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Experimental Investigation of Environmental Factors Affecting Cosmic Ray Cascades in a University Laboratory Setting

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Dr. Elena G. Gregg is a Senior Professor of Physics at Oral Roberts University, where she has taught since 2006. She holds an M.S. in Theoretical and Applied Spectroscopy from St. Petersburg State University and a Ph.D. in Optics from the State Optical Institute, Russia . Her research background includes molecular spectroscopy and light–matter interactions, with current scholarly work focused on experimental physics education and cosmic ray cascade investigations in undergraduate laboratory settings. Dr. Gregg is an active member of the American Society for Engineering Education (ASEE) and the American Association of Physics Teachers (AAPT), and she has contributed extensively to advancing physics pedagogy through curriculum development, laboratory innovation, and student-centered research experiences . She has co-authored multiple conference presentations on cosmic ray cascades and experiential learning, and her work has been recognized with an Honorable Mention Best Paper Award at the ASEE Midwest Section Conference. In addition to her teaching and research, Dr. Gregg is deeply engaged in service, including curriculum advisory roles for the Oklahoma Office of Educational Quality and Accountability and mentoring undergraduate engineering and pre-med students. Her recent work integrates environmental factors into cosmic ray detection experiments, enhancing hands-on learning in modern physics laboratories.

Pavel Navitski, Oral Roberts University

Dr. Pavel Navitski is Associate Professor at Oral Roberts University from 01/2020 after a stint as a Fulbright Visiting Scholar at Oklahoma State University, where he was researching drift detecting using sensor systems for field spraying and guest lecturing. He is originally from Belarus, where he was the head of the department of agricultural machines at the Belarusian State Agricultural Academy. The Belarusian State Agricultural Academy is where he earned his B.S., M.S. and Ph.D. degrees. Dr. Navitski's professional interests are mostly in modern agricultural machinery: setting the main types of agricultural machines for quality work; device features of configuration of new agricultural machinery; perspective cropping systems; precision agriculture; modern machines for chemical plant protection; renewability and bio-energy. He represents Oral Roberts University at ASME and Tulsa Engineering foundation.

Wesley David Klehm, Oral Roberts University

Wesley is from Tulsa, Oklahoma, and is 20 years old. Since he was a kid, he was always interested in how things worked and how they were made, with many disassembled toys to prove it. This curiosity inspired Wesley to pursue a degree in engineering to further satiate this desire. In 2021, Wesley Klehm and Jordan Swan founded Esque Box while students at Oral Roberts University to teach a new generation of kids what they wished they knew at the same age.

Gabriel Pendell, Oral Roberts University

Gabriel Pendell is a senior studying mechanical engineering at Oral Roberts University and will graduate with a bachelors of science in engineering in May. Afterward, he will continue to graduate education at the University of Illinois. His research interests include manufacturing processes, thermal-fluid systems, and combustion.

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Abstract

The Advanced Physics course is designed to prepare students for careers in engineering and research by integrating hands-on, adaptable laboratory projects relevant to applied physics and engineering disciplines. A central component of this curriculum involves a student-led investigation into cosmic ray cascades, emphasizing the detection and characterization of muons—massive elementary particles analogous to electrons, generated through high-energy interactions between cosmic rays and atmospheric molecules.

This research represents the latest phase of an ongoing experimental series exploring cosmic ray cascade phenomena. Previous phases optimized detection methodologies by calibrating steel plate thickness to enhance cascade visualization and by mapping the angular distribution of muons under varying geometrical configurations. The current phase focuses on quantifying the effects of environmental parameters on cascade formation and muon detection. Students conducted systematic measurements correlating cascade frequency and intensity with atmospheric temperature, pressure, and meteorological conditions using an optimized detector array (11 plates inclined at 70° toward the northern horizon).

Preliminary results suggest that environmental variations play a significant role in muon flux at ground level. Elevated atmospheric temperatures correspond to reduced muon counts due to increased meson decay altitudes, while lower pressure conditions appear to enhance muon transmission to the surface. Additional influences, including humidity, solar activity, geomagnetic effects, and altitude, further modulate detection rates.

These findings advance the pedagogical integration of experimental particle physics into undergraduate education, while contributing meaningful data to the broader study of cosmic ray interactions and environmental modulation of high-energy particle cascades [5, 6, 7, 8].

Introduction

The Earth is continuously exposed to cosmic radiation originating from both galactic and extragalactic sources. Early investigations initially assumed this radiation to be purely electromagnetic; however, pioneering experiments in the early twentieth century established that cosmic radiation also includes high-energy charged particles, primarily protons and heavier nuclei. Today, it is estimated that approximately 10–15% of the ionizing radiation at Earth's surface originates from cosmic rays.

A significant secondary product of cosmic ray interactions in the atmosphere is the muon. Muons are charged leptons with a mass approximately 207 times that of the electron and a mean lifetime of 2.2 μs. They are produced primarily through the decay of charged pions and kaons formed when primary cosmic rays collide with atmospheric nuclei. Despite their short lifetime, relativistic time dilation allows muons to reach the Earth's surface in substantial numbers, with an average flux of roughly 10,000 muons per square meter per minute.

Because muon flux is sensitive to both geometric and environmental factors, muon detection provides a powerful and accessible platform for undergraduate investigations in modern physics. This experiment builds on prior work by focusing on how atmospheric pressure and temperature modulate muon detection rates at ground level, while simultaneously reinforcing core concepts in particle physics, statistics, and experimental design

Theory

The Standard Model of particle physics provides the framework for understanding the particles and interactions relevant to this experiment (Figure 1). Matter consists of fermions, leptons and quarks, which interact via bosonic force carriers. In high-energy cosmic ray interactions, quarks and gluons dominate the initial collisions, producing unstable hadrons such as pions.

Neutral pions decay almost exclusively into pairs of high-energy photons, initiating electromagnetic cascades via pair production and bremsstrahlung. Charged pions decay predominantly into muons and muon neutrinos. While electromagnetic cascades are responsible for the "soft" component of cosmic radiation, muons constitute the dominant "hard" component at ground level due to their high penetration depth.

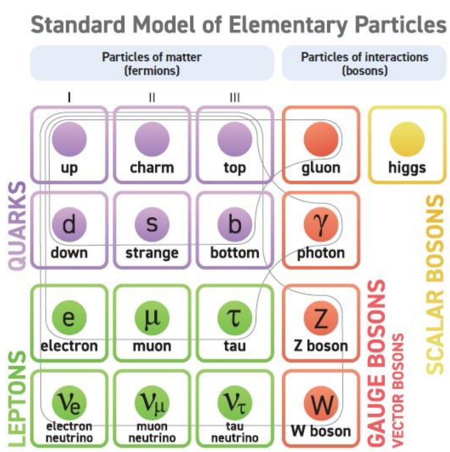

Figure 1. Standard Model of elementary particles [13]

The Standard Model categorizes particles into three groups: bosons, leptons, and quarks. All matters consist of leptons and quarks, collectively referred to as fermions. As shown in Figure 1, there are six types of leptons and six types of quarks. Quarks combine in groups of two or more form hadrons. Familiar examples of hadrons include protons and neutrons, while others, such as pions, exist only briefly under high-energy conditions.

A fundamental principle of the Standard Model is that fermions can only interact and influence one another through intermediary particles known as bosons. These bosons serve as force carriers, enabling interactions between particles. The gluon mediates interactions exclusively between quarks, the W and Z bosons interact only with fermions, and the photon interacts solely with charged particles. Bosons also play a critical role in facilitating the decay and transformation of certain leptons into other leptons.

As noted earlier, some particles can only exist under very high-energy conditions. According to Albert Einstein's mass-energy equivalence principle ($E=mc^2$), the greater the mass of a particle, the more energy is required to produce it. The total energy needed to create a particle is directly proportional to its mass. As high-energy particles lose energy, they decay into lighter particles, transforming their mass into energy while conserving the total mass-energy balance.

Particle	Type (Composition)	Charge	Mass (MeV)	Interactions
Pion	Boson ($u\bar{d}/u\bar{u}/d\bar{d}/d\bar{u}$)	$0, \pm 1$	$139.57/134.9$	Strong, Weak, Electromagnetic
Muon	Lepton	-1	105.66	Weak, Electromagnetic
Photon	Boson	0	N/A	Weak, Electromagnetic
Electron	Lepton	-1	0.511	Weak, Electromagnetic
Positron	Lepton	1	0.511	Weak, Electromagnetic

Figure 2. Information about some of the particles that may be present in this experiment [13]

Most cosmic particles originate as high-energy pions in deep space, undergoing decay into lighter particles as they lose energy.

Pions have a relatively large mass, requiring substantial energy for their production. These particles can be positively charged, negatively charged, or neutral. In this experiment, only the decay of neutral pions leads to the electromagnetic cascades under investigation. Charged pions, on the other hand, decay into muons or muon neutrinos, which account for approximately 75% of the cosmic particles striking Earth. Neither muons nor muon neutrinos contribute to the formation of electromagnetic cascades.

Neutral pions decay into two high-energy photons, known as gamma rays. The electromagnetic cascade begins when a gamma ray interacts with the strong electric field of an atomic nucleus. Despite having no electric charge, the electromagnetic nature of the gamma ray allows it to produce an electron-positron pair in a process known as pair production. This process requires over 1 MeV of energy, as dictated by the masses of the electron and positron (Figure 2). Gamma rays, however, typically carry thousands of MeV of energy, making them well suited for this phenomenon. Once formed, the fast-moving electron and positron can interact with other nuclei, experiencing intense acceleration due to the positive charge of protons. Accelerated charged particles emit electromagnetic radiation, producing additional gamma rays capable of generating new electron-positron pairs. This initiates a chain reaction, with the original gamma ray's energy eventually manifesting numerous particles through repeated cycles of pair production and gamma ray emission (Figure 3).

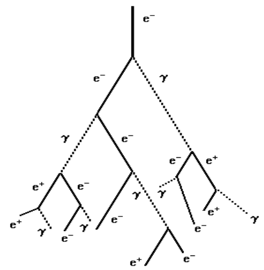

Figure 3. The creation of the electron-positron pair [1]

The cascade slows down when the energy of the electrons and positrons drops below the threshold required generating additional gamma rays. This energy threshold, known as critical energy (E_c), typically ranges from 5 MeV to 30 MeV for most metals [4].

E_c = (800MeV)/ (Z + 1, 2), where Z is an atomic number.

If cosmic radiation consisted of mono-energetic electrons, the number of particles in the resulting cascade would grow exponentially until reaching a maximum absorber thickness, after which it would gradually decrease to zero.

Muons are sometimes referred to as "hard cosmic rays" due to their high penetrating power, enabling them to travel through thick layers of material, such as lead. In contrast, "soft cosmic rays" consist primarily of electrons and other less-penetrating particles, which are easily absorbed by matter. The distinction between hard and soft cosmic rays lies in their differing energies and particle types, which directly influence their ability to penetrate materials.

The precise angular dependency will depend on e.g. the momentum spectrum of the muons at their creation in the upper atmosphere. It is possible under certain assumptions to show that the intensity at the zenith angle θ is approximately proportional to $\cos^2(\theta)$. This dependency could be more "broad-shouldered" (approx. 30% higher values at 45°) and in this case, the exponent on the cosine factor is not necessarily exactly 2 – often a slightly higher value (like 2.16) is seen.

Experiment

The Cosmic Ray Cascades apparatus demonstrates the interaction of cosmic rays with matter, producing a shower of secondary particles [1].

The experiment employed a PASCO Muon Observatory consisting of three Geiger–Müller (GM) tubes, a coincidence module, and data acquisition software. Measurements were conducted in two configurations: Shower Mode and Telescope Mode [1, 2].

In Shower Mode (Figure 4), the GM tubes were arranged in a triangular geometry to ensure that only secondary particle cascades could produce triple coincidences. Steel absorber plates were placed above the detectors to enhance cascade production. Measurements were conducted over ~20-hour intervals for each absorber thickness to determine the optimal configuration.

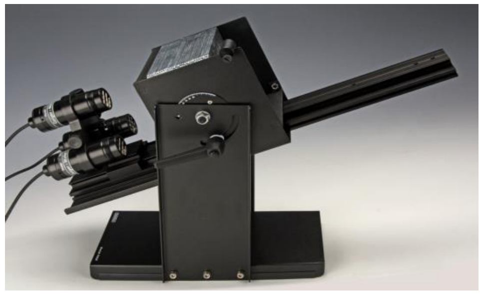

Figure 4. Shower mode setup [12]

For the **Shower Mode** configuration, the muon observatory was aligned vertically, with the absorber plates positioned horizontally. The GM tubes were placed in a special holder with 6–7 cm from the nearest absorber plate. The tubes were connected to the coincidence box, which in turn was linked to a computer running the appropriate software (Figure 5) [2].

In Telescope Mode (Figure 6), the GM tubes were aligned collinearly to measure the angular dependence of muon flux. The zenith angle was varied in 10° increments, and data were collected along both the north–south and east–west directions. Based on earlier optimization, eleven steel plates (total thickness 33.74 mm) were used for extended environmental measurements.

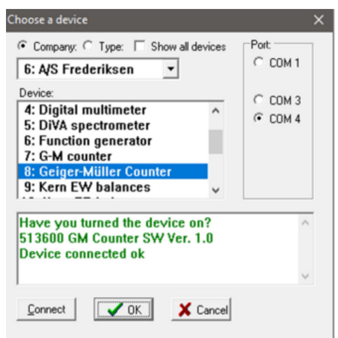

Figure 5. Software setup [2]

To test the equipment, each slide switch on the coincidence box was enabled one at a time, ensuring that LED flashes were generated for each active switch. The absorber steel plates were then removed, and data collection began once the "Datalyse" software was properly installed and connected.

Starting with air, additional absorber plates were placed over the GM tubes, and the coincidence counting rates for all three tubes were recorded. As the thickness of the material increased, so did the number of particle cascade detections. Once the counts peaked, multiple plates were added simultaneously while still measuring the total thickness. The thickness at the peak corresponds to the range of the particles in the shower. Measurement periods were approximately 20 hours.

Ideal conditions for this experiment involve performing it indoors in a one-story building with a thin roof. Although the experiment can be conducted in other environments, such as multi-story buildings with different ceilings or roofs, results may vary. Factors like temperature, barometric pressure, altitude, and time of day can also influence cosmic particle cascade counts. While these variables could be explored in future experiments, they were not considered in this study.

A potential concern is the possibility of the three Geiger tubes being triggered simultaneously by three particles not originating from a cascade (random coincidence r_R). However, Peter Dunne of Preston College in Lancashire, UK calculated the probability of such an occurrence to be 5×10^{-7} per hour of operation. This indicates that accidental detections are highly unlikely and should not be a significant concern [1].

$r_R = K \bullet r_A \bullet r_B \bullet r_C \bullet \tau^2$, where r_A, r_B and r_C are the count rates for the three inputs, τ is the pulse width (10-6 s), and K is a constant in the order of magnitude 1 (that depends on experimental details). With count rates for the individual inputs in the order of 0.5 s^{-1}, a random coincidence will happen once every 10^5 years.

The intensity of muons at the Earth's surface depends on the zenith angle θ. Under simplifying assumptions, the muon intensity is approximately proportional to $\cos^n(\theta)$, with $n \approx 2$–2.2 depending on the muon energy spectrum and atmospheric conditions. This angular dependence arises from the increased path length through the atmosphere for inclined trajectories, which enhances decay and interaction probabilities.

In the second part of our experiment, we explored the angular dependence of muon incidence by positioning the three GM tubes in Telescope Mode (Figure 6). The students adjusted the Zenith angle of the apparatus to identify the angles that would produce the highest number of cascade events. Measurements were taken over several weeks, varying the angle from 0 to 180 degrees in 10-degree increments. Data was recorded along both the North-South and East-West directions. The experiment utilized 11 steel plates, which had been determined in the first part of the experiment to be the optimal quantity for detecting cascade events. The combined thickness of the 11 plates was 33.74 mm. Most muons were detected when the telescope was oriented vertically, while virtually no coincidences were recorded when it was horizontal. Muons may interact with air molecules on their way through the atmosphere and can decay into primarily electrons, positrons, and neutrinos. The muon flux was found to be proportional to $\cos^2(\theta)$, where θ is the angle from the vertical. The GM tubes are positioned perpendicular to the unit's axis, and the distance between the two tubes furthest apart defines the angular resolution. For counting rates, achieving highly precise angles is not necessary.

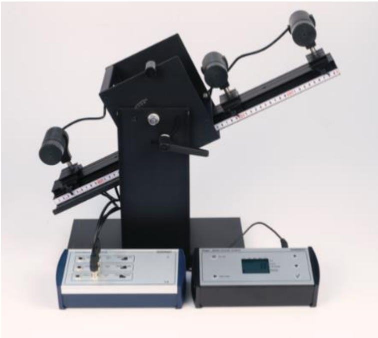

Figure 6. Telescope mode setup [12]

The uncertainty on the zenith angle Δθ is given by the formula: $\Delta\theta = \arctan(D/L)$,

where D is the effective diameter of the Geiger tube (28.6 mm), and L is the distance between the two outermost Geiger tubes.

Plot the count rates on the y-axis and the zenith angle θ on the x-axis with vertical line segments to represent the uncertainty in the count rates. Add horizontal line segments to represent the uncertainty in the zenith angle.

Count Rate as function of zenith angle θ is approximately proportional to $\cos^2(\theta)$.

$R(\theta) = K \bullet \cos^2(\theta)$, where R (θ) is a count rate, θ – zenith angle, K is a constant that will be determined by fitting the data near zero.

Experimental results

In this experiment, we investigated how varying the thickness of the steel plating above the Geiger tubes affected the number of cosmic ray cascades detected. The relationship between the number of steel plates and the number of cascades detected was not expected to be linear. As discussed earlier, cascades are initiated when a gamma ray passes close to an atom's nucleus. By adding steel plating above the detectors, we provided more nuclei for the gamma rays to interact with, thereby increasing the number of cascade detections. However, if the steel plating became too thick, the electrons and positrons produced in the cascades would lose energy, eventually reaching the critical energy level, at which point the cascade would end before it could reach the Geiger tubes. This experiment aimed to identify the optimal plate thickness that produced the highest number of cascade detections.

The summarized results of cosmic ray cascade count as a function of plate thickness are presented in Figures 7 and 8.

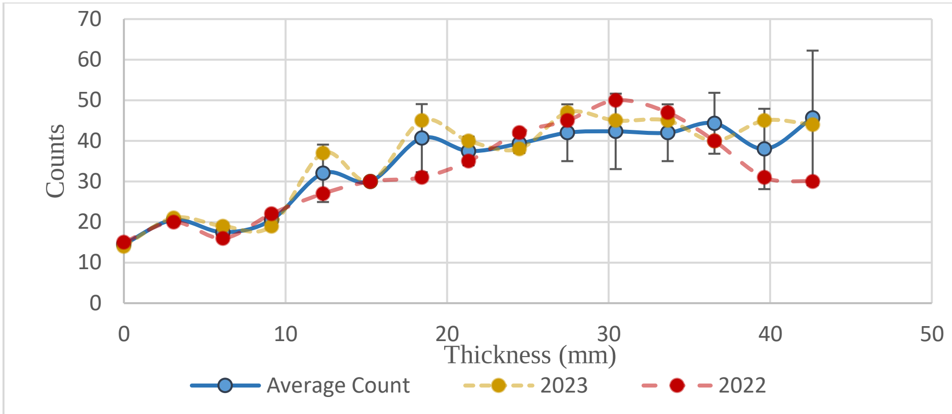

Figure 7. "Box and Whisker" graphs of muon events count vs. plate thickness.

The graph above shows the collected muon data from 2022 and 2023, along with an average line representing the data trends. A "muon event" refers to the simultaneous detection of a muon in all three Geiger-Müller tubes. These events are also referred to as "counts." The red line represents the data collected in 2022, while the gold dashed line corresponds to the data from 2023. The blue line indicates the meaning of all collected data (including reruns of certain 2023 experiments), with whiskers denoting the standard deviation based on the sample size.

"Box and Whisker" plots are a useful graphical tool for displaying the variation within a data set. Unlike histograms, they provide additional insights into data distribution, including locality, spread, and skewness, all within the same graph. The top and bottom of the whiskers represent the extreme data points [3].

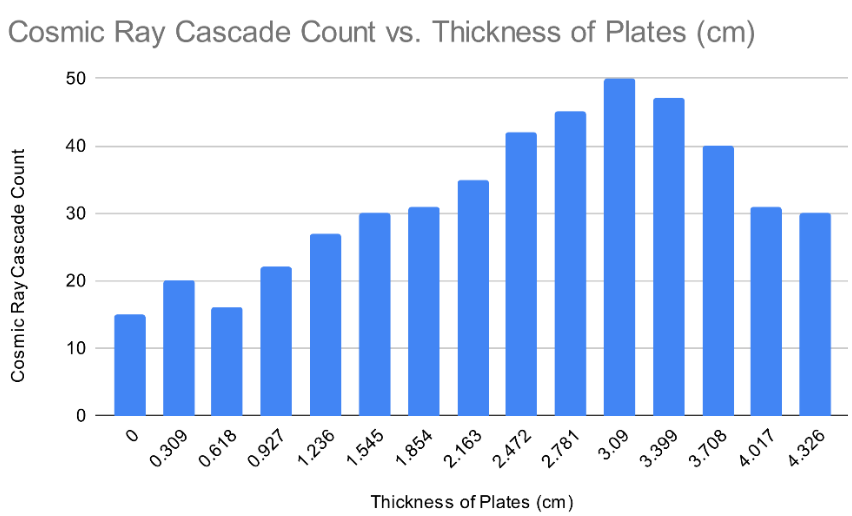

Figure 8. Simplified histogram of muon event counts versus plate thickness.

As shown in Figure 8, the experimental results align closely with the theoretical predictions made by B.B. Rossi [4], who conducted two landmark experiments that significantly advanced the understanding of cosmic rays. Both experiments involved triple coincidences of pulses from three Geiger counters. In the first experiment, the counters were aligned and separated by blocks of lead, while in the second, the counters were arranged in a triangular configuration, ensuring that no single particle could traverse all three counters in a straight line.

The results from the first configuration demonstrated the existence of cosmic-ray particles capable of penetrating up to 1 meter of lead [9, 16]. In the second experiment, with the counters enclosed in a lead box, it was observed that some cosmic rays interact with lead to produce multiple secondary particles. As an extension of this setup, Rossi measured the rate of triple coincidences as a function of the amount of lead above the counters. The plot of this rate against thickness, which became known as the Rossi curve, revealed a rapid increase in coincidence events with increasing lead thickness, followed by a gradual decline [10]. These findings confirmed, as we discussed earlier, that ground-level cosmic rays consist of two components: a "soft" component, capable of generating multiple particle events, and a "hard" component, capable of penetrating great thicknesses of lead.

In our case, the counting rate increased exponentially as the thickness of the absorber material increased. The rate reached its peak at approximately 3.09 cm of steel plating before gradually decreasing.

In the second part of our experiment, we investigated the angular dependence of muon incidence. The results of this experiment are shown in Figure 10. The measured angular distribution of muons was well described by a $\cos^2(\theta)$ dependence. Maximum count rates were observed near the vertical orientation, with negligible rates near the horizontal configuration. These results align with established measurements of atmospheric muon flux.

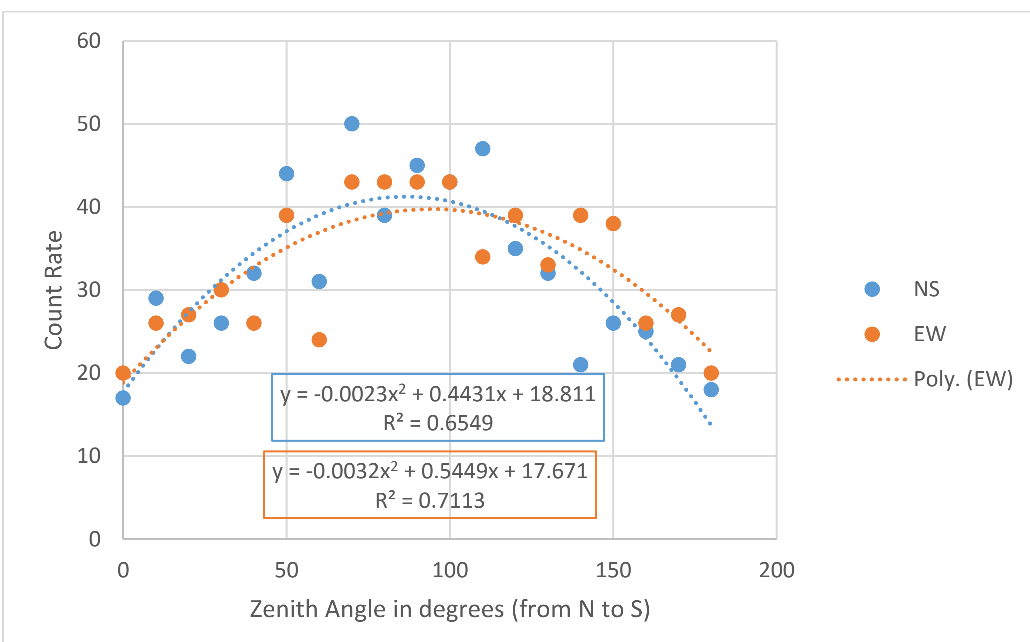

Figure 9. The Count Rates vs. Zenith Angle (θ)

The students concluded that the optimal angle for detecting cascade events was 70 degrees from the northern horizon and between 70 to 100 degrees from the eastern horizon.

The final set of measurements was conducted using a fixed optimal geometry over an extended period. A negative correlation was observed between the count rate and barometric pressure (Figure 10) and positive correlation was observed between the count rate and atmospheric temperature (Figure 11).

A clear negative correlation was observed between muon count rate and barometric pressure. This relationship can be expressed using the barometric coefficient β: $\Delta N / N = -\beta \, \Delta P$, where β is typically on the order of 0.1–0.2% per hPa for ground-level muons. The measured values in this experiment fall within this expected range.

Atmospheric pressure and temperature influence muon flux through changes in atmospheric density and scale height. Increased pressure corresponds to a denser atmospheric column, increasing the probability of muon decay and energy loss before reaching the detector. Conversely, higher atmospheric temperatures cause the atmosphere to expand, shifting meson production to higher altitudes where decay into muons is more likely than interaction, resulting in increased muon flux at ground level [14, 15].

Atmospheric pressure and temperature data were obtained from local meteorological records and synchronized with muon count measurements.

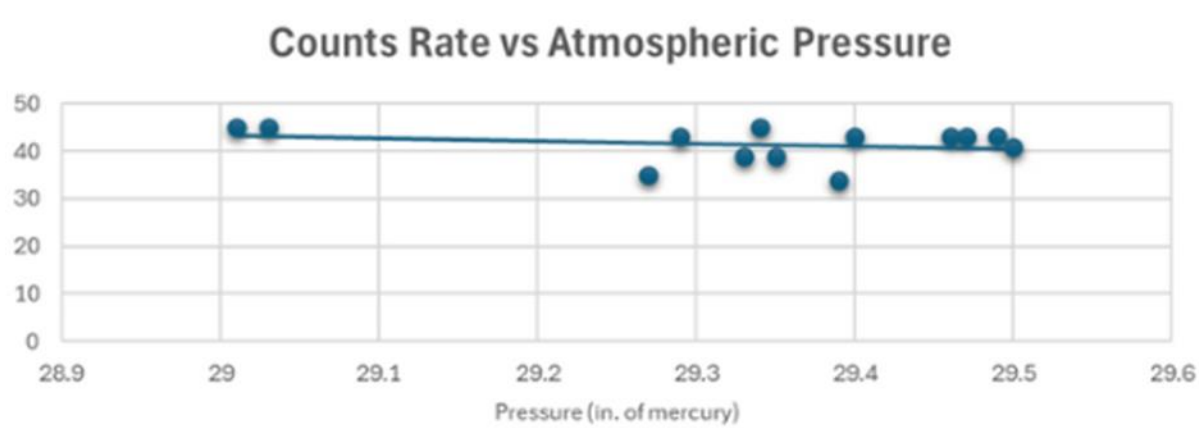

Figure 10. Dependence on Atmospheric Pressure

As atmospheric pressure increases, the muon count rate decreases. Higher pressure means a denser and thicker atmosphere, which increases the probability of muon decay before reaching ground level and enhances the chance of muon interactions (e.g., scattering or absorption) with atmospheric particles.

This effect is often quantified using the barometric coefficient: $\Delta N/N = -\beta \cdot \Delta P$, Where N is the muon count rate, ΔP is the change in atmospheric pressure; β is the barometric coefficient (typically ~0.1–0.2% per hPa for ground-level muons).

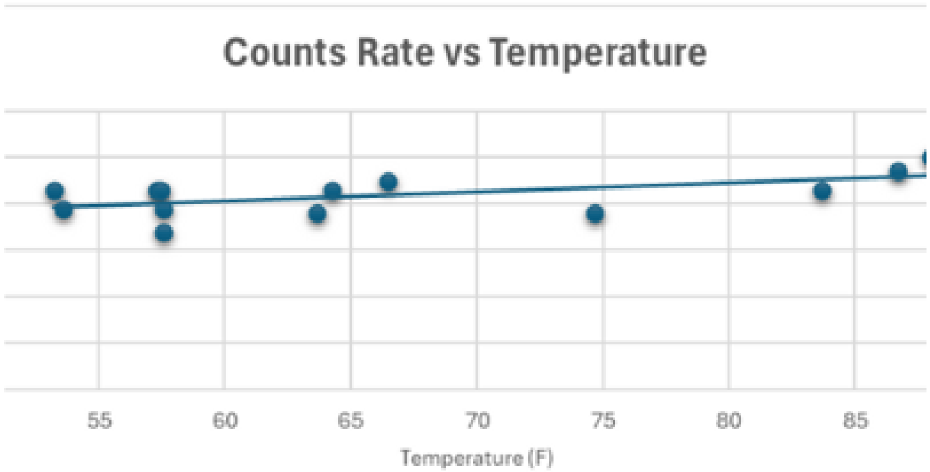

Figure 11. Dependence on Atmospheric Temperature

Higher temperatures cause the atmosphere to expand, raising the altitude at which cosmic ray interactions produce pions and kaons. This results in more mesons decaying into muons rather than interacting, since the air is less dense at higher altitudes. Consequently, more muons reach ground level, increasing the count rate.

This is described by the temperature coefficient: $\Delta N/N = \alpha_T \cdot \Delta T/T$,

Where: α_T is the temperature coefficient (typically ~0.1–0.3 for muons, depending on energy and zenith angle), T is the effective temperature of the atmosphere (a weighted average over altitude, not ground level temperature).

Experimental Limitations and Data Interpretation

Although statistically meaningful correlations were observed, several limitations affected precision.

1. Low Count Statistics. Muon coincidence detection is inherently a low-rate process. Long acquisition intervals reduce Poisson uncertainty but do not eliminate statistical spread.
2. Environmental Coupling Variables. Atmospheric pressure and temperature are not fully independent. Seasonal changes, humidity, and weather systems introduce correlated variation.
3. Detector Resolution and Geometry. Angular resolution is limited by detector spacing and effective tube diameter. Minor misalignments introduce systematic uncertainty.
4. Moderate R^2 Values. Some environmental fits exhibited moderate R^2 values. This is physically expected because pressure effects are small and local meteorological variability introduces noise.

Student Experience and Pedagogical Reflection

A major objective of this project was to provide students with authentic exposure to experimental particle physics.

Students were responsible for:

- Apparatus assembly and calibration
- Software configuration and data logging
- Long-duration data acquisition
- Statistical uncertainty analysis
- Curve fitting and parameter extraction
- Interpretation of non-ideal data

Students encountered real research challenges including instrument drift, background noise, environmental variability, and imperfect correlations. These experiences strengthened understanding of Poisson statistics, systematic versus random error, physical modeling, and scientific integrity.

Conclusion

The PASCO Muon Observatory apparatus provides substantial educational value by demonstrating the existence and behavior of cosmic rays, coincidence detection methods, and the relationship between particle physics, atmospheric science, and statistics.

Scientifically, this investigation confirms that ground-level muon flux is measurably modulated by atmospheric pressure and temperature. The observed anti-correlation with pressure and positive correlation with temperature agree with established cosmic ray physics within expected uncertainty.

Pedagogically, the experiment demonstrates that advanced topics in particle and atmospheric physics can be successfully incorporated into undergraduate engineering laboratories while fostering critical thinking, statistical literacy, and experimental integrity.

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