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Investigate cosmic rays: Analysis of the air showers

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Abstract: In this lab report, the concept of cosmic rays and their components that can be detected on the earth's surface is introduced. In this experiment, four CosmicWatch muon detectors were used to detect the components of cosmic rays. This report describes the setup of the experiment as well as the method and algorithms used to filter the true signals of cosmic rays out of the background radioactive noises. Some process of the algorithm is visualized using histograms. The rate of air showers was found to be 0.151 mHz ± 0.022 mHz for a separation of 6.73 cm ± 0.08 cm, and 0.096 mHz ± 0.015 mHz for a separation of 13.5 cm ± 0.1 cm. Other sources of uncertainties are also analyzed in this report.

1. Introduction

The study of cosmic rays has been an important aspect of particle physics since the discovery of cosmic rays by Victor Hess in 1912 [1]. It is not yet possible to build observatories based on image-forming optics due to various detection problems. For example, the integration time of detectors can be too long to distinguish cosmic rays from noises [2]. Thus, there are several ways to observe cosmic rays from other aspects, such as scintillation detectors and Air Cherenkov detectors. For our experiment, we use what is called the Cosmic Watch Muon detector, which can be taken as a kind of scintillation detector.

Developed as a portable device, the Cosmic Watch muon detector has become a valuable tool in Astro / particle research applications [3]. In this case, it is used to detect cosmic rays, which are composed of high-energy relativistic particles that originate from the sun or outside the solar system. The two main instruments within Cosmic Watch detectors performing the function of detection are photomultipliers and scintillators. When charged particles pass through a scintillator, they deposit energy and thus produce photons. The photomultiplier then converts the photons captured into electrical signals, which can be recorded by the detector.

In this experiment, we tried to detect the muon component of cosmic rays using Cosmic Watch muon detectors. By setting up different configurations of the detector system, we can filter the background radioactive noises and observe particles with different incident angles. Another goal of this experiment is to develop a method to synchronize all detectors in the detector system, to provide a comprehensive measurement.

2. Theory

The main components of cosmic rays are ionized hydrogen and helium nuclei, with the former being the dominant component [4]. These particles being relativistic means that they have a speed close to the speed of light, hence their large kinetic energy. However, high-energy cosmic rays undergo a series of energy losses including GZK cutoff, which is caused by energy loss due to the interactions with the CMB (cosmic microwave background), and effects of the solar wind and the geomagnetic field of the earth, hence that the primary cosmic rays reaching the upper atmosphere cannot exceed the energy limit of 10^6 GeV [5][6]. As the primary cosmic rays collide with the atmosphere, nuclear collisions happen due to their high energy, producing mesons like pions and kaons [7]. While the neutral meson would decay into photons, the charged meson would decay into neutrinos and highly penetrative muons, which do not lose much energy besides their ionization when they pass through a variety of materials [8][9]. With a mean lifetime as short as 2.197 μs, muons would also decay into electrons, positrons, and neutrinos. Yet a muon with sufficiently high energy would travel fast enough to reach the sea level considering the time dilation before decaying. As calculated, the time for a muon to travel from where it is created (an altitude of 15 km) to sea level is about 5.5 μs in the frame of the muon. Thus, there is only a reduction by a factor of 10 in the sea-level flux of muons [10]. In addition, electrons and positrons, which are less penetrative, would be easily blocked by solid-like concrete walls in buildings, and thus cannot be the dominant particles we detected. In summary, when cosmic rays enter the Earth's atmosphere, they interact with air molecules, resulting in proton scattering. The protons scatter into pions, which then decay into muons [11].

By indirectly measuring the energy of photons released in ionization, only charged particles can be detected when passing through the scintillators inside Cosmic Watch detectors [12]. Heavy-charged particles are rarely observed due to their special interactions with various scintillators [13]. Thus, the most commonly detected particles are high-energy charged particles including electrons and muons in this experiment. The data was taken indoors, hence most of the particles detected were muons. The background radioactive noises which include the alpha, beta, and gamma decay are the most common signals that are detected. We need to find the actual signals from cosmic rays out of the background noises.

3. Methodology

The experimental apparatus consists of 4 Cosmic Watch Muon Detectors shown in Figure 1.

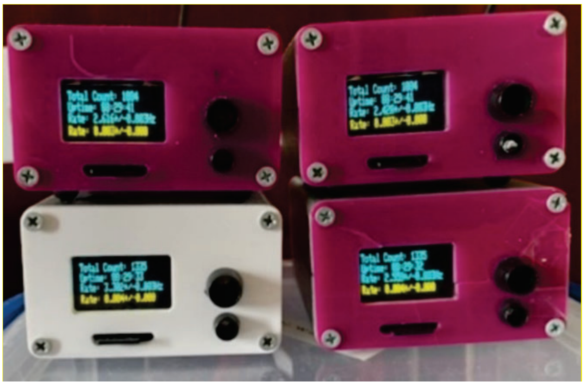

Figure 1: The 4 Cosmic Watch detectors used in this experiment.

The Cosmic Watch detector will record an event when it detects high-energy charged particles, which can be muons, electrons, and other radioactive background noises. One main function of the device is that two detectors can be connected using a cable. When a signal is detected by both detectors that are connected within a short time window, they will report a coincidence for that event. This could happen when one particle passes through two detectors, or it is a real coincidence between two different particles. The main data we need from the detectors are the index of the events, the timestamp, and the coincidence number, which indicates whether it coincides with the other detector.

The first step we did was to filter muons from the background noise. To achieve this, we used two detectors, one on top of the other, and connected them. Hence when a particle passes through both detectors in a short time, we consider it to be a muon. Also, the path of muons coming from the atmosphere is more likely to be vertical. The overall angular distribution of muons at sea level is approximately $I_0\cos^2\varphi$, where φ is the zenith angle and $I_0 \approx 70\ m^{-2}\ s^{-1}\ sr^{-1}$ is the flux at θ = 0 [8]. Hence a large percentage of muons would be able to pass through both detectors. That is, we can only look at the data with the presence of coincidence. The detector was run for 12 hours in this step.

Next, we wanted to filter the signals for air showers. We used four detectors that were built as in Figure 1. The top-left detector is connected to the top-right one. The bot-left detector is connected to the bot-right one. We expect that air showers will travel through the four detectors at the same time. However, we cannot connect more than two detectors. Hence, we need to find an algorithm to filter the events where four detectors coincide.

Known that two detectors on the top are connected, the same as the bottom two. Hence, we know that when a coincidence happens, it is either a muon traveling horizontally or an air shower. What we need to do now is to search for the air showers in the coincidence data. Consider the timestamp of coincidence on the top as t_i, at the on the bottom as b_j. Note that the index i and j are different. We can generate a new sequence d_{ij} by taking the difference: $d_{ij} = t_i - b_j$.

Note take the sequence has the length $i \times j$. Ideally, for d_{ij} that is small enough, t_i and b_j are possibly the timestamps for the same particle.

The main problem is, there is a time offset between two detectors. The two detectors on the top might record an air shower at 1000 ms, but the same air shower might be recorded at 9000 ms by the bottom detectors. This happens when the detectors at the bottom are turned on 8 seconds earlier than the top detectors. Also, the clock in the detector can deviate over a long time, hence the time offset is time-dependent. We can find the time offset by plotting a 2D histogram, where the y-axis is the difference d_{ij}, and the x-axis x_{ij} is generated by $x_{ij} = i$. Note that x_{ij} also has the length of $i \times j$.

Now we can find the function of the time offset $O(t)$ over time. Hence, we can find the adjusted t_i by using $t_i' = t_i - O(i)$. The new time difference is $d'_{ij} = t'_i - b_j$, hence for all d'_{ij} that is small enough, it is an air shower. This can be visualized using a histogram which is shown in the result section. The 4 detectors were run for 88 hours.

For the next setup. Based on the setting in Figure 1, we increased the distance between the left and right detector to the width of 1 detector. Other settings remained the same. We used the same method to find the air showers in this case. The detectors were run for 113 hours.

4. Result and Analysis

4.1 Result

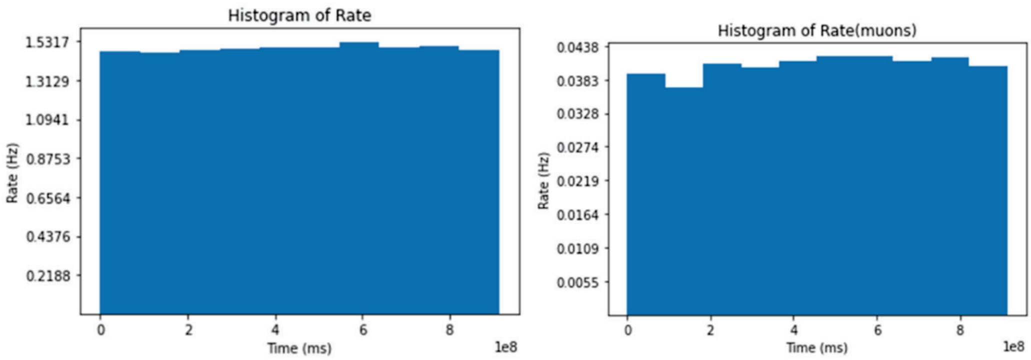

Figure 2: The rate histogram for all signals (left), for muons (right). The x-axis is time in ms. The y-axis is the rate in Hz.

We filtered the muons out of background noises first and made 2 histograms for comparison as in Figure 2. We observed that the detection rate of the detector is about constant, but the rate varied a little for muon detection, which means that the number of muons detected on the Earth's surface does not need to be constant.

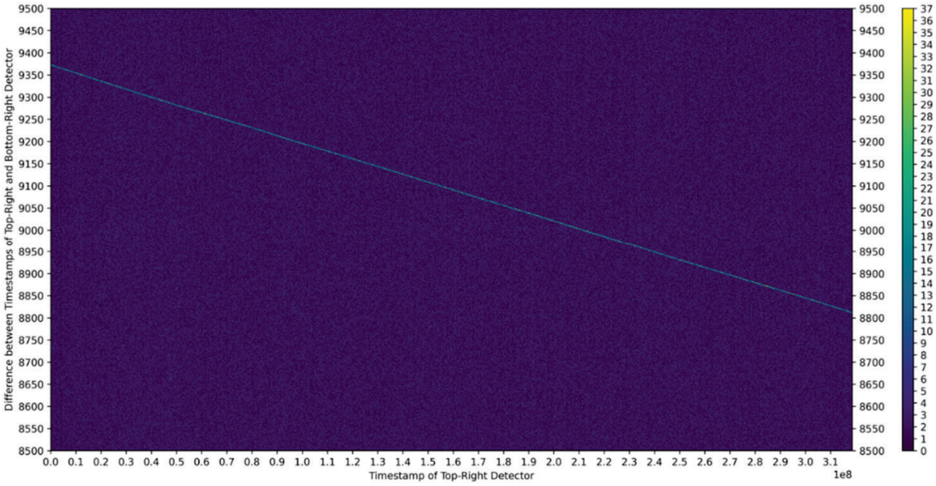

Figure 3: The 2D histogram of the top-right detector and the bottom-right detector in the first air shower detection. The x-axis is the timestamp x_{ij} of the top-right detector in ms. The y-axis is the time difference d_{ij} in ms. The green line is the function of time offset $O(t)$.

For the first air shower detection, we used the 2D histogram to find the time offset between the top and bottom detectors. Figure 3 is a sample 2D histogram for the top-right detector and bottom-right detector. We observed a straight line in the graph which means the function $O(t)$ is a linear function over time.

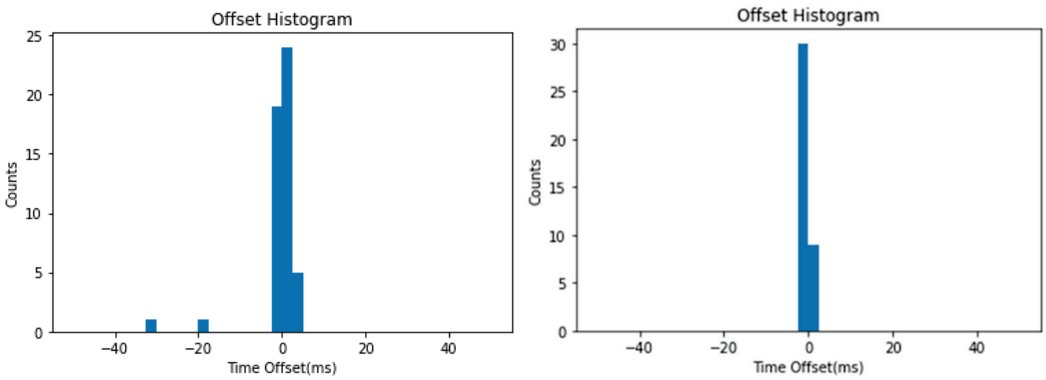

Figure 4: The histogram of the adjusted time difference d'_{ij} for the first air shower detection (left), and the second air shower detection (right). The x-axis is the time offset in ms. The y-axis is the number of counts. The bin width is 2.5 ms.

Note that for d'_{ij} that is small enough, it is an air shower. By Figure 4, we claim that for $d'_{ij} < 5\,ms$, it can be considered as an air shower. Hence in the first air shower detection, there were 48 air showers detected in 88.5 hours. The rate is 0.151 mHz ± 0.022 mHz. In the second air shower detection, there were 39 air showers detected in 113 hours. The rate is 0.096 mHz ± 0.015 mHz. Remind that in the first air shower detection, the detectors on the left and right are contacted. In the second air shower detection, they are separated by the width of one detector. The width of the detector is 6.73 cm ± 0.08 cm.

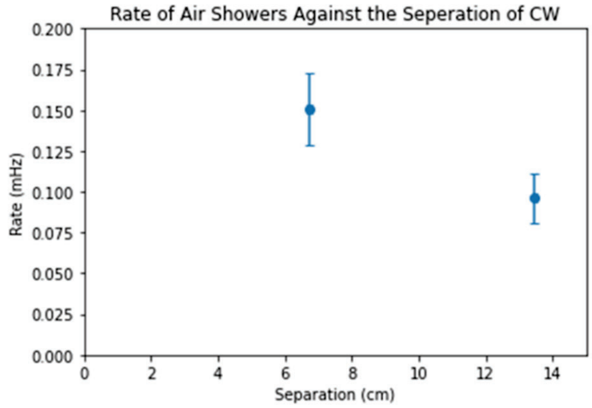

Figure 5: The rate of air showers against the separation of CosmicWatch detectors with error bars. The x-axis is the separation in cm. The y-axis is the rate of air showers in mHz.

Note that in Figure 5, we can see that the rate lies outside of each other's uncertainties. Hence, we conclude that the change in the separation of muon detectors will affect the rate of air showers.

4.2 Uncertainty analysis

Note that independent counting follows Poisson distribution, where the standard deviation is simply the square root of the number of counts. Hence the number of air showers with uncertainties should be 48.0 ± 6.9, and 39.0 ± 6.2.

The other uncertainty is that there might be a real coincidence instead of an air shower in the detection. We need to calculate the rate of coincidence, that is $R = 2N_1N_2\tau$. N_1 and N_2 are the rate of coincidence for the 2 detectors, and τ is the coincidence window, which we set to be 10 ms. Both N_1 and N_2 are at about 10^-9 Hz. Hence the rate is too low to be considered.

The insufficiency for this experiment is that in our setup, the detectors can only capture muons or air showers with an incident angle no greater than about 40 degrees. However, we can still analyze the data to observe the trend due to its generality.

5. Conclusion

In conclusion, the Cosmic Watch muon detector can be used to detect single muons and air showers. After analyzing the data given by the detector, we found out that when the horizontal separation of detectors is 6.73 cm ± 0.08 cm, the rate of air showers is 0.151 mHz ± 0.022 mHz. When the separation is 13.5 cm ± 0.1 cm, the rate of air showers is 0.096 mHz ± 0.015 mHz. The plus-minus sign here means 1 standard deviation. Through the observation, the rate of air shower decreases as the separation of Cosmic Watch detectors increases. Since we only have 2 samples, we cannot find the trend. However, we can conclude that the separation of detectors will affect the rate of air showers that are detected. Further analysis of the momentum and radius of air showers can be made with more experiments.

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