ch3 2.0mV Bw
M 400ns 1.25GS/s 800ps/pt
A Ch1 -160mV
Tek Stopped 106884 Acqs 16 Jan 15 14:47:56
Buttons
Ampl(C3)! 1.92mV
μ: 2.1418832m
m: 720.0μ M: 2.96m
σ: 254.0μ n: 592.0
Pk-Pk(C3) 5.6mV
μ: 5.8434858m
m: 4.96m M: 8.32m
σ: 434.0μ n: 592.0
S/Nratio(C3)! 6.458
μ: 6.7527596
m: 1.392 M: 9.542
σ: 1.289 n: 592.0
NoiseP-P(C3) 1.2mV
μ: 1.3327298m
m: 960.0μ M: 4.48m
σ: 350.2μ n: 592.0
Vb = 73.5mV
Amp = 4.6mV
Pk-Pk = 5.2mV
Ch3 2.0mV Bw
M 400ns 1.25GS/s 800ps/pt
A Ch1 -160mV
Tek Stopped 143627 Acqs 16 Jan 15 14:49:19
Buttons
Ampl(C3)! 2.64mV
μ: 2.7469719m
m: 2.08m M: 3.92m
σ: 271.4μ n: 581.0
Pk-Pk(C3) 6.96mV
μ: 7.4473m
m: 6.24m M: 10.24m
σ: 594.6μ n: 581.0
S/Nratio(C3)! 6.57
μ: 6.7586834
m: 1.398 M: 10.7
σ: 1.271 n: 581.0
NoiseP-P(C3) 1.68mV
μ: 1.7573941m
m: 1.2m M: 7.6m
σ: 493.5μ n: 581.0
Vb = 74mV
Amp = 6.2mV
Pk-Pk = 7.0mV
Ch3 2.0mV Bw
M 400ns 1.25GS/s 800ps/pt
A Ch1 -160mV

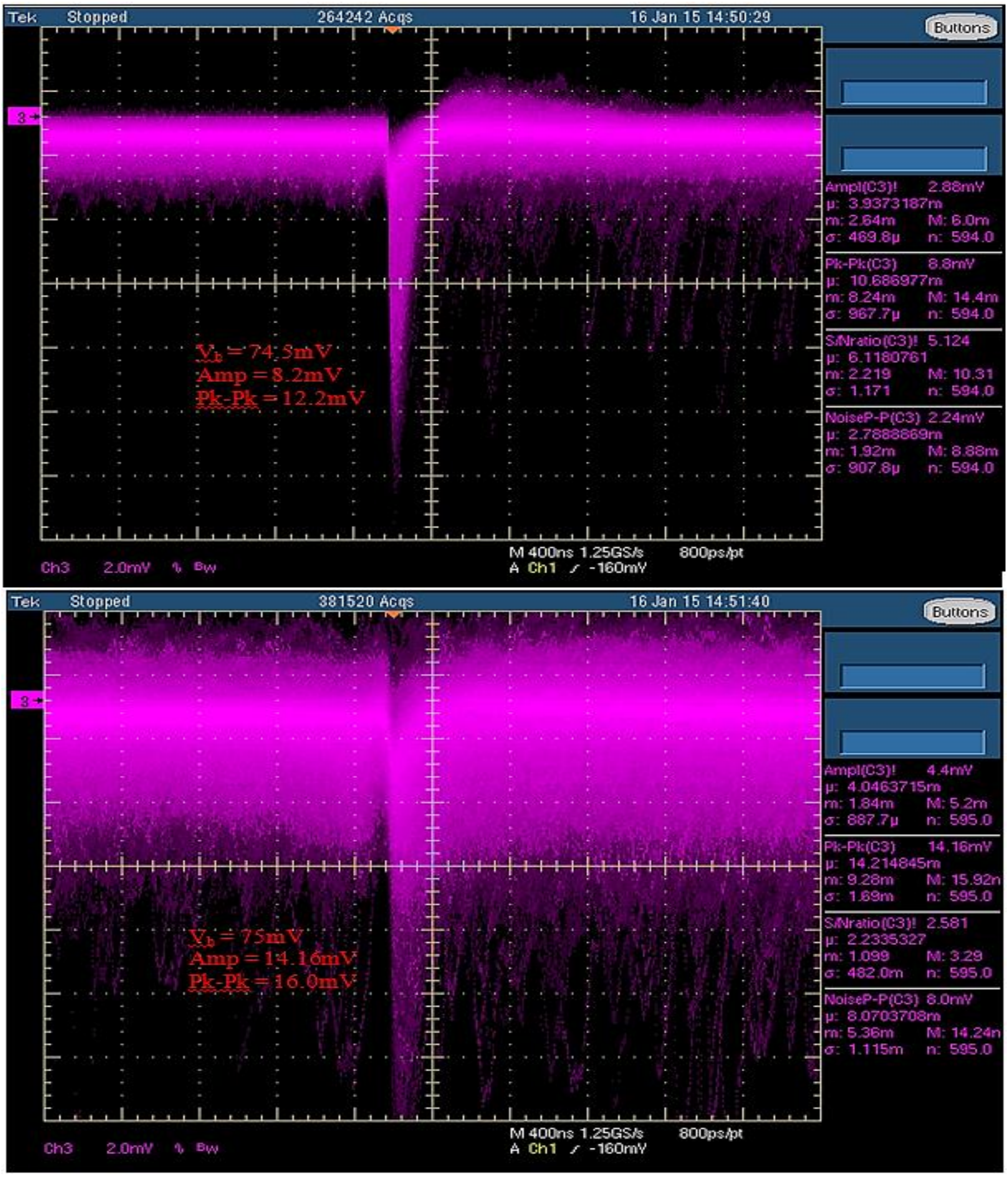
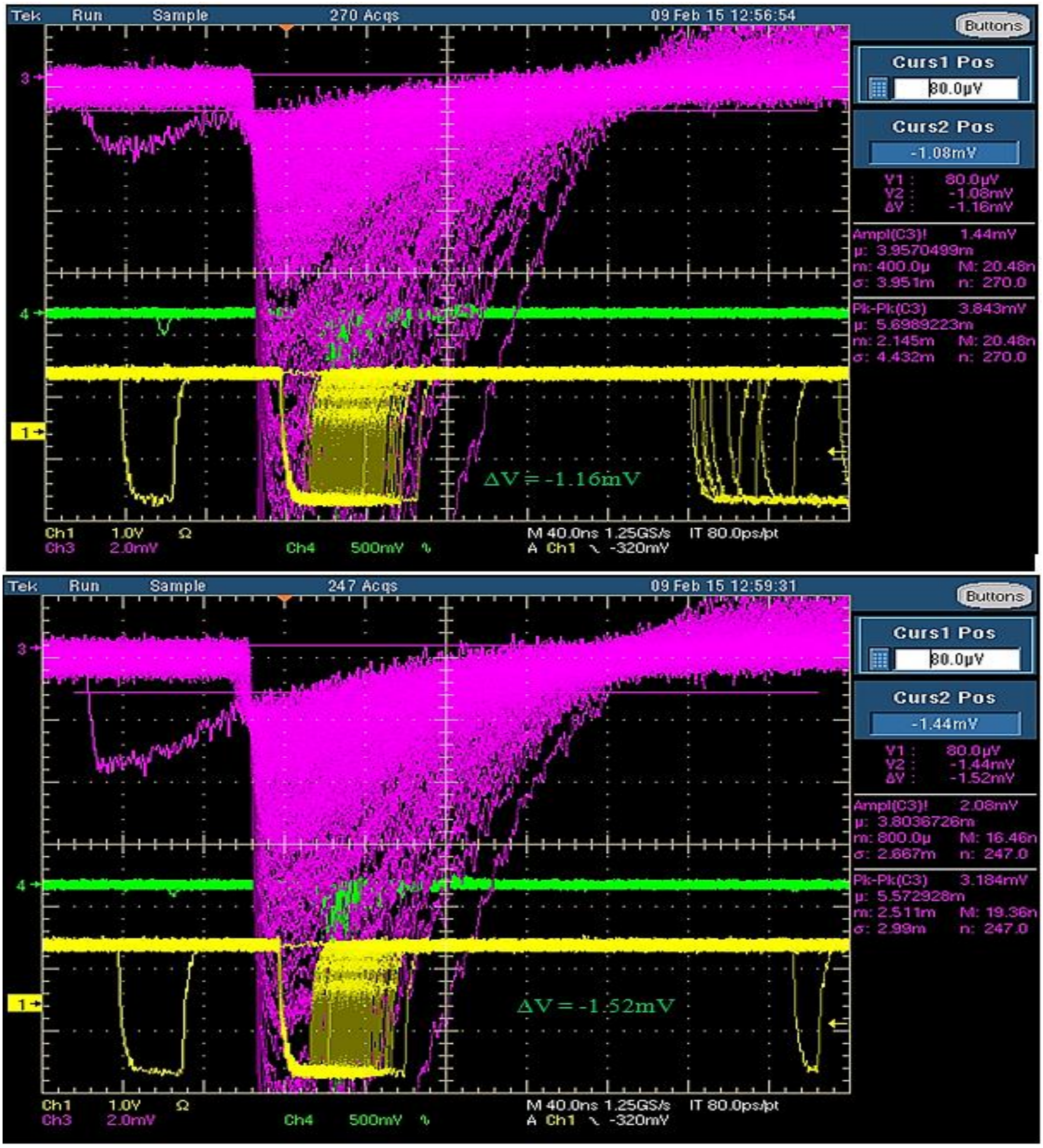


Fig. 2: *Helium Gas Scintillation as a Function of Bias Voltage at Constant Pressure of 10 Bar.*

Scintillation Measurement from Plastic Scintillator

The same APD use in the gas cell was coupled directly to a plastic scintillator. Cosmic muons were used as source in this second part of the experiment. When muons strike the plastic scintillator material, they will lose some of their energy by ionization. The energy is then transferred to the scintillator material thereby promoting the electrons in the material to an excited state. Upon de-excitation, light (scintillation) is emitted in the blue and near UV region of the electromagnetic spectrum. Just like in the gas cell, the plastic scintillators also have a wavelength shifter that absorbs the scintillation in the UV region and re-emits it in visible region. The scintillation produced is detected by the APD. The photoelectrons produced by the APD are received as signals on the digital oscilloscope.

Several measurements were taken by varying the discriminator threshold settings at an equal interval to observe the pulse shape as the discriminator threshold was varied. Cosmic muon hits the plastic scintillator from different angular distribution ($\cos^2\theta$), because of this, the energy deposited in the detector vary with the direction through which the muons enter or hit the detector (zenith angle). Those muons incident on the detector at approximately the vertical direction deposit much larger energy as compared to those that are incident at other angular direction. Cosmic muons can loss energy through the following ways: Coulomb scattering, ionization loss, Compton scattering and bremsstrahlung. The most probable way is through ionization because they are massive. On average muons produced by hadronic reactions in the atmosphere have energy of around 2 GeV once they reach sea level [10]. This isotropic nature produces a signal with multiple events as can be seen in Figure 3. The measurements were carried out at a constant bias voltage of 73.5 V, and varying the discriminator threshold settings.



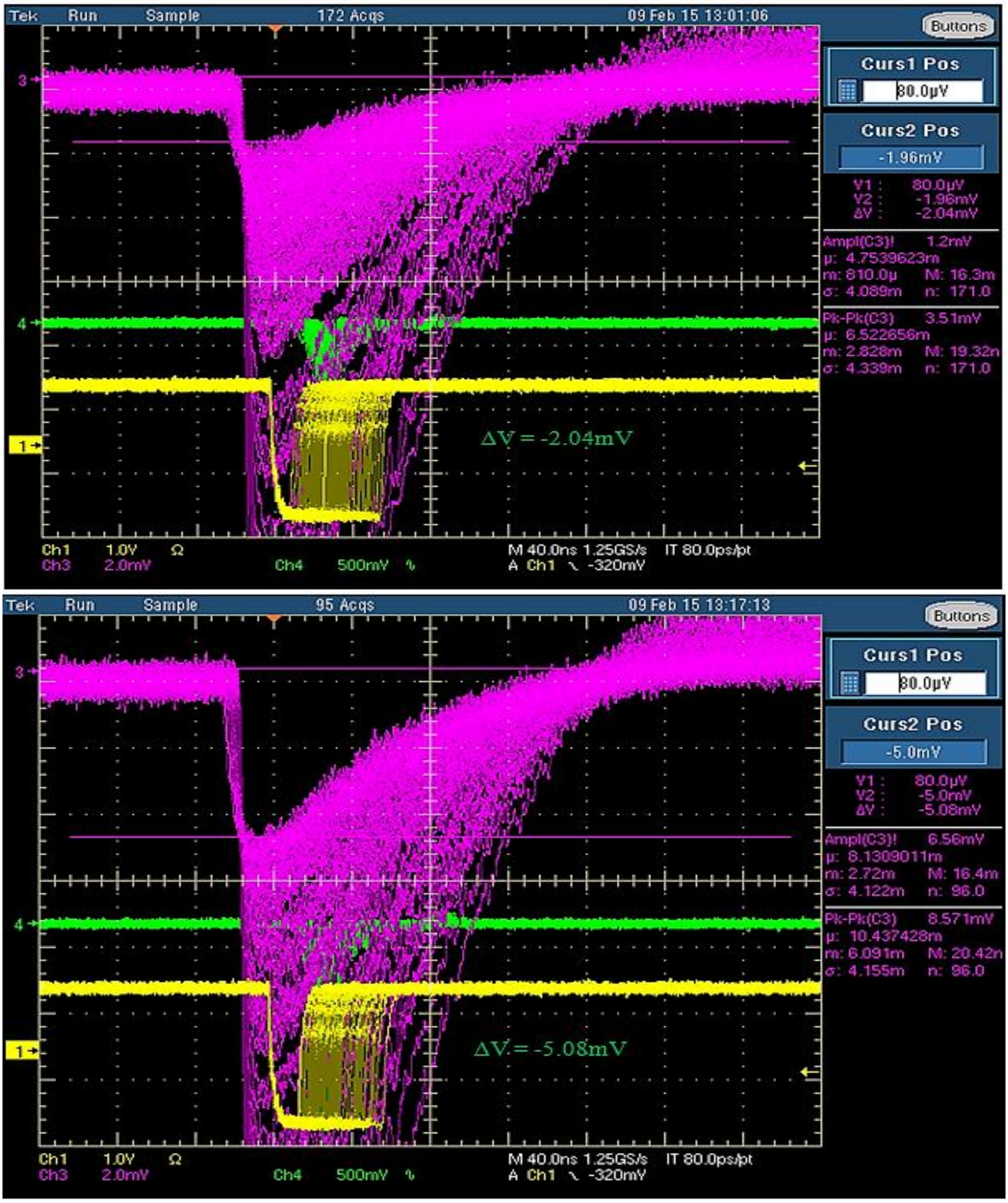


Fig. 3: *Scintillation from Plastic Scintillator as a Function of Threshold Settings at Constant Bias Voltage of 73.5 mV, ΔV is the Change in the Threshold Voltage, Magenta is the Signal from the APD while Yellow Signal is the Response Time.*

GEANT-4 SIMULATION

The purpose for doing the simulation is to determine the actual energy deposited in both the gas cell and the plastic scintillator.

An Overview of GEANT-4

The desire to understand how modern computing techniques could be used to improve the already existing simulation program known as GEANT-3 was explained in 1993 by two independent studies at CERN and KEK [11]. GEANT- 4 was built using a well-known object oriented language called C++. It is built on the existing experience gathered from many different contributions in the field of Monte Carlo simulation of the detectors used in physics and other physical process. It also has a geographical user interface through which the user can interact with the toolkit, visualise the geometry, navigation and particle tracking, event scoring, physics models electromagnetic, hadronic and optical interaction [12]. The software toolkit has been used in different scientific applications ranging from nuclear physics, medical physics and even space physics. The simulation used in this project was developed and ran on a Fedora Linux machine. The main idea of the simulation was to determine the energy deposited in both the gas cell and the plastic scintillator.

Detectors Description

The geometry of the plastic scintillator was much simpler in the detector construction as compared to the gas cell. The plastic scintillator is rectangular in shape; the construction therefore involves basically the length, width and the thickness. 50 mm, 26.3 mm and 16.5 mm were used for the length, width and the thickness, respectively (Figure 4).

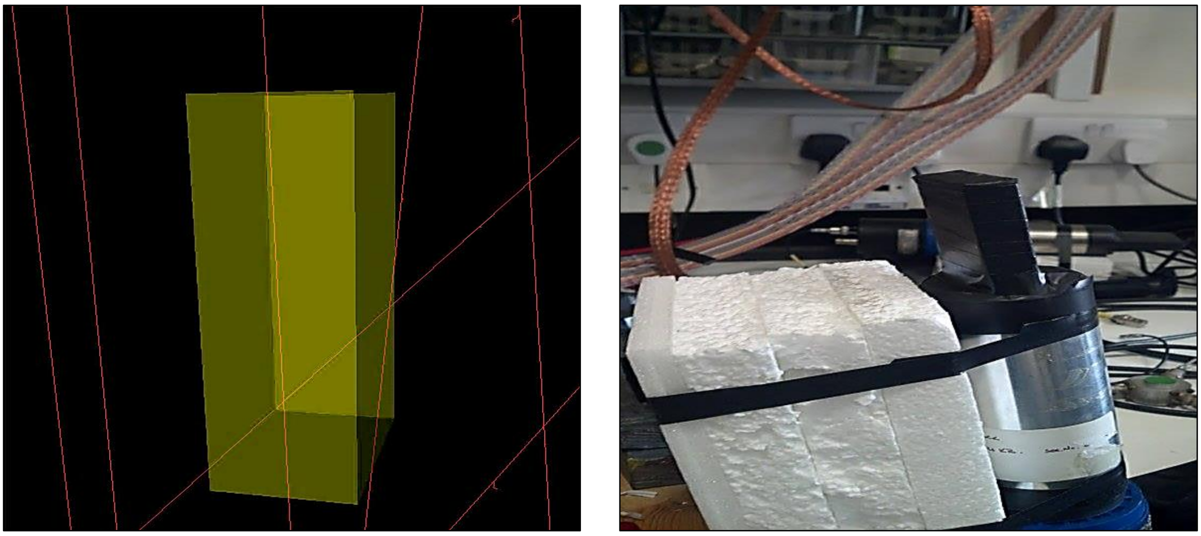
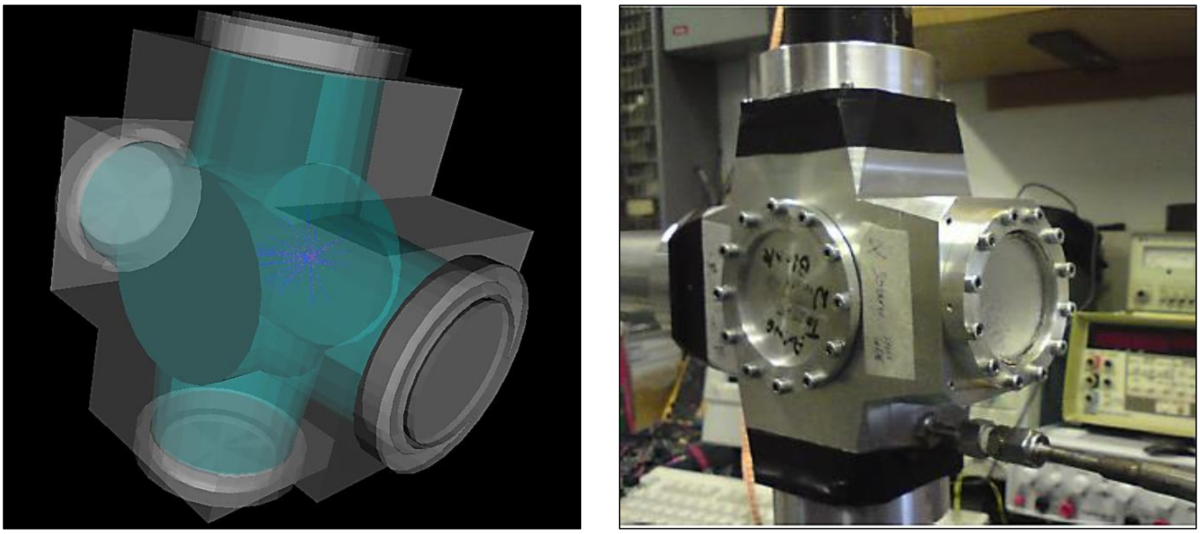


Fig. 4: *Right Picture Shows the Plastic Scintillator from the Simulation and Left Picture Shows the Plastic Scintillator Covered with Black Mastic Tape. The Red Lines are the Scintillation Photons Across the Plastic Scintillation.*



(a) *(b)*

Fig. 5: (*a) Shows a Transparent View of the Simulated Gas Cell Geometry; (b) Present a Photograph of the Gas Cell.*

On the other hand, the gas cell detector construction was complicated as compared to the plastic scintillator. This was because the gas cell construction involves the use of several Boolean operators such as the union, intersections and subtraction as there are more shapes to be put together to make the single shape as shown in Figure 5a. The alpha particle source was placed directly opposite the APD, as can be seen in the simulated Figure 5(a, b) pointed by an arrow. The simulation was run over a 100,000 event, and all the events were counted. This implies that no photon was able to make it out the gas cell.

RESULTS & DISCUSSION

Results

Table 1: *Comparison of the Results Obtained from Both the Gas Cell and the Plastic Scintillator.*

	Bias voltage (V)	Mean amplitude (mV)	Energy deposited (MeV)	β(mV/MeV)
Gas cell	73.50	5.00	4.30	1.16
Plastic scintillator	73.50	8.00	4.76	1.68

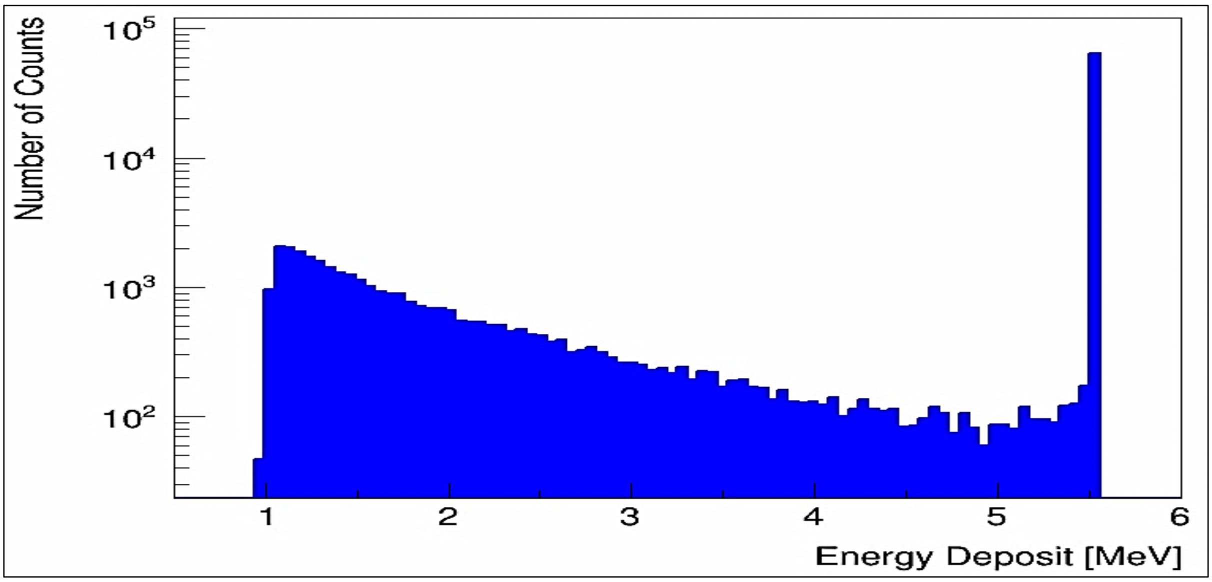


Fig. 6: *Graph of the Energy Deposited in the Gas Cell from Simulation.*

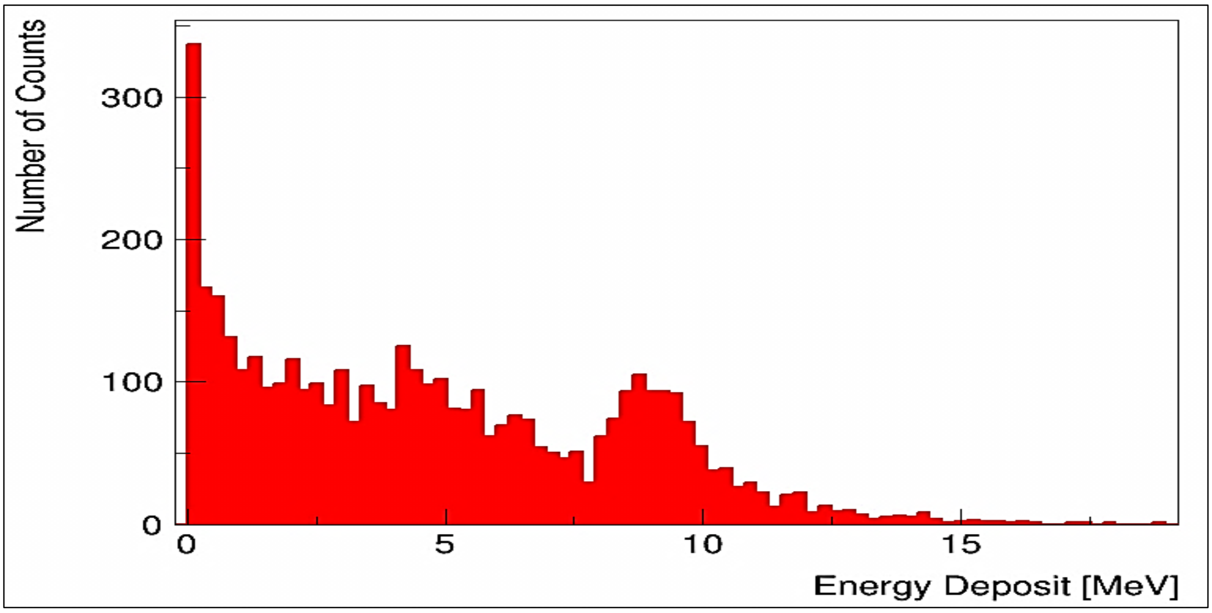


Fig. 7: *Graph of Energy Deposited by the Cosmic Muons in the Plastic Scintillator.*

Discussion

The cosmic muons measurement was carried out at a constant bias voltage of 73.5 V. The mean amplitude from this measurement was used to compare the energy deposited in both the detectors at similar bias voltage of the gas cell. The scintillation photons produced in both the detectors follows a Gaussian distribution. The mean values of the scintillation photons were therefore determined by the expression given in Eq. (1):

$$N(E_{dep}) = E_{dep} \times Y_{scint} \quad (1)$$

Where, E_{dep} = energy deposited in the detector
Y_{scint} = scintillation yield of the scintillator

The signal voltage observed in any detector is directly proportional to the amount of energy deposited in that detector. The energy deposited is therefore dependent on some constant that describe the optical efficiency of the detector, scintillation yield, amplifier gain and in this case the APD gain.

$$V \propto E_{dep} \quad (2)$$

$$V = \beta E_{dep} \quad (3)$$

$$\beta = \text{constant} = Y_{scint} \times \varepsilon_{optical} \quad (4)$$

Where, $\varepsilon_{optical}$ = scintillation photon collection efficiency From Eq. (3), the value of $\beta_{plastic}$ was found to be 1.45 times the value of β_{cell}. This value indicates that the scintillation photon collection efficiency of the plastic scintillation is higher than that of the gas cell. Since the same APD was used in both cases, the gain is assumed to remain the same.

Figure 6 shows the energy distribution in the gas cell. From the graph, it is clear to notice that most of the alpha particle energies deposited was around 5.6 MeV. This result implies that the alpha particles deposit all of their energies within the gas cell. Though, some back scattered particles deposited their energies at lower ranges.

In Figure 7, the graph presents the energy distribution in the plastic scintillator by cosmic muons. Cosmic muons strike the plastic scintillator from different zenith angle. Higher energies are deposited by those muons that enter the detector through an angle reasonable enough to provide longer path length through the scintillator. The mean energy deposited by the muons was 4.76 MeV. Table 1.

CONCLUSION

We have observed the pulse shape from an APD in both the gas cell and the plastic scintillator. The APD provides a nice pulse shape at certain range of bias voltage. Because of this nice shape, small in size and less expensive, APD may replace PMT photon sensor. Understanding the optical efficiency of the detectors will allow the measurement of the actual energy deposited in both the gas cell and the plastic scintillator, and this was not within the scope of this project. Further experiment should therefore be carried out to measure both the scintillation yield and the optical efficiency.

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