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Cosmic Muon Detection Using Cherenkov Radiation: A Novel Approach with Arduino Integration

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Abstract - *A muon is another entity categorized as a lepton among the many elementary particles. Like an electron, a muon consists of a charge of -1e and a spin of ½, but with greater mass. Muons exist as mere by-products of cosmic ray collisions with the particles in the Earth's atmosphere. Over ten thousand cosmic muons reach every square meter of the Earth's surface each minute. Experimental findings about cosmic muons indirectly provide us with information about the properties of cosmic rays. The purpose of this project is to propose an innovative and unique method of detecting cosmic muons. This method utilizes the emission of Cherenkov radiation as an indicator for detecting cosmic muons. Cherenkov radiation's emission occurs when a charged particle travels through a dielectric medium at a speed faster than that of light in a vacuum. The emission of a characteristic blue light can identify it. The experimental setup proposed in this project consists of photodiodes in a light-proof container filled with water to detect these blue light pulses. Since cosmic muons will travel faster than light in water, they will emit blue light pulses, confirming their detection. In order to make the inquiry automated, the light pulses are counted via an Arduino circuit. Furthermore, a predictive machine learning model is developed to predict the number of pulses detected (~120 in one hour).*

Key Words: Machine Learning, Cosmic Muon, Arduino

1.INTRODUCTION

Like an electron, a muon consists of a charge of -1e and a spin of ½, but with greater mass (~207 times). Since it is a lepton, it does not contain any other particles. Hence, it is a fundamental particle. It has a mean lifetime of 2.2 µs, much longer than other elementary particles. Due to being an elementary particle, its decay is only mediated by weak interaction forces and is slow.

Moreover, a muon decay almost always produces at least three particles (electrons and two types of neutrinos). In an electromagnetic field, muons accelerate slower than electrons due to greater mass, providing them the required energy to penetrate materials far more profoundly than an electron. Due to this inherent property, a cosmic muon can penetrate the atmosphere, reach Earth's land surface, and even into deep mines.

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1.1 Background

Muons have been the subject of intense scientific research for their unique properties and practical applications. They have been instrumental in experimental tests of time dilation, enabling nuclear fusion at room temperatures, and creating alternate (muonic) versions of atoms. In a recent breakthrough, cosmic muon radiography has aided archaeologists in navigating corridors inside the Great Pyramid of Giza, showcasing the diverse applications of muons in scientific research.

Cherenkov radiation is emitted when electrically charged particles travel at a speed faster than that of light in a transparent medium like water. These charged particles excite the water molecules in their path, which causes photons to be released and emit blue or violet light. Since the particles are moving faster than the speed of sound, they create a "shockwave" of visible light. An analogy to explain this phenomenon would be the sonic boom generated by a supersonic aircraft. Just as the sound waves generated by an aircraft are slower than the aircraft itself, creating a sonic boom, the photons emitted by the charged particles in Cherenkov radiation are slower than the particles, creating a similar shockwave of light.

The discovery of Cherenkov radiation in 1958 by the esteemed scientist Pavel Cherenkov was a pivotal moment in the field of physics. During an experiment, his keen observations led him to observe a bluish light around a radioactive preparation. These observations, coupled with his understanding of the anisotropy of the radiation, led him to conclude that the bluish glow was not a fluorescent phenomenon, but a new and significant discovery in the world of physics.

1.2 Emission Angle

In the given figure (Fig 1.1), the charged particle (red arrow) travels with speed $\mathbf{V_p}$ through the medium. The ratio between the speed of light and that of the particle could be defined as **β**.

Thus,

$$\beta = \frac{V_p}{c} \qquad \text{(eq. 1)}$$

Additionally, the emitted light waves travel at a speed of V_{em} , where **η** is the refractive index of the medium.

$$V_{em} = c\eta \qquad \text{(eq. 2)}$$

Vertex A represents the particle's position at an arbitrary point in time (t), assuming t=0. Now, at some other point in time (t=T), the distance traveled by the particle is x_p (AC).

$$x_p = V_p t$$

$$x_p = \beta ct \qquad \textit{(From eq. 1)}$$

On the contrary, the waves emitted by that particle travel the distance x_{em} (AB).

$$x_{em} = V_{em} t$$

$$x_{em} = \frac{c}{\eta} t \qquad \textit{(From eq. 2)}$$

From the Figure 1.1, the emission angle θ is equal to:

$$\cos \theta = \frac{AB}{AC}$$

$$\cos \theta = \frac{c}{\eta} t \div \beta ct$$

$$\cos \theta = \frac{1}{\eta\beta}$$

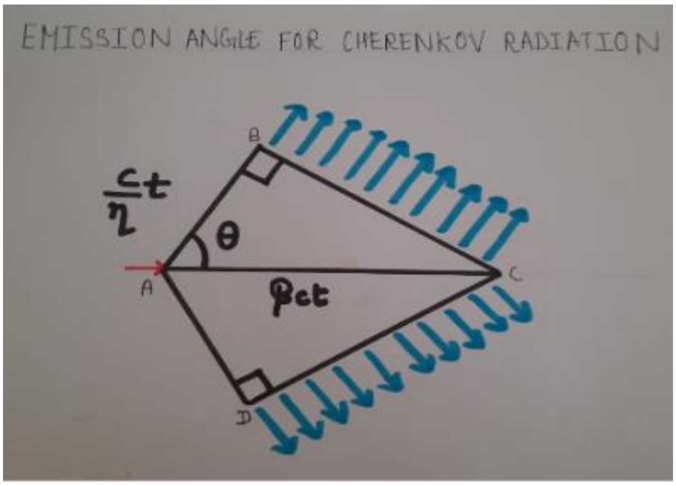

Figure 1.1: *Hand-Drawn Diagram Depicting Emission Angle For Cherenkov Radiation.*

There are two fundamental methods to produce a muon. The first method involves cosmic ray collisions, a natural source of muon production. The second method uses a particle accelerator, where an H+ ion is accelerated to collide with the target particle (e.g. Lithium nuclei). This collision leads to a pion decay, which produces various pion variations. It's important to note that a pion is produced 80 % of the time, while an anti-pion is produced only 20 % of the time. When a pion is contained in a vacuum, it spontaneously decays (after 26 nanoseconds) into a muon and a neutrino.

Muons bond with atoms like hydrogen and carbon exactly like electrons do; however, they are not bound by Pauli's exclusion principle. In other words, they can combine with an atom's orbital valence even though they are filled with and already filled with electrons. Once an electron occupies an atom's orbital, it interacts (later combines) with the protons inside it. This process transforms the muon into a neutron and releases energy from a host particle called a neutrino.

$$\mu^- + p \rightarrow n + \nu_\mu$$

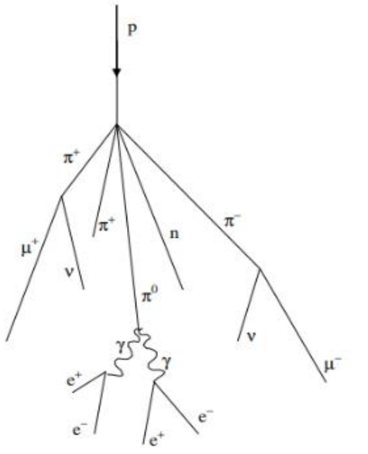

Figure 1.2: Cosmic ray cascade induced by a cosmic ray proton striking an air molecule nucleus present in the atmosphere.

Depending on whether or not the muon has combined with a proton, a muon's average lifetime inside a material can differ. By comparison, negatively charged muons have a shorter lifetime than positively charged muons since they tend to combine with the target atom's proton due to electrostatic attraction. At the same time, the positively charged muon tends to push away the target atom's proton due to electrostatic repulsion. Furthermore, the probability of a muon combining with the target atom's proton depends on the atomic number of that element. In other words, the more protons are available, the more chances a muon combines with the proton.

In the graph below (Fig 1.3), the x-axis represents the time interval when the muon penetrates the target material and when it decays, respectively. In contrast, the y-axis represents the number of muons. Approximately 1000 muons were initially available in the medium; however, the number started to fall dramatically within a few microseconds. However, the difference to note comes when comparing the slopes of the positively charged muons versus the negatively charged muons.

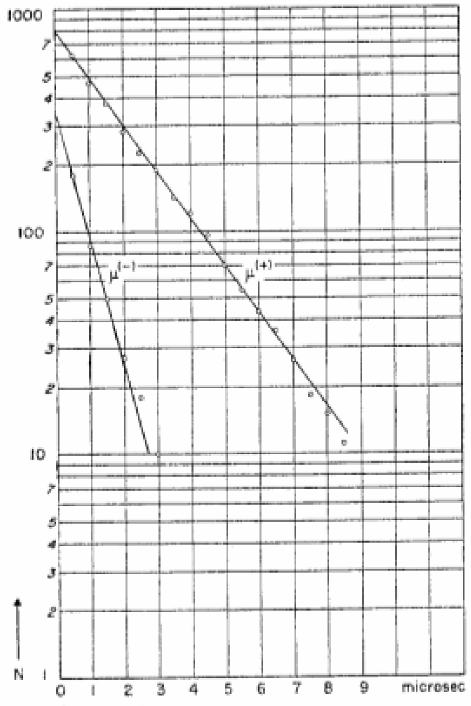

Figure 1.3 : *Disintegration curves for positive and negative muons in aluminum. The ordinates at t = 0 can be used to determine the relative numbers of negative and positive muons that have undergone spontaneous decay. The slopes can be used to determine the decay time of each charge species. (From Rossi, p168.)*

The line representing positive muons, assume as A, starts at a y-intercept representing approximately eight hundred muons. On the other hand, the line representing negative muons,assume as B, has a y-intercept representing almost three hundred muons, and that number starts to decline, too. Overall, it is evident that the slope of line A is less than that of B. In other words, the negative muons disappear faster than the positive ones. Negative muons can do this because of their advantageous electrostatic attraction towards an atom's protons, which later results in the formation of a neutron.

As discussed previously, any particle that travels at a speed faster than that of light will emit Cherenkov radiation. These muons will polarize the molecules in the medium and cause them to emit photons in the form of Cherenkov radiation. In this project, we use this property of Cherenkov radiation to detect cosmic muons. Since cosmic muons pass through almost any substance, they will emit Cherenkov radiation if we isolate them to travel faster than light. In this experiment, water is used the medium to observe and measure cosmic muons. Since the refractive index of water makes light travel at a speed less than 3 x 10^8 m/s. Despite the speed of muons being less than the speed of light, it still is more than the speed of light in water.

2. METHODOLOGY

Our experimental setup involves a light-proof tin box filled with tap water, serving as the detection medium. Inside this container, a photodiode is strategically positioned to detect Cherenkov radiation each time a cosmic muon passes through the box. These photons are then converted into electrical signals and counted by the 555 IC Timer, which plays a crucial role in automating the process of counting each blue light pulse, representing the emitted Cherenkov radiation.

The tin container was sealed to light passing through it using M-Seal, M-Seal is a multi-purpose sealant that can be used to fill and seal gaps, cracks, and holes in almost any surface. It has various industry applications including sealing joints in PVC pipes and fixing water leaks. A small hole was drilled in the corner of the container to place the photodiode through it. The photodiode was placed on the side of the container at a sufficient depth to submerge and orient towards the water surface. The photodiode's anode was connected to the Arduino UNO's analogue input pin via a jumper wire. Its cathode was to the GND pin of the microcontroller. The LED's anode was connected to a digital pin on the board via a resistor (220 ohms) and another jumper wire. Similarly, its cathode was connected to a GND pin. The VCC pin of the 555 Timer IC was connected to a 5V pin on the Arduino using a jumper wire. The GND pin of the 555 Timer IC was connected to the GND pin on the Arduino. The OUT pin of the 555 Timer IC was connected to a digital pin on the Arduino using a jumper wire. The battery's anode was connected to the VCC pin on the breadboard. The battery's cathode was connected to the GND pin of the breadboard. On a laptop, Arduino IDE was installed and a program was written to count the number of times the photodiode detects a light pulse , i.e detects a cosmic muon, consequently blinking the LED. The program was uploaded into Arduino UNO. With this modified setup, one can detect cosmic muons using Cherenkov radiation without an amplifier. Detailed records were taken of the number of muons detected per minute and hour at different times of the day. The tin container in different environments (e.g., ambient light), and materials to observe the fluctuations in the number of muons detected by the setup.

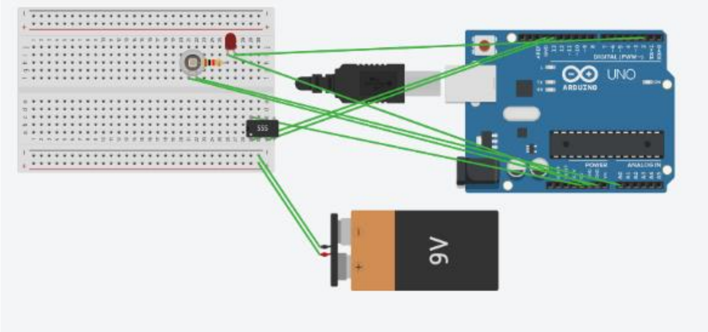

Figure 2.1: Simulation of the proposed setup on Tinkercad (9V Battery, Arduino Uno, Photodiode, 555 IC Timer, LED, 220 Ohm Resistor, Jumper Wires)

The purpose of this experiment was to evaluate the impact of external light sources on the accuracy of our readings. The readings were taken in two different sets (Figure 6):

- Reading Set 1 consisted of readings taken at noon under sunlight.
- Reading Set 2 consisted of readings taken at night in a dark room (9 pm).
- Each reading set consists of two cases: Case 1 (readings taken every 5 seconds) and Case 2 (readings taken every minute).
- Each case consists of 60 readings taken.

To make plotting the graph automated and minimise errors, the readings were noted down in Excel, saved as a .csv file, and later plotted on the graph using a Python Library called Matplotlib.

3. OBSERVATIONS

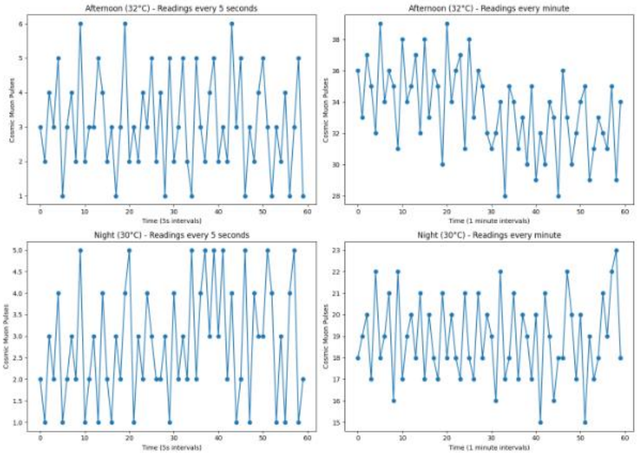

Figure 3.1: Matplotlib graph of cosmic pulses Vs time interval

In Figure 3.1, the y-axis denotes the number of cosmic muon pulses detected. On the other hand, the time interval is given by the x-axis. This graph helps us understand the significance of the light from external sources (e.g., sunlight) that influence our readings. Despite the photodiode being placed in a light-proof container, the sunlight in the afternoon (12 pm) did influence the readings taken, as observed by the stark contrast in the number of cosmic pulses detected at night (9 pm). This indicates that our Arduino setup had misinterpreted nearby light signals as cosmic pulses. Thus, for this setup to accurately detect cosmic muon pulses, it needs to be in a system without external forms of light.

In order to develop a machine learning model to predict the number of cosmic muons detected by the setup after a specific time interval, we would need to bifurcate the readings collected by the experiment into training data and testing data.

Thus, thirty readings were taken from each case to create them into training data. Training Data is a data set for which our model has both x-axis and y-axis values. After writing the Python script using libraries such as Numpy and Panda, the model created is provided with the testing data set (30 other readings for each case).

The following thirty readings act as the x-axis values for the model for which the y-values are missing. The model we created will predict what those thirty readings will be. By comparing the y-axis values in the observation table to those predicted by our model, we can calculate the accuracy of the machine learning model. Usually, a machine learning model utilising data on this small scale uses Linear Regression. However, to increase the model, we have utilised the Random Forest Regressor algorithm. Throughout the different figures (Figure 3.2- Figure 3.5), the average accuracy that we have received is 97.98%.

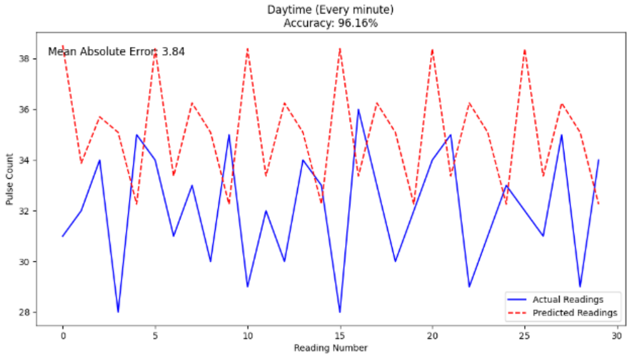

Figure 3.2: Predictive model for Daytime Readings (per minute)

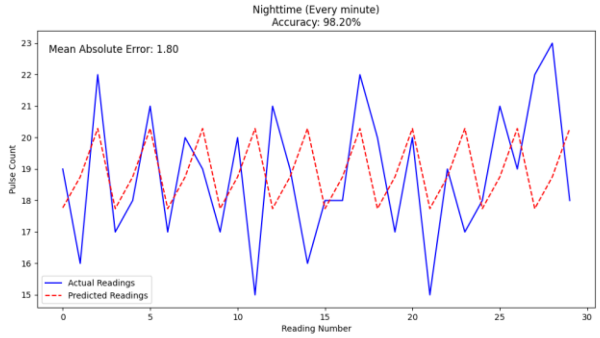

Figure 3.3: Predictive model for Nighttime Readings (per minute)

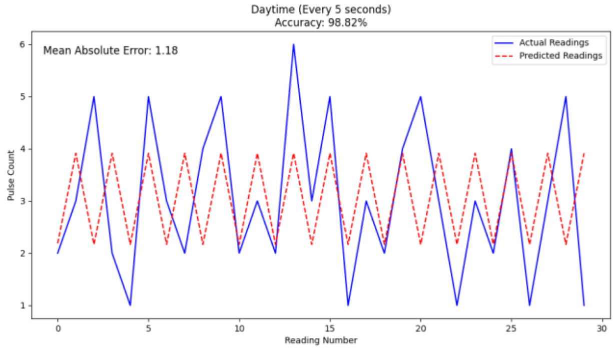

Figure 3.4: Predictive model for Daytime Readings (every five seconds)

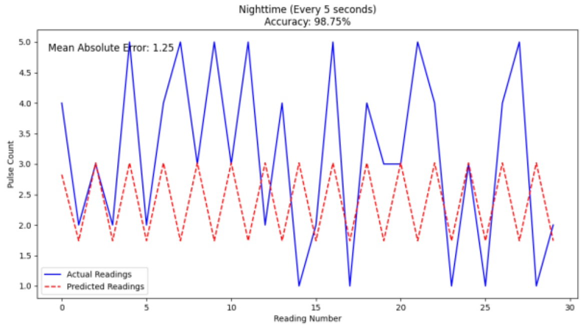

Figure 3.5: Predictive model for Night-Time Readings (every five seconds)

4. CONCLUSIONS

The future applications of this particular setup range from being an educational tool to being a portable device for radiation monitoring. This novel approach to detect cosmic muons could potentially be showcased in educational institutions to explain the key concepts of radiation detection and particles. It provides students with a hands-on approach towards learning scientific concepts. Constructing this setup also involves a student understanding principles of electrical engineering, computer programming and experimental physics. A modified version of this setup consisting of temperature sensors, geiger counter, oscilloscope and a photomultiplier tube could also be used for radiation and environmental monitoring. It could provide useful insights about present atmospheric conditions and variations in cosmic radiation levels.

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