Doi: 01.0015/j.Science.2023.06.001

Studies of cosmic ray muons using CosmicWatch portable particle detectors

Zhe Zhang

Research Background

Properties of muon

Muons are unstable subatomic elementary particles that have a half-life of 2.2 μs. A muon has a negative electric charge of *e* and a mass of 105.65 MeV, approximately 207 times as heavy as an electron. However, it is a lepton, which means it does not take part in strong nuclear interaction and can penetrate through materials much better than hadrons and mesons.

Source, Energy, and Interaction

As part of cosmic-ray showers, mons observed at sea level are produced by mesons decaying charged π-meson and K-meson specifically. In contrast, mesons are produced by a collision between primary cosmic-ray particles and the nucleus of atmospheric molecules [1]. Muons produced with sufficient energy are relativistic. With energy greater than 2.4 GeV, a muon can have a speed close to the speed of light, where it may be able to travel to sea level before decaying due to the time dilation effect. A typical cosmic-ray muon has an energy of approximately 4 GeV, where the muon loses energy going through the atmosphere mainly by ionization and excitation of interacted particles. Muons with much higher energy are rare and mostly decay away fast into an electron, an electron neutrino, and a muon neutrino, or their antiparticles.

Factors of muon flux variation

Muon detection rate at the Earth's surface may vary for different reasons. It is mainly brought about by geological factors like the Earth's magnetic field and solar activities and by varying atmospheric conditions such as atmosphere density. Earth's magnetic field can influence the path of charged cosmic-ray particles like muon. Therefore, muon flux is different at different locations on Earth with inconsistent magnetic field strengths and directions. From the perspective of this study, the Earth's magnetic field has a very limited effect on the muon path in the lower atmosphere [2]. Atmospheric density may affect the energy cost for muons to travel to the surface of the Earth. A muon that goes through the atmosphere with a higher density (which increases linearly with pressure or reciprocal of temperature due to ideal gas law) may lose more energy and be less likely to reach the Earth's surface, as it would interact with more air molecules. The relationship is stated in Ref [1].

$$\Delta\, Intensity\, /\, Intensity = \beta\, \Delta\, P \qquad (1)$$

Intensity is the muon intensity, β is a constant, Δ *and P* is the pressure variation. Due to the same reason, a non-vertically incident muon may travel a longer distance and be less likely detected. The relationship between muon intensity and the angle from where the Intensity is highest follows a squared cosine law [1].

$$Intensity(\theta)\, /\, Intensity_{max} = cos^2(\theta) \qquad (2)$$

where θ is the angle to where the muon intensity is highest, *Intensity (θ)* is the muon intensity at angle θ, and $Intensity_{max}$ is the highest muon intensity.

Cosmic-ray showers

Cosmic rays comprise positively charged protons and helium nuclei (alpha particle, 2 protons, and 2 neutrons). When hadrons such as protons go through the atmosphere, they rarely reach the surface of the Earth directly. Instead, they interact with other atmospheric particles. When the protons collide with the nucleus of air molecules, particles such as mesons or more protons are produced. Protons produced secondarily may collide with more nuclei and repeat the hadronic cascade process with enough energy. Neutral mesons produced may decay quickly into protons that lose energy through pair production processes. While charged mesons may either decay into muons or collide with other atmospheric particles and create more muons.

Muon attenuation penetrating through materials

As mentioned, muons penetrate through materials well, as they do not participate in strong nuclear interactions. How much a muon can penetrate depends largely on its energy and the density of the material. For a typical cosmic-ray muon with an energy of around 4 GeV, its energy-decreasing rate is nearly constant, which gives a simple way to calculate the maximal distance it can penetrate through a certain material. The calculation method is $D = E_{muon}/(2.2\ MeV\ cm^{-1} \times \rho)$ as stated in [1], where D is the distance that the muon with energy E_{muon} can penetrate through the material with density ρ.

Experiment Setup and Analysis

Detectors setup

Four muon detectors were built up in two stacks; in each stack, one detector was placed on top of another. The four detectors marked as 1, 2, 3, and 4 were assembled in the arrangement shown in Fig.1. Detailed working mechanisms and instructions of CosmicWatch portable particle detectors used here can be found in Ref. [3].

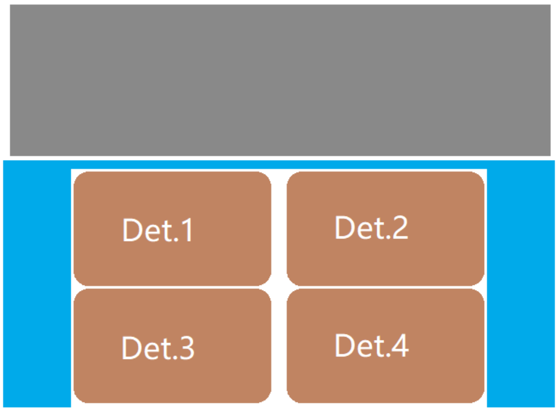

Fig.1. Left: How detectors 1 to 4 were placed. Brown rectangles are the detectors, the blue part placed on top of the detectors is the stand for lead, gray part is the lead added above the detectors. Right: Picture of how the detectors were built up.

As shown in Fig.1, the four detectors were placed horizontally on a flat LEGO plate, with a stand for lead made of LEGO picks above them. Lead bricks with increasing thicknesses were added on top of the stand. Theoretically, the difference in event time recorded between two detectors when muons go through is approximately constant. Therefore, between any two detectors possible for muons to go through, there could be a peak of several recorded events at a certain time difference representing how many muons have passed through the scintillators of both detectors. The rest of the coincidence events recorded with much lower frequencies for all time differences are considered as caused by background ionizing radiation.

Data recording and analysis

The four detectors started recording coincidence events at the same time. Data recorded by each detector were written into one txt file and stored in a micro SD card for analysis. The date, time, and time stamp were recorded for each event, along with temperature and atmospheric pressure.

A CosmicWatch analysis pipeline programmed by Python is used to analyze the data. First, it reads the text data files of any two detectors and uses time stamp data to calculate the time difference of each two events between the two detectors. It then writes a txt file of all the event pairs with a time difference smaller than 2500 ms, with the format of “time difference (in ms), the time stamp for the first event, the time stamp for the second event (both in s), the index for the first event, the index for the second event “ for each row. Sequentially, it reads the output file of the previous chunk and plots the time difference of the event pairs (in ms) vs. event time of one set of data (in s) and a histogram of the time difference. A prominent number of events at a certain time difference is the mark of muons detected. In the following section of the pipeline, a timing correction is applied to the data read in the first step. It finds the coincidence peak position in the first and the last few thousand events and determines a linear correction that moves the peaks in No, of events at a certain time difference to 0. The corrected data can then be plotted into a delta t vs. t graph and delta t histogram. Finally, the coincidence rate of the muon flux detected by the two detectors can be calculated. It is simply the outstanding number of event pairs minus the average number of event pairs, then divided by detection time (measurement duration). Lead bricks were added after each measurement. As stated in [1], how far a typical cosmic ray muon can penetrate through a lead can be calculated through

$D = 4\ GeV / (2.2\ MeV\ cm^{-1} \times 11.3\ g\ cm^{-1}) = 160.9\ cm$ (3)

This research calculated and analyzed the muon flux rates of detector pair 1&3, 2&4, 1&4, and 2&3 with lead thicknesses of 0cm, 5cm, 10cm, and 15cm. Ofdetector pair 1&2 and 3&4 were also attempted to be calculated, but there was no reasonable result, as expected. The muon flux rates at all lead thicknesses were then fitted to an exponential curve and plotted. Furthermore, the muon intensity and atmospheric pressure equation was calculated to prove the ignorable effect of pressure varying to muon rate-lead thickness relation.

Results and Discussion

Data from detector pair 1&3 and 2&4 generated elegant results as expected since they are arranged vertically. Theoretically, the largest number of muons can be detected in the vertical direction, as a muon is more likely to penetrate vertically (in the shortest distance) through the atmosphere. Histograms of the time difference of the event pairs for detectors 1&3 and 2&4 with different lead thicknesses are shown in Fig.2.

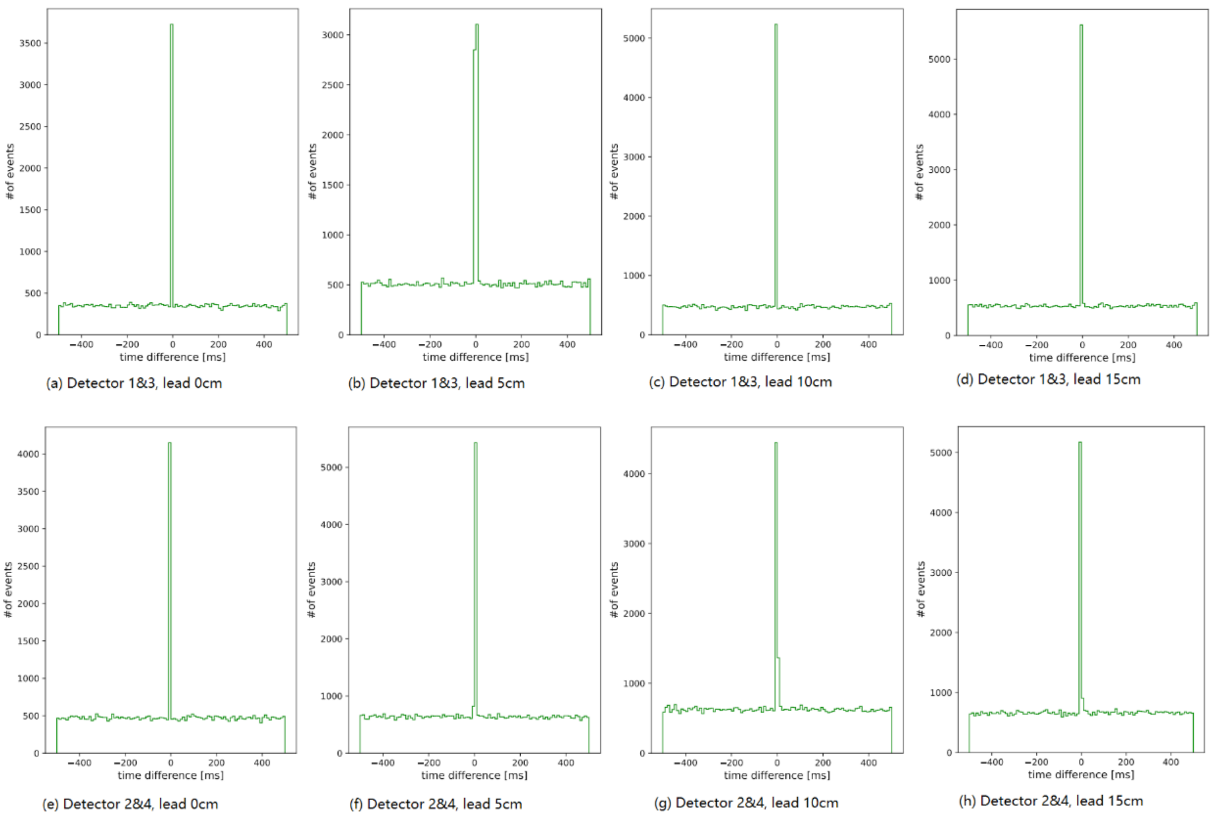

Fig.2. Number of event pairs at corresponding time differences from detectors 1&3 and 2&4 data with a lead thickness of 0cm, 5cm, 10cm, and 15cm.

The uncertainty of the coincidence rate of each muon detection is calculated by, based on the total number of event pairs,

$$\sigma = (1 / \sqrt{N}) \times rate_{\mu} \quad (4)$$

where s is the uncertainty in the coincidence rate, N is the total number of event pairs, and $rate_{\mu}$ is the coincidence rate of muon detection (in Hz). The uncertainties of each detection by detectors 1&3 with 0-15cm lead and detectors 2&4 with 0-15cm lead are [0.00038243, 0.00028746, 0.0002811, 0.00025817, 0.00034359, 0.00025503, 0.00024017, 0.00023067] respectively. These are the absolute uncertainties of the coincidence rate and are considerably small. With these data, the muon flux rate curve can then be calculated. It is fitted into an exponential equation in the form of

$$rate_{\mu} = c + a \times e\hat{}(-\lambda X) \quad (5)$$

where a and c are constants, λ is the exponential decay constant, *and* X is the lead thickness (in cm). The curve of the fitted equation is plotted, as illustrated in Fig.3. The uncertainties of coincidence rates are also plotted in Fig.3 but are too small to be observed.

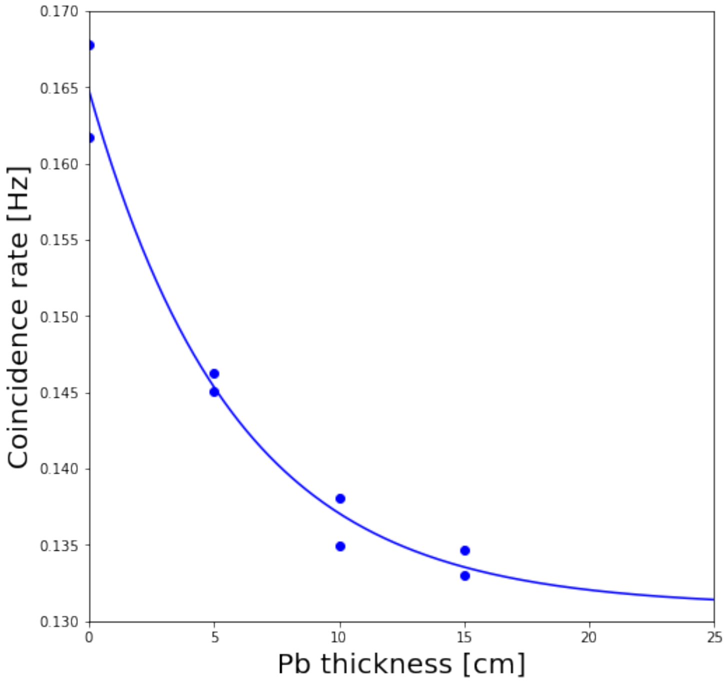

Fig.3. Coincidence rate (Hz) against lead thickness (cm) curve, fitted as an exponential curve. Blue dots are muon flux rates of detectors 1&3 or 2&4 at 4 different lead thicknesses.

It is calculated that a = 0.0338, c = 0.131, λ = 0.171. The curve of muon detection rate against lead thickness is then $rate_\mu$= 0.131 + 0.0338 e^(-0.171X). The exponential decay function concluded is therefore

$$d(rate_\mu) / d(lead\ length) = -0.171 \times (rate_\mu - 0.131) \quad (6)$$

The uncertainties of the coefficients a, c, and l are 0.00322, 0.00303, and 0.0417, respectively. Consequently, the equation for the rate of muon detected at lead thickness X in the given temperature or atmospheric pressure is

$$d(rate_\mu) / d(lead\ length) = -0.171 \pm 0.0417 \times (rate_\mu - 0.131 \pm 0.00303) \quad (7)$$

As lead thickness increases, a clear declination of muon rate can be observed, representing the attenuation of muons going through lead. An asymptote of muon rate at $rate_\mu$ = 0.131 is seen. It is probably due to the space above the detectors that the lead bricks cannot cover. When the incident angle of a muon is large enough, the muon goes through the scintillators of the two detectors without penetrating lead bricks. This effect is small enough as the muon intensity drops rapidly with increasing incident angle. As mentioned, the relationship between muon intensity and the angle from which the Intensity is highest follows the cosine squared law. The muon intensity-pressure relationship was also calculated, with constant β = $-2.31 \times 10^{-3} \pm 8.92 \times 10^{-3}$ Pa^{-1}. Large $P(\chi^2)$ test values between observed and estimated atmospheric pressure of detection at lead thickness larger than 0cm evidenced very little influence of pressure changing during muon detection to muon rate-lead thickness relationship. For detector pair 1&4 and 2&3, the muon rates remained at approximately 0.02 for all lead thicknesses. This is most likely the result of the same reason that caused the coincidence asymptote. For detector pair 1&4 and 2&3, the incident angle required for the muons to be detected by both detectors is larger than that of detectors 1&3 and 2&4, which are stacked vertically. Due to the cosine above squared law, the number of muons detected is much smaller. In addition, the distance of lead the muons need to go through is shorter because of the larger incident angle. Conclusively, it is reasonable to see a low but relatively constant (less affected by lead thickness) muon rate with data from detectors 1&4 and 2&3.

Data from detectors 1&2 and 3&4 were also calculated to find possible coincidence events. Muons produced in the process of the electromagnetic shower may theoretically reach the parallel detectors simultaneously and generate coincidence data for all four detectors. However, there is no valid coincidence rate between the two sets of parallel detectors. Further experiments in different lab/atmosphere conditions may be carried out with the same method.

Conclusion

In the experiment, muon rates are concluded by the detection results of vertical and diagonal detectors. Muon rate in the vertical direction shows an exponential decreasing trend with increasing lead thickness, with equation (7). Muons from directions that lead bricks cannot cover should be considered in future experiments. Still, it has a limited effect on the results as the muon rate significantly lowers when the incident angle increases. A further experiment of determining electromagnetic shower rate was attempted by finding the coincidence rate of parallel detectors, but there was no significant coincidence result.

Acknowledgment

Many thanks to Gunther M. Roland for the help in the experiment setup, data collection, and result presentation. I sincerely appreciate the provision of the experiment apparatus, data calculation pipeline, and advice during the experiment.

Reference

[1] Axani S.N., 2019. The Physics Behind the CosmicWatch Desktop Muon Detectors, MIT.

[2] Oneci C.P., 2022. Experimental study of the muon detection rate dependence on the atmosphere and sky direction using Cosmic Watches, MIT.

[3] Axani S. N., Frankiewicz K., and Conrad J. M., 2018. The CosmicWatch Desktop Muon Detector: A self-contained, pocket-sized particle detector. Journal of Instrumentation. Vol.13, p. P03019.