Instrumental Methods in Particle Astrophysics (2022 Spring)
Final Report

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Muons are one of the most common particles in the cosmic shower observed on the ground. In order to observe the cosmic muons, we constructed a simple portable muon counter to record the number of muons passing through the device. To further explore the number of passing muons in different context, we conducted four sets of experiments: (A.) Muon Count v.s Incoming Angle, (B.) Muon Count v.s. Depth, (C.) Muon Count v.s. Altitude, and (D.) Radiation from the Concrete. Useful skills and experiences were learned in the process, and the results of the above experiments qualitatively agree with the predictions of cosmic ray science.

I. INTRODUCTION

A muon (often written as μ in equations) is an elementary particle similar to the an electron. A muon shares most of the physical properties with an electron except that a muon is much heavier, and have a limited lifetime (about 2,200 ns [1]).

Muons are one of the most common particles in the cosmic shower observed on the ground. They are mostly generated from the decayed pions (Eq. (3)), which are generated from the primary particles (often protons) interacting with the air particles (Eq. (1)), or from another pion (Eq. (2)). [2]

$$p + N \to p + N + \pi + \text{others}, \tag{1}$$

$$\pi \to \pi + \pi, \tag{2}$$

$$\pi \to \nu_\mu + \mu. \tag{3}$$

Properties of cosmic muons is highly related to the nature of cosmic showers. First, they are highly penetrative for their relativistically high energy, and can therefore be observed in the buildings, or even in tunnels or caves. Second, the number of the observed cosmic muons is related to the altitude. Theoretically, this number is low on the sea level, increases as the altitude increases, and decreases after the peak at about 15 km. And there are more properties that will be discussed later in this article.

II. METHOD

In order to observe the cosmic muons, we constructed a simple muon counter that records the number of muons passing through the device. Our goal here is to make this device small, portable, easy to use/build, reliable, and durable for field experiments, so anyone with basic knowledge and tools can build and operate this device at their demand.

A. Geiger–Müller Tube

The Geiger–Müller tubes (GM tubes) are responsible for detecting the passing muons. A GM tube is consist of a metal wire in the center as the anode, and a cylindrical metal shell as the cathode. Thin gas is filled into the tube and high voltage is apply to the electrodes. Whenever a charged particle passes by, some gas molecules are ionized and accelerate toward to the electrodes, which causes more gas molecules to be ionized, triggering an avalanche. When the ionized particles reach the electrodes, a detectable current pulse is generated.

B. Coincidence Method

However, GM tubes only tell if there is a "charged" particle passing through, but it may not be a muon. Nucleus, β particles (electrons), and even γ ray interacting with the metal shell produce the same effect as muons do. Hence, a method needs to be used to distinguish muons from others.

The solution is the coincidence method: We arrange two GM tubes in parallel, separated by a few centimeters. Since cosmic muons are very penetrative and travel in relativistic speed, they are the few kinds of particles in cosmic showers that is almost guaranteed to trigger both tubes in a time difference less than 1 nanosecond without being blocked by the metal shell. Furthermore, by the relative positions of the the tubes, we can have a rough idea of where the muons are coming from.

C. Circuits

The circuit of the device is composed of 3 major boards: high voltage (HV) board, analog to digital converter (ADC) board, and counter board. The schematic of the circuits is shown in Fig. 1. In the later version, an Arduino UNO micro controller unit (MCU) and some modules were added. These circuits form the data acquisition (DAQ) system of the device.

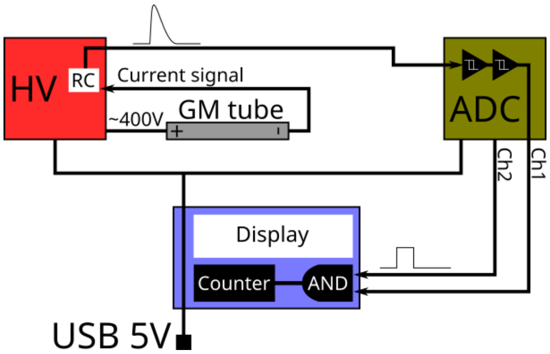

FIG. 1. The schematic of the circuits. The red, green and blue rectangles represent HV board, ADC board and counter board respectively. The power is supplied via USB on the counter board, and distributed to other boards. Note that Ch2 is omitted before ADC board for simplicity.

1. *HV Board*

HV Board is responsible for converting the 5V input voltage to the working voltage of GM tubes at about 400V. This board is made out of a general-purpose printed circuit board.

This board is essentially a DC-DC transformer, mainly composed of a clock and a inductor to pull up the voltage, and a filter to stabilize the output. There is a variable resistor that can control the voltage gain between input and output.

2. *ADC Board*

ADC board is responsible for taking in the analog signals from the HV board, and converting them into digital voltage signal. This board is a home-made single layer printed circuit board (PCB).

When a current pulse is sent by a GM tube, it is passed through a RC circuit on HV board to generate a voltage pulse with proper time length before entering ADC board. On ADC board, the pulse is then fed into 2 consecutive Schmitt triggers to make it a square pulse, which is easier to be processed with digital chips.

3. *Counter Board*

Counter board is responsible for generating the trigger signal by using coincidence method, and keeping the number of the passing muons. The PCB of this board ordered from the company.

This board takes in 2 channels of signal from 2 GM tubes. The signal is passed into an AND gate for the coincidence and output a trigger signal. The number of event is recorded in a counter chip, which is connected to a 3-digit 7-segment LED display to show the current count of the passing muons. The signal from both channels as well as that from the trigger output can also be easily read out for further analysis.

D. Dimensions and Geometries of the Device

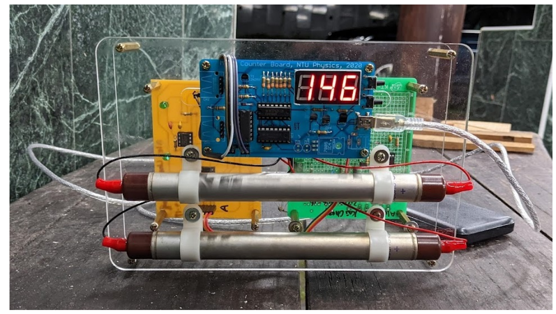

FIG. 2. A photo of our muon counter.

The relevant dimensions of the device should be only the geometry and the positions of GM tubes (supposed that the DAQ system works as expected). The measurement results are listed in Table I.

TABLE I. Fixed dimensions of the Muon Counter

Description	Symbol	Value
Length of a tube	L	20.0 cm
Diameter of a tube	d	2.0 cm
Distance between tubes	D	4.25 cm

The dimensions in Table I are fixed on the frame of the device and *should* be fixed for consistency. However, the device can be oriented to different directions to obtain the muons from those directions. We define the plane on which the tubes lay as the “incident plane”. We then define the angle between the vertical line and the incident plane as the “dip angle (θ)”, and use the projection of the down-going normal vector of the incident plane to define the “orientation”. The visualization of these definition is show in Fig. 3. To sum up, the dip angle and the orientation roughly tell us the “incoming direction” of the observed muons.

III. RESULTS

A. Muon Count v.s. Incoming Angle

1. *Experiment Setup*

In this experiment, the orientation of the device was set to east or west, and we selected several dip angles.

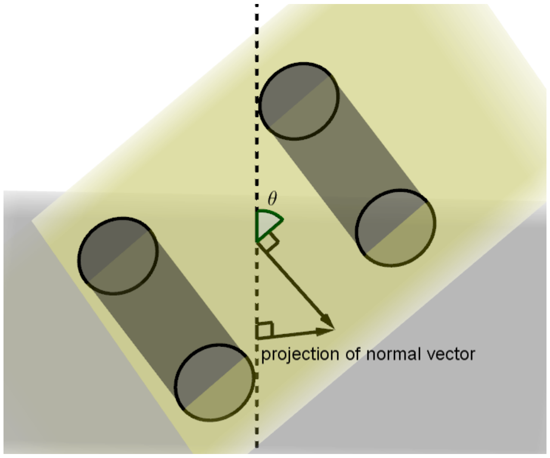

FIG. 3. The spacial relations of incident plane, dip angle and orientation. The cylinders are the GM tubes, the yellow plane is the incident plane, and the dash line is the vertical line. The dip angle is marked as θ, and orientation is the direction of the projection of the normal vector.

The device was moved outdoor to avoid the building from blocking muons.

2. Results

The count rates of different angles at east and west are shown in Fig. 4.

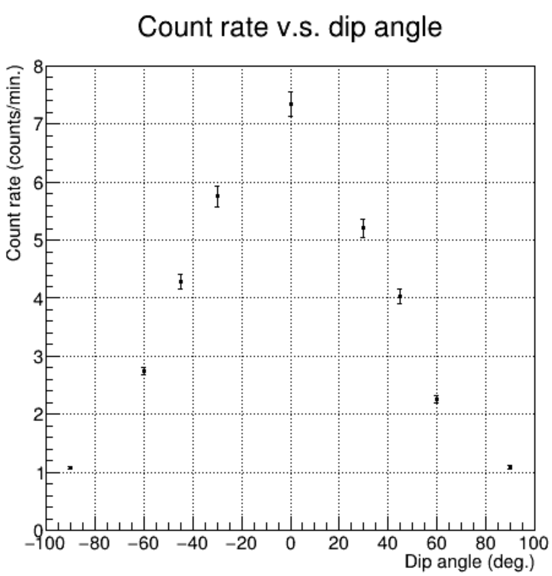

FIG. 4. The muon count rate of different dip angles. Negative dip angle means that the device is oriented to the west, while positive dip angle means that the device is oriented to the east.

From Fig. 4, one can spot that (1) there are more muons from the top than those from the sides, and (2) the muons from the west is slightly more than those from the east. (1) is because the muons from the sides need to go through longer path, which increase the possibility to decay and also lose more energy. (2) is because the geomagnetic field limits the primary particles (usually protons) from entering the atmosphere from some western trajectories, which is referred as "east-west effect".

B. Muon Count v.s. Depth

1. Experiment Setup

The experiment was carried out in Xinhai Tunnel. The device is placed at several locations inside the tunnel, above which the height of mountain can be estimated with Google Earth Pro. The dip angle was set to 0 for all runs, and we oriented one device ("device 1") to be perpendicular to the axis of the tunnel, and another device ("device 2") to be parallel to the axis of the tunnel. The configurations of these 2 setup is shown in Fig. 5

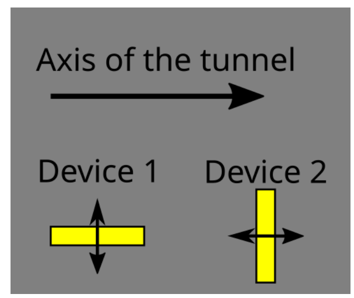

FIG. 5. The configurations of device 1 and 2. The yellow boxes are the top view of the GM tubes, and the arrows are the orientations of the device, by the definition in Sec. II D.

2. Results

The raw data of this experiment can be found in Table II, and the results of count rate verses depth can be found in Fig. 6.

TABLE II. Raw data of the tunnel experiment.

Distance from the entrance	Count 1	Count 2	Time
outside	86	84	10 min.
6.0 m	26	28	10 min.
12.0 m	18	17	20 min.
18.0 m	9	10	15 min.
30.0 m	10	12	15 min.
69.6 m	1	9	10 min.

Unfortunately, the error was very large because we did not have much time collecting data, especially when the counts dropped rapidly as we went deep into the tunnel. Also, the estimation of depth could be off due to

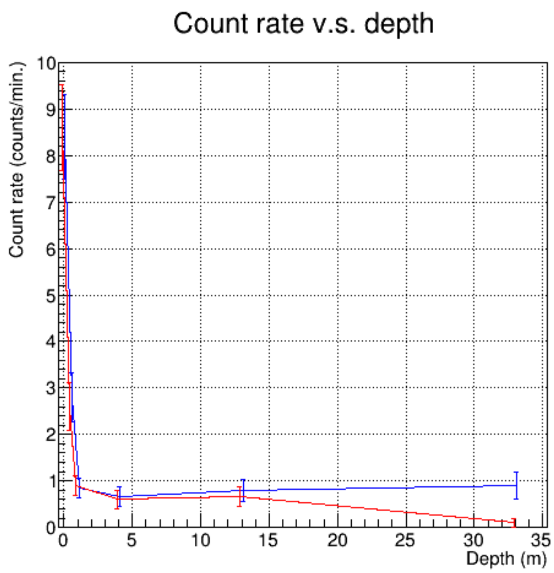

FIG. 6. The graph plotted from Table II. The red curve is data from device 1, and the blue curve is the data from device 2. Note that the 2 curves are slightly separated along x axis to avoid overlapping, but the 2 devices are actually placed next to each other.

the limitations of Google Earth Pro. However, the fact that count rate dropped rapidly as soon as we enter the tunnel is a good demonstration of muons attenuating in materials.

After fitting the data inside the tunnel with exponential function

$$y = Ce^{-x/\gamma}, \tag{4}$$

where C is a constant, and γ is the average attenuation length in soil. Then we can further calculate the average material depth (range) a muon is able to penetrate (assuming the density of the soil is 2 g/cm^3). The results are shown in Table III.

TABLE III. The fitting results.

Setup	C	γ	Muon range
Device 1	7.3 ± 3.5 min $^{-1}$	48 ± 15 cm	96 ± 29 g/cm^2
Device 2	9.1 ± 4.2 min $^{-1}$	42 ± 11 cm	84 ± 22 g/cm^2

Compared to the suggested value for muon range 553.4 g/cm^2 [3], it was off by a large amount. We think that is due to the low statistics and limitation of observation time.

C. Muon Count v.s. Altitude

1. *Experiment Setup*

This experiment was done on several spots on Southern Cross-Island Highway (Nanheng) in Taiwan. The device was kept inside the car to avoid the rain and moist. The dip angle was arranged to as close to 0 degree as possible, and the orientation was set to east-west direction. The time of each experiment was depend on how long we parked the car there.

2. *Results*

The results of this experiment can be found in Table IV and Fig. 7. However, since we didn't plan to stop at many spots and the weather was turning bad later in that afternoon, there are only 3 data points, which could not provide us enough statistics for any significant quantitative analysis.

TABLE IV. The Results of Experiment on Nanheng. The "Milepost" column is Taiwan Provincial Highway No. 20 mileposts near the locations of experiments. The unit of the count rate is counts/minute. The rows are sorted by their altitudes.

Location	Milepost	Altitude	Count rate
Ground	N/A	~ 0 m	7.34 ± 0.20
Shan-Iang Police Station	154.5 km	2,345 m	12.98 ± 0.18
Mt. Taguan Trailhead	33.2 km	2,580 m	14.44 ± 0.29
Yakou	147.5 km	2,722 m	16.10 ± 0.42

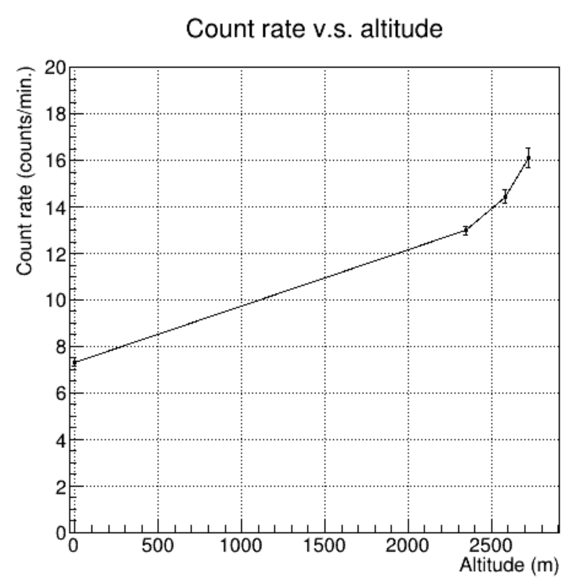

FIG. 7. The graph plotted from Table IV.

As we can see, the count rate of muons increases as the altitude increases. Also, compared to the counts on sea level (about 8 counts/min.), those in the mountains are much higher. This is, to some extent, a reproduction of Hess' hot air balloon experiment done about 100 years ago [4].

In addition to that, the lifetime of muons can also be estimated. Since we have calculated the average material depth of muons in Sec. III B, and we have the approximated air density

$$\rho_{\text{air}} = 1.02[\text{g/cm}^3]e^{-h/8[\text{km}]} \times 10^{-3}, \tag{5}$$

it is possible to consider both muon decay and muon absorption in the air.

We made the following assumptions in our calculations: (1) Cosmic muons are created at 15 km above sea level, (2) muons have approximately 1 GeV energy, and (3) muons have average lifetime τ and muon range R. Therefore, the count rate at altitude h is

$$y = Ce^{-\frac{\int_h^{15[\text{km}]}\rho_{air}dh}{R}}e^{-\frac{15[\text{km}]-h}{c\gamma\tau}}, \tag{6}$$

where gamma is the boost of muons, which is about 10 for 1 GeV muons.

Unfortunately, we obtained negative muon lifetime with the muon range we calculated in Sec. III B. However, with the suggested value $R = 553.4\text{g/cm}^2$, we managed to get the result: $\tau = 3.53 \pm 0.40\mu\text{s}$, which is at the same order compared to the suggested value $\tau = 2.19\mu\text{s}$ [5].

D. Radiation from the Concrete

In this experiment, we would like to explore one of the most common radiation source in our daily life - concrete. Concrete is composed of aggregate and glued together with cement and water. Aggregate is usually sand, gravel, or even slag, and the radiation level of the aggregate is one of the many factors that affect the mechanical properties of the concrete [6].

1. Experiment Setup

We replaced the AND gate to an OR gate to count the *total number* of charged particles passing by. The dip angle was set to 90 degrees, and the device was placed on 3 spots: next to the concrete wall, next to a wooden door, and outdoor.

2. Results

The time-accumulated counts is showed in Fig. 8, and the average values are listed is Table V.

This result shows that there is more radiation indoor than that outdoor, and the walls have contribution to the radiation. In this case, we observed about 10% more radiation indoor, and about 3% more next to a wall.

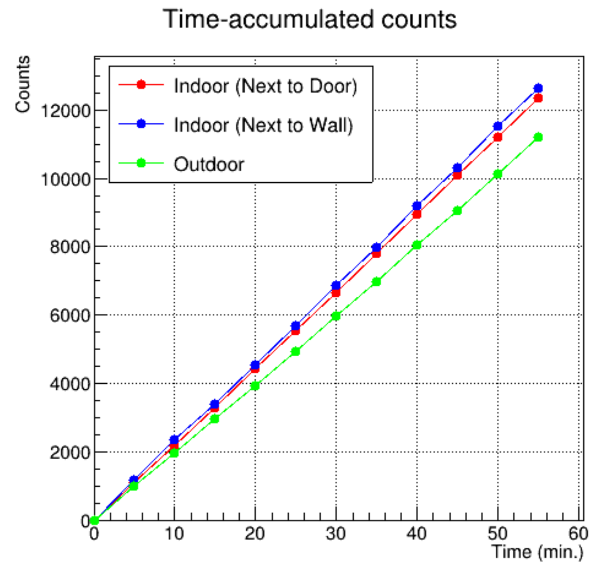

FIG. 8. Time-accumulated counts at different locations.

TABLE V. The time-averaged counts at different locations. The unit of count rate is counts per minute.

Location	Counts at 55 min.	Count rate
Indoor (next to door)	12,329	224.16 ± 2.02
Indoor (next to wall)	12,637	229.76 ± 2.04
Outdoor	11,212	203.85 ± 1.93

IV. CONCLUSION

In this project, we built a portable muon counter and carried out several experiments to verify the knowledge learned from the classes or from other sources. We verified the angular distribution and the east-west effect of cosmic muons, we observed that the cosmic muons can be blocked by a few meters of soil inside a tunnel, we found that there are significantly more muons at high altitude, and we also modified the device to detect the radiation from the concrete. Our results qualitatively agree with the prediction.

In addition to the knowledge of cosmic ray science, precious skills and experiences were also gained in the process. We learned how to use tools like drills and soldering iron, and learned how to debug when there is a problem. We also learn some basic data analysis and error estimation.

In conclusion, this project was a great experience of the basic experimental astrophysics.

ACKNOWLEDGMENTS

First and foremost, we would like to thank Prof. Jiwoo Nam for organizing this class project for us to explore field of cosmic ray by our own hands. He provided us

FIG. 9. The authors of this report and their device. Chen is on the left and Cheng is on the right.

the essential knowledge and the materials to build and operate the device, and kindly helped us when we ran into problems.

Besides, the (unofficial) teaching assistant, Chung-Yun Kuo, helped us assemble the device when Prof. Nam was busy. He gave us precious suggestions on how to assemble and debug our device faster, and taught us how to properly use electrical tools.

I would also like to thank Hec Lam and Chin Zhe Tee for cooperating with us and sharing their data in the tunnel experiment (Sec. III B). We had a good time discussing and conducting the experiment in the noisy and sultry tunnel. Also, special thanks to Chin Zhe Tee again for arranging the purchase of GM tubes online.

Thanks again to anyone who help us during the project!

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