Procedings of Technical Sesions, 37 (2021) 16-23
Institute of Physics- SriLanka

Detection of ionizing radiation using simple instruments

P.B.B. Weligampola[1, *], C.P. Jayalath[1] and T.P. Ranawaka[1]
[1] *Department of Physics, University of Peradeniya, Peradeniya*
[*] *pavithraweli@gmail.com*

ABSTRACT

Since human senses are incapable of perceiving ionizing radiation, radiation detectors are necessary to identify and measure different radiation types. The diffusion cloud chamber detector is an amazing scientific instrument that can visualize the paths created by ionizing radiation. In this project, a prototype was built to identify the factors affecting the ionization track characteristics. It was observed that the shape of tracks mainly depends on the ionization power, energy, and type of radiation. Next, a Geiger-Muller counter system was reconstructed using a defective Geiger counter to measure radiation levels. A transformer-less high voltage supply and an ARDUINO-based counter were designed in the process to replace the damaged circuits in the original counter. Results from the experiments to calculate the voltage plateau of the Geiger tube and the mass attenuation coefficient of aluminium proved that the reconstructed Geiger counter is accurate enough to use for radiation measuring purposes.

1. INTRODUCTION

1.1 Ionizing Radiation Detection

Ionizing radiation has always been present in the natural environment since the beginning of the earth. But it came into recognition after Wilhelm Röntgen's discovery of X-rays in 1895. Ionizing radiation is a subatomic particle or a photon with sufficient energy to directly or indirectly eject an orbital electron from an atom, causing the atom to become charged or ionized. Some examples for ionizing radiation are α (a Helium nucleus), β (high energy electrons and positrons), X rays, and Gamma rays [1].

However, ionizing radiation cannot be detected by the human senses. Therefore, ionizing radiation detectors are required to identify sources of radiation, specific radioisotopes, and their interactions. They also provide a valuable opportunity for the scientific community to learn the basics of nuclear and particle physics. Furthermore, some ionizing radiation detectors are very useful in practical applications of measuring radiation levels.

To detect ionizing radiation, measurements are made with the aid of a radiation sensitive material placed inside the detector. Since the interaction of radiation with matter depends on the type and energy of the radiation, a detector that efficiently measures a particular kind of radiation may not be able to measure another with the same efficiency or accuracy. Therefore, the detector is determined considering the nature of the sensitive material's response to the ionizing radiation and its energy range to be measured. Gas-filled detectors, Scintillation detectors, Semiconductor detectors, Chemical detectors, and Calorimetric detectors are some examples of such different types of radiation detectors [2].

In this project, two types of ionizing radiation detectors were constructed to detect ionizing radiation qualitatively and quantitatively. First, a diffusion cloud chamber was made from scratch to visualize ionizing radiation trails. Then, a Geiger-Muller counter system was reconstructed in the laboratory to measure radiation levels.

1.2 The Diffusion Cloud Chamber

The Cloud Chamber is an instrument that allows the observer to see the trails created by ionizing radiation with the use of a supersaturated vapour medium. This instrument was first invented by a Scottish physicist Charles Thomson Rees Wilson in 1911 using an expansion technique to create a supersaturated water vapour inside a cloud chamber [3]. He observed that apart from dust or other solid particles, ions can serve as condensation nuclei for droplets. Wilson used an air mixture saturated with water vapour for his chamber and observed trails of different types of ionizing radiation.

In 1939 Alexander Langsdorf came up with an idea of a diffusion type cloud chamber to replace the expansion technique [4]. In his method, a thermal gradient is set up between the top and bottom of the chamber to generate the supersaturation inside the chamber. Here, the evaporating medium is placed at the top of the chamber, which diffuses the vapour downward towards a cooled base due to the temperature gradient. At the lower temperatures near the cooled base, the gas inside the chamber (air) becomes supersaturated with the vapour (highly evaporating alcohol medium). With a suitable gas-vapour combination and an appropriate cold temperature at the cold base, the supersaturation can exceed the critical value necessary to cause drop-wise condensation upon ions. The collision of an electrically charged particle (radiation) with air or alcohol vapour molecules, ionizes the vapour along its path. This leaves behind a trail of positively charged ions. Then, the close-by vapour molecules are attracted to these ions and initiate the condensation process. When enough molecules are attracted together, cloudlike tracks are created along the path left by the particle moving through the chamber. Track length and thickness will vary depending on the charge, mass, and energy of the particle [5]. A prototype very similar to this was built in this research project using thermoelectric modules to cool down the cold plate and an analytical-grade isopropyl alcohol vapour medium was used to form the supersaturated state.

1.3 The Geiger-Muller Counter (GM Counter)

The Geiger–Müller tube or GM tube is the sensing element of the Geiger counter instrument used for the detection of ionizing radiation. It was named after Hans Geiger, who invented the principle in 1908, and Walther Müller, who collaborated with Geiger in developing the technique further to detect multiple types of radiation. A GM tube consists of a chamber filled with an inert gas mixture (He, Ar, or Ne) at a low pressure of about 0.1 atm. The chamber contains two electrodes to apply a potential difference of several hundred volts. The metal wall of the tube acts as the cathode while a thin wire mounted axially in the center of the tube acts as the anode. When ionizing radiation passes through the tube, some molecules of the filled gas are ionized and create ion pairs within the gas. The strong electric field inside the chamber accelerates the positive ions towards the cathode and the electrons towards the anode. When approaching the anode, free electrons gain sufficient energy to ionize additional gas molecules by collision and create a large number of electron avalanches. These spread along the anode and throughout the avalanche region. Due to this "gas multiplication" effect, the tube can produce a significant output pulse from a single original ionizing event which varies from 10 μV to 1V [6]. This pulse is amplified by using a signal amplifier and fed into a pulse counter to measure the radiation level. In this project, a transformer-less high voltage circuit was designed to replace the HV supply to the GM tube and an ARDUINO based counter was designed to replace the counting mechanism of the damaged Geiger counters (The Nucleus – Model 550) in the laboratory.

2. METHODOLOGY

2.1 Construction of The Prototype Diffusion Cloud Chamber

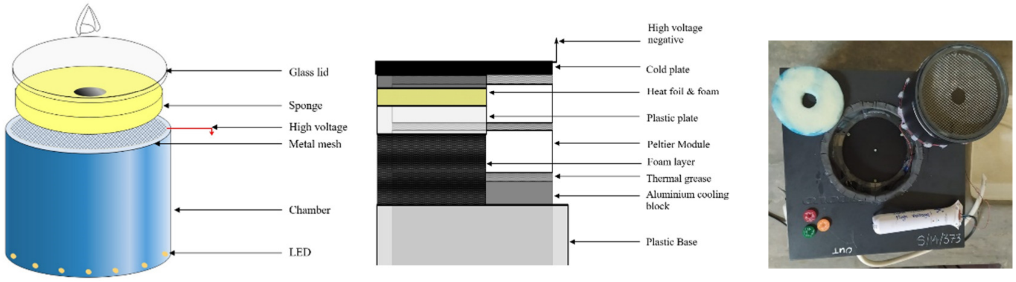
The most significant part of the Diffusion cloud chamber is its cooling mechanism which cools down the cold plate to sub-zero temperatures to form a supersaturated vapour. For this particular instrument, thermoelectric modules were used instead of dry ice to reach temperatures around -30 °C on the cold plate. Here, the low-power module (TEC1-12710 [7]) was stacked on top of the high-power module (TEC1-12715[7]) and three such pairs were used to cool down the cold plate. Then, water-cooled aluminum heat sinks were attached to the hot side of each pair to rapidly remove the dissipated heat. To make the cold plate, a powder-coated steel disk with a diameter of 14.5 cm was cut out from an old computer casing. It was noted to apply thermal paste on the contacting surfaces of the cold plate, thermoelectric modules, and heat sinks to increase the thermal contact. Next, the cooling elements were glued to a plastic base, which was laser engraved and prepared to fit the cooling elements perfectly. The cold plate was then married to the thermoelectric modules and fixed to the plastic base with plastic nuts and bolts. An ATX power supply (450 W) with a high current output was used to power up the instrument. Then, both the power supply and the cooling mechanism were housed inside an old PC casing to provide strength and stability to the final instrument. A 16-inch diameter PVC tube was cut and modified to make the chamber of the instrument. White LEDs were integrated along the bottom circumference of the chamber to uniformly light up the supersaturation layer. A glass lid was cut to cover the top part of the chamber and a sponge ring was glued to it to store Isopropyl Alcohol. To improve the track visibility, an electric field of around 140 V cm^{-1} was introduced to the chamber by connecting a metal mesh placed inside the chamber with the (+) electrode and the cold plate with the (–) electrode of the High Voltage supply. After the final assembly of the instrument, different types of ionizing radiation were observed.

2.2 Construction of The Geiger-Muller Counter System

High voltage required to operate the GM tubes in the laboratory was generated by step-up transformers which were found to be damaged. Thus, a circuit which had been previously designed by Tom Napier [8] was modified to produce around 1000 volts to replace the outdated transformer-based technique. The modification was done by integrating a voltage doubling circuit to the original circuit. Additionally, to future-proof the instrument, an ARDUINO based pulse counter was programmed and designed from scratch to replace the existing counting circuit. The ARDUINO Uno Rev 3 model was used in this circuit to count the voltage drops given out by the signal modifier and a 16×2 LCD was used to display the functions of the counter. To operate the counter, 4 push buttons were used; S1 for mode selection, S2 and S3 for down and up function, and S4 to initiate the counting. An external reset button was also added in case the circuit needs to be reset. The pulse-modification circuit of the old Geiger counter was still in good condition. Therefore, it was used with the new counter to convert the Geiger tube's analog pulses to digital signals. A salvaged power supply casing was modified and prepared to house all three circuits mentioned above. Experiments were conducted to calculate the voltage plateau of the GM tube (The Nucleus-EG 2) and the mass attenuation coefficients of aluminium for gamma rays using the modified GM counter system and an existing GM counter (The Nucleus - Model 550).

3. RESULTS AND DISCUSSION

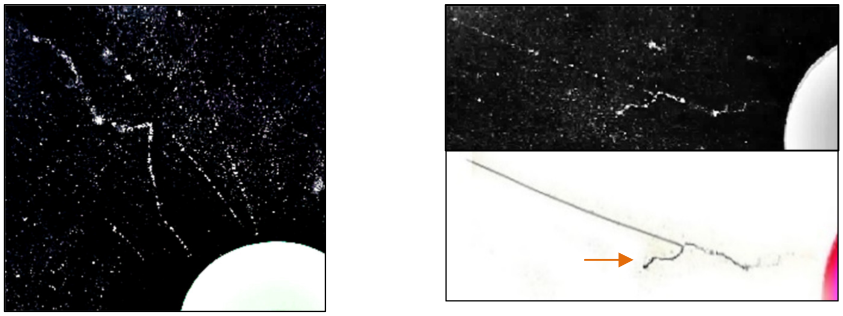
3.1 Results from The Prototype Diffusion Cloud Chamber



(a) (b) (c)

Figure 1: (a) Schematic of the chamber (b) Schematic of the cooling system (c) The cloud chamber

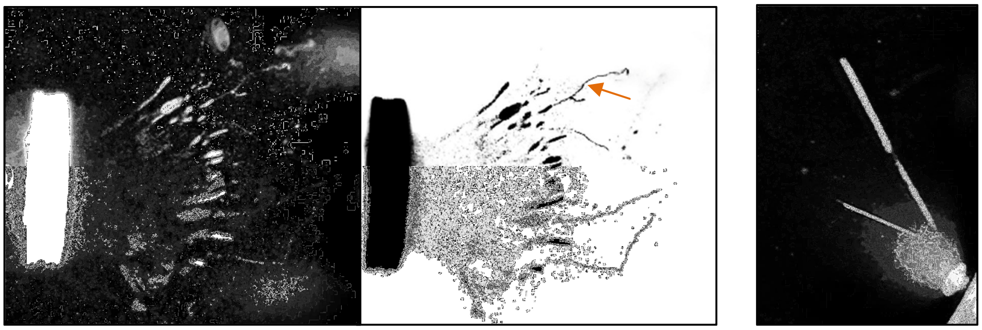
Each component of the prototype cloud chamber played a vital role in the success of the instrument. The use of a thermoelectric modules-based cooling mechanism improved the reliability and the practicality of the instrument by cutting down the maintenance costs involved with the dry ice cooling method. Also, it created the supersaturated state under a minute. The electric field (around 140 V cm^{-1}) supplied using a salvaged high voltage circuit of a mosquito racket swept away the unnecessary ions inside the chamber. A significant improvement in track visibility and sharpness was observed as a result of this modification. The cold plate temperature, which decides the thickness of the supersaturated layer, was proportional to the water temperature and flow rate of the water-cooling system. Water at room temperature (25 °C) and flow rates close to 70 ml s^{-1} were sufficient enough to reach around -30 °C on the cold plate. Once the supersaturated state was reached by the instrument, ionization tracks were observed using the background radiation, ^{241}Am (for the α radiation) and ^{90}Sr (for the β radiation). Observations were recorded using a camera mounted on top of the chamber which only allowed to observe the 2-dimensional behaviour of tracks. Therefore, any vertical motion of tracks inside the supersaturated layer (≈ 1 cm thickness) was unable to observe using this arrangement. Random motion of vapour inside the chamber and variation in vapour density deformed the tracks occasionally. As a result, track thickness, length, and visibility varied accordingly. However, a pre-calibration conducted using known radiation sources helped to identify the basic characteristics of tracks formed by the relevant type of radiation. Placing radiation sources at room temperature on the cold plate disturbed the supersaturation region around the source. Therefore, observations were made after allowing the supersaturation to restore around the radiation source.



(a) (b)

Figure 2: (a) Image of beta radiation observed using ^{90}Sr (b) A delta ray emission

Beta particles are fast-moving electrons (or sometimes a positron which is the anti-particle of an electron) emitted from the nucleus during radioactive decay [9]. These particles are light and therefore get easily deflected when collided with a heavy atom. But, if not met with an obstacle, they can travel long distances before losing energy due to their low ionization power compared to alpha particles. Figure 2(a) illustrates the observations made using the prototype cloud chamber for both such encounters. Figure 2(b) shows the emission of a Delta ray, which is a secondary free electron with enough energy to ionize the vapour medium and travel a small distance away from the primary radiation beam. The incident high energy beta ray gets slightly deflected due to the collision while the ejected free electron quickly stops within a short distance because of its low energy. After studying the main characteristics using a ^{90}Sr source, it was possible to separately identify beta radiation from the background radiation observed inside the cloud chamber. Here, low-energy beta radiation created curved and short traveled tracks while high-energy beta radiation created less deflected long tracks.



(a) (b)

Figure 3: (a) Alpha radiation observed using ^{241}Am (b) Observed background radiation

3.2 Results from The Reconstructed Geiger Counter System

Since alpha radiation is having the highest ionization power, a +2 charge, and a higher mass, it produced thick short tracks inside the cloud chamber when observed using the ^{241}Am source [8]. As shown in Figure 3(a), the origin of the observed tracks was unpredicted since the used ^{241}Am source was not a point source. However, the tracks which traversed diagonally through the supersaturation medium were observed. Figure 3(a) illustrates a cascading event of alpha and low energy beta particles, observed using the cloud chamber. Unlike beta radiation, alpha particles followed a straight path with less deflections due to its higher mass. When alpha particles collide with the atoms and the molecules in the medium, it generates free electrons with enough energy to further ionize and generate secondary free electrons in the medium. Figure 3(b) illustrates two tracks formed due to background radiation. Comparing with the observations made using known radiation sources, it can be predicted that these two tracks were generated due to some highly ionizing heavy particles. Most probably, these could be alpha particles emitted during the radioactive decay of Radon-220 in the atmosphere.

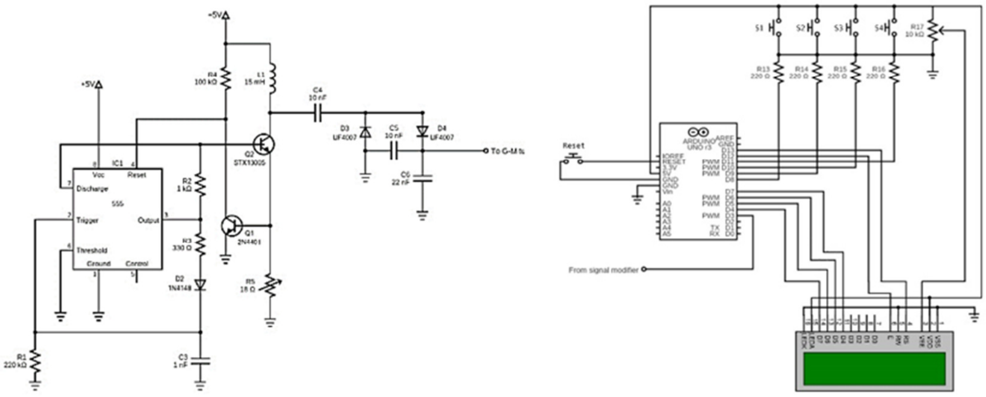


Figure 4: Modified high voltage supply (Left) and the ARDUINO Counter (Right)

Therefore, a prototype diffusion cloud chamber of this type can be easily constructed and used to identify different types of ionizing radiation in a lab without having to use advanced technology. Furthermore, this easy-to-handle instrument could be very useful in inspiring school students and undergraduates to explore their knowledge in nuclear and particle physics.

Geiger counters (The Nucleus – Model 550) in the laboratory were more than thirty years old, and many were not in working condition due to the defective transformers. However, the Geiger tubes were functional. Therefore, a modified counter system was developed to make maximum use of them. The modified high voltage circuit generated a maximum voltage of around 910 V, and it was more than enough to supply the high voltage to the Geiger tube. The ARDUINO counter counted pulses precisely without a lag and showed its capability in handling high count rates.

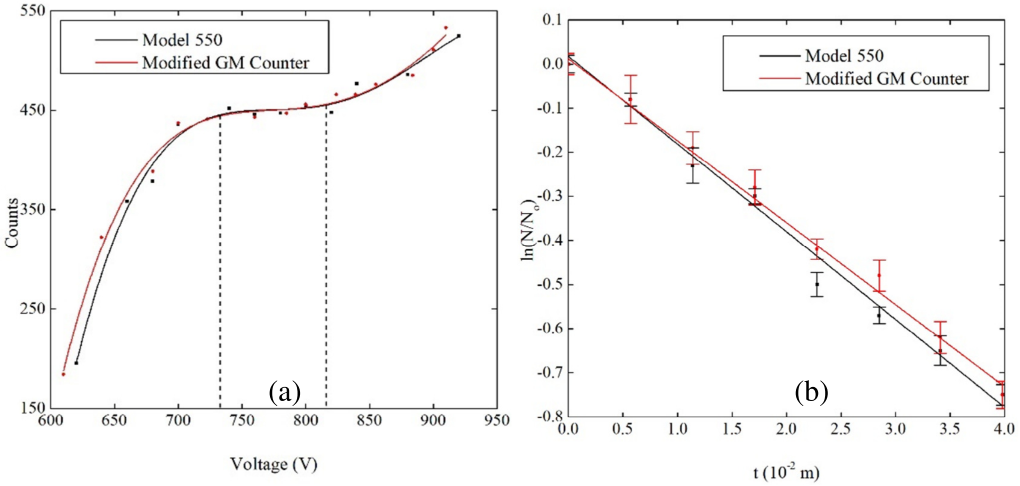


Figure 5: (a) Relationship between the counts and the voltage (b) Relationship between the normalized count rate [$\ln(N/N_0)$] and thickness (t)

Each Geiger tube has a characteristic voltage plateau that defines the suitable voltage range required for its accuracy and durability. Figure 5(a) illustrates the comparison of the voltage distribution curves plotted using a model 550 counter and the modified Arduino based counter. In this experiment, counts per minute value given out by the same Geiger tube was measured for a range of voltages while keeping the radiation source unchanged. According to Figure 5(a), both the instruments have measured the starting voltage to be around 600 V. The voltage plateau region predicted by both the counters are identical and found to be between 732 V and 816 V. Therefore, a center value of 780 voltage was selected as the operating voltage of the Geiger tube using the above results.

To further verify the accuracy of the modified Geiger counter, a simple experiment was conducted to calculate the linear attenuation coefficient of aluminum (μ) using a gamma source (^{137}Cs – Gamma 0.662 MeV). Here, the count rate of the unattenuated radiation (N) was measure by varying the aluminium thickness (t) between the Geiger tube and the radiation source. (N_0 is the count rate of the incident radiation)

$$N = N_o e^{-\mu t} \tag{1}$$

Next, graphs were plotted as in Figure 5(b) using the readings taken from both Geiger counters. Then, the linear attenuation coefficient of aluminium was calculated using the gradients of the plotted graphs. Linear attenuation coefficients of aluminium calculated using the Model 550 Geiger counter and the reconstructed Geiger counter were 19.52±0.87 m^{-1} and 18.76±0.58 m^{-1}, respectively. Though the values are not identical, they were close enough to compare with each other.

All these experimental results proved that the reconstructed Geiger counter is operating with good accuracy and can be used for future radiation measurements in the laboratory.

4. CONCLUSIONS

Out of many different ionizing radiation detectors, the diffusion cloud chamber and the Geiger counter are two main detectors that can be used to measure ionizing radiation qualitatively and quantitatively. The diffusion cloud chamber is a simple instrument that can be made without using any advanced technology. It can be used by anyone who has an interest to observe the behavior of different types of ionizing radiation to the naked eye. In the future, this instrument can be modified to identify the charge of the ionizing radiation by applying a strong magnetic field inside the chamber to bend the path.

The newly developed high voltage generation circuit and the ARDUINO based signal counter can easily replace the damaged circuits of a typical Geiger counter system without affecting the accuracy of the final instrument. For this project, the Signal Modification Circuit was salvaged from the old Model 550 counter. But, if necessary, a complete Geiger Counter System can be made by designing a suitable signal modification circuit to work with the designed high voltage generator circuit and the ARDUINO counter.

5. REFERENCES

[1] Friedberg, W. and Copeland, K., *Ionizing Radiation in Earth's Atmosphere and in Space Near Earth*, Fed. Aviat. Adm. (2011) 1.

[2] Silva, M. D. R., *Ionizing Radiation Detectors*, Evol. Ioniz. Radiat. Res. (2015) 190.

[3] Wilson, C. T. R. and P. R. S. L. A, *On a Method of Making Visible the Paths of Ionising Particles through a Gas*, Proc. R. Soc. London. Ser. A, Contain. Pap. a Math. Phys. Character 85 (1911) 285.

[4] Langsdorf , A., *A Continuously Sensitive Diffusion Cloud Chamber*, Rev. Sci. Instrum. 10 (1939) 91.

[5] Snowden, M., *The Diffusion Cloud Chamber* ,Elsevier Ltd, (2013).

[6] Knoll, G. F., *Radiation Detection and Measurement*, *Fourth Ed.*,Wiley, 2010 207-210.

[7] Ruciński, A. and Rusowicz, A., *Theoretical and Experimental Analysis of Thermoelectric Power Generation*, J. Power Technol. 100 (2020) 250-254.

[8] Napier, T., *Measure Low-Level Radioactivity: Build a Sensitive Radiation Counter*. Circuit Cellar, 184 (2005) 52.

[9] *Ionizing Radiation: Fact Book*, Radiat. What You Need to Know (2007) 3-4.