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BOARD #148: Exploring High-Energy Cosmic Particles: Integration into the Advanced Physics and Experiential Learning for Undergraduate Engineering Students using PASCO Apparatus and Software.

Dr. 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.

Elena Gregg Dr, Oral Roberts University
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.

Exploring High-Energy Cosmic Particles: Integration into the Advanced Physics and Experiential Learning for Undergraduate Engineering Students using PASCO Apparatus and Software.

Abstract.

The School of Engineering has strategically redesigned its Advanced Physics course to address the evolving demands of global education. This initiative equips undergraduate engineering students with essential research skills and practical experiences, fostering their development as competent professionals and researchers in alignment with the university's mission to contribute to the betterment of the human condition.

A cornerstone of the course is the integration of experimental research using the PASCO Muon Observatory. This apparatus enables students to investigate muons—elementary particles with 200 times the mass of electrons—produced by cosmic ray interactions in Earth's upper atmosphere. Students explored the detection of muons and secondary particle cascades by systematically varying the thickness of steel plates atop Geiger tubes. This investigation aimed to optimize cascade detection and analyze the angular distribution of cosmic ray muons.

The results revealed the relationship between material thickness and cascade detection efficiency, offering insights into the behavior of relativistic particles during matter penetration. These findings contribute to understanding particle interactions, inform future research directions, and enhance experimental methodologies.

By embedding hands-on research within the Advanced Physics curriculum, the course enriches students' comprehension of complex physical phenomena while cultivating a passion for scientific discovery [5, 8]. This approach underscores the university's commitment to preparing students for real-world challenges and advancing scientific knowledge [6, 7].

Introduction

At every moment, our planet is continuously bombarded by cosmic radiation originating from within our galaxy and beyond. For centuries, scientists believed that this radiation was composed solely of electromagnetic waves, such as visible and infrared light. However, groundbreaking discoveries in the early 20th century revealed that cosmic radiation also includes atomic nuclei, ranging from hydrogen (1 proton) to iron (26 protons and 28 neutrons). These findings have since established cosmic particles as a subject of significant scientific interest. Today, it is estimated that approximately 13% of the ionizing radiation affecting Earth's biosphere originates from extra-solar cosmic rays.

Among these particles are muons—charged particles with a mass approximately 200 times greater than that of electrons. Muons decay via the weak interaction $\mu^{\pm} \rightarrow e^{(\pm)}\, \nu\, \bar{\upsilon}$ with an average lifetime of 2.2 microseconds, making them longer-lived than many subatomic particles.

These muons are primarily generated in the upper atmosphere through collisions between cosmic rays and atmospheric molecules, which produce pi mesons (pions) that subsequently decay into muons.

Despite their short lifetimes, muons can travel significant distances due to their relativistic speeds, allowing them to reach Earth's surface. On average, approximately 10,000 muons pass through each square meter of Earth every minute, providing a constant stream of particles for scientific investigation.

Theory

Particle physicists currently rely on the Standard Model of Particle Physics (Figure 1) to describe the interactions between subatomic particles. Although the Standard Model is not account for gravitational interactions, it provides the framework for this experiment.

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.

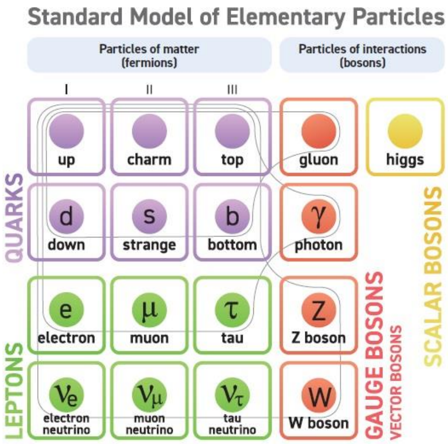

Figure 1. Standard Model of elementary particles. https://en.wikipedia.org/wiki/Standard_Model

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.

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

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 encountered in this experiment.

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).

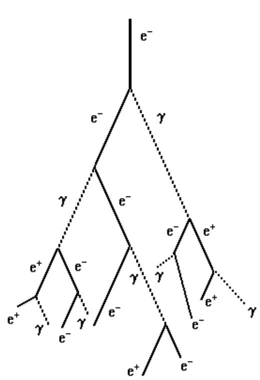

Figure 3. The creation of the electron-positron pair.(Dunn, 1999)

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 experimental setup includes three Geiger-Müller (GM) tubes, a Geiger counter, a coincidence box, and software for data collection and analysis. The Complete Muon Observatory is designed to detect cosmic rays and demonstrate their angular dependence in two distinct modes: shower mode and telescope mode [1, 2].

In **Shower Mode** (Figure 4), a cosmic ray shower is recorded as a coincidence event across the three GM tubes, arranged in a triangular configuration. This geometry ensures that no single particle can be detected by all three tubes simultaneously. To enhance the production of showers, radiation is passed through a material denser than air, such as multiple steel plates. In this mode, the muon observatory is typically aligned vertically, and measurements are conducted over periods of approximately one day. As the thickness of the steel plates increases, the number of cascade detections also increases, reaching a peak before stabilizing.

Figure 4. Shower mode setup. (PASCO manual 3.01.11)

In **Telescope Mode**, the three GM tubes are arranged in line (Figure 6). If a muon passes through all three tubes, a pulse is output from the coincidence box. By varying the angle of the telescope, the angular distribution of the muons can be measured.

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) (http://www.datalyse.dk/).

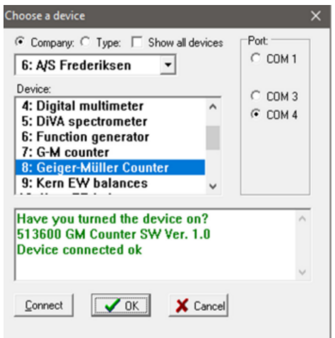

Figure 5. Software setup. (Datalyse website 2002)

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.

In the second part of our experiment, we explored the angular dependence of muon incidence by positioning the three GM tubes in Telescope Mode. 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.

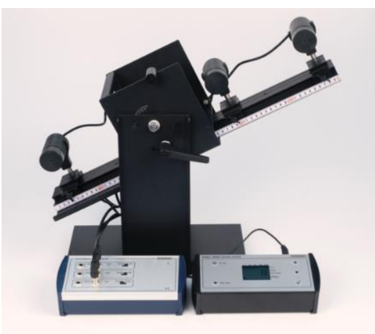

Figure 6. Telescope mode setup.(Pasco manual 3.01.2011)

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.

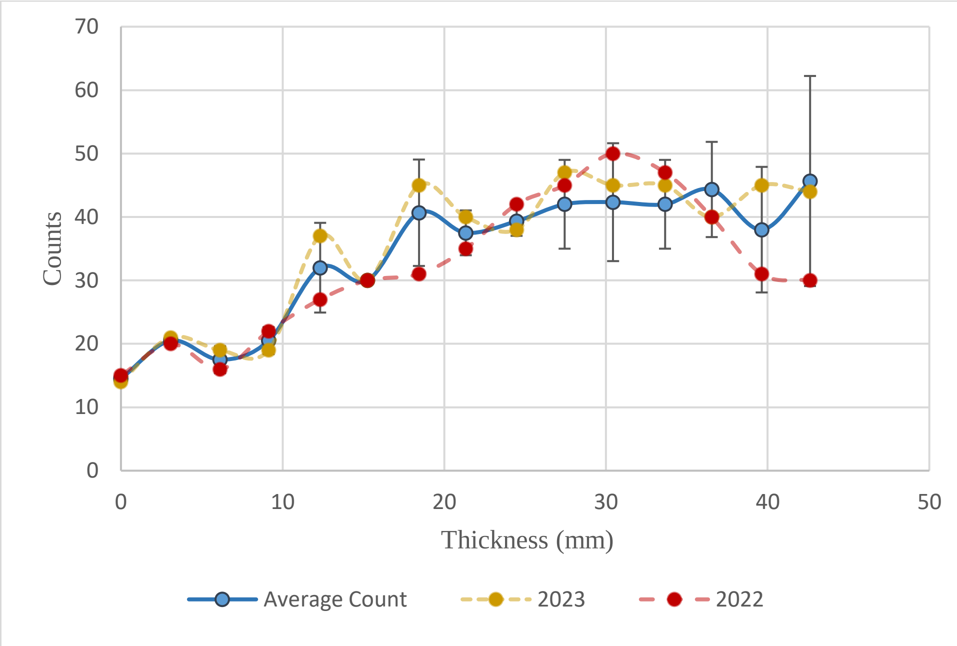

Figure 7. "Box and Whisker" graphs of muon events count vs. plate thickness.

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].

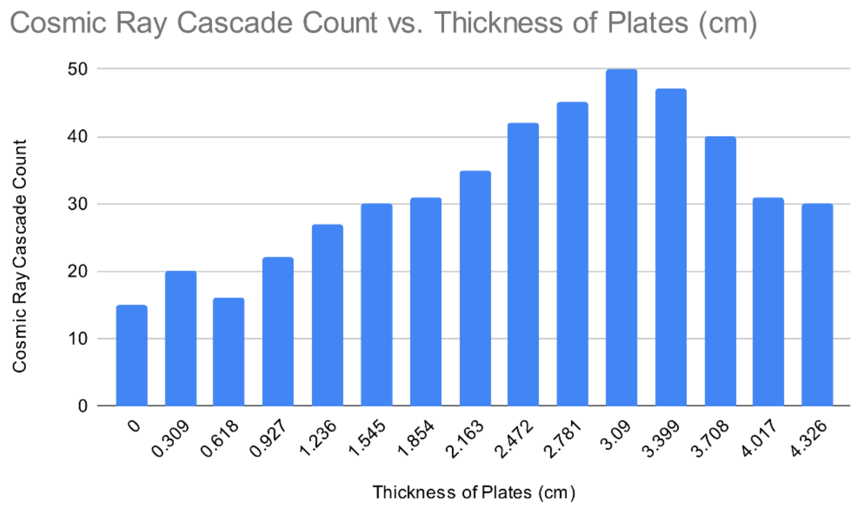

Figure 8. Simplified histogram of muon event counts versus plate thickness.

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]. 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.

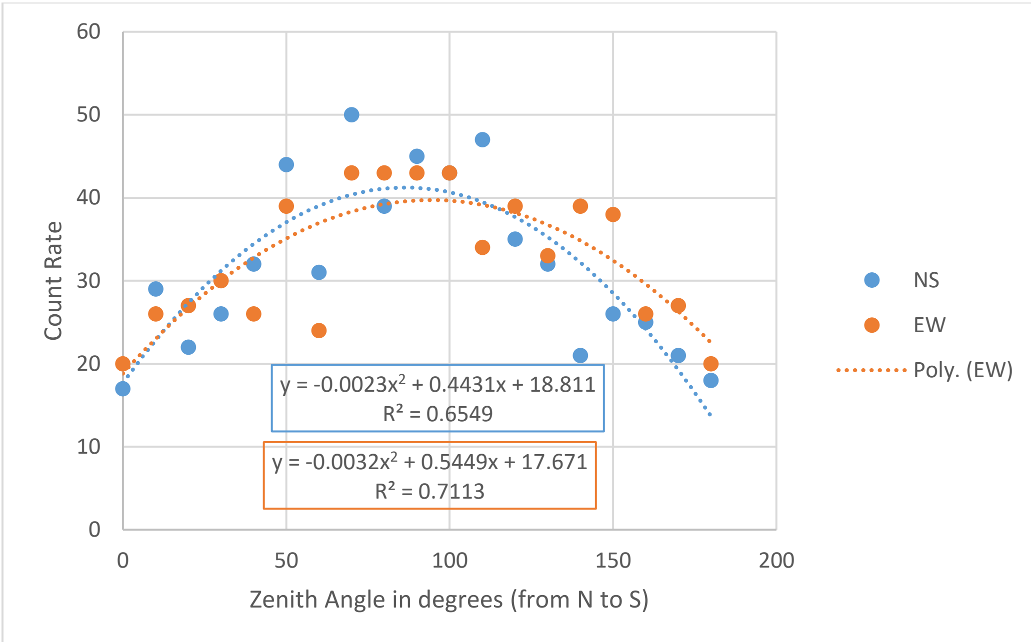

Figure 10. The Count Rates vs. Zenith Angle (θ)

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.

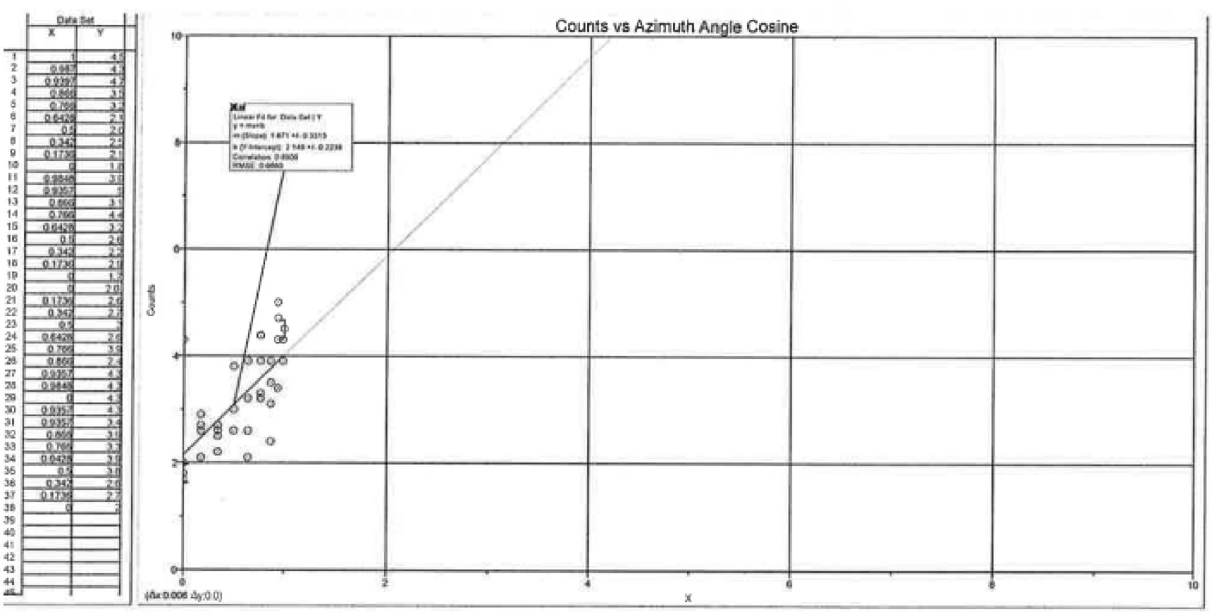

Figure 11. The Count Rate as function of cos (θ) of zenith angle θ

On the Figure 11, you could see that exponent on the cosine factor is not exactly 2 (slope=1.87) which is agree with the theory [11].

Conclusion

Pasco Muon Observatory Apparatus has an exceptional educational value:

1. Demonstrates the existence and behavior of cosmic rays.
2. Allow students to study the concept of particle detection and coincidence circuits.
3. Provides hands-on experience with fundamental particle physics concepts.

When relativistic electrons and photons penetrate matter, they initiate a cascade of particles, distributing the energy until the energy per particle becomes too low for pair production to occur. At this point, the particles are rapidly decelerated. Muons exhibit similar behavior, but the length of their interactions is approximately 40,000 times greater than that of electrons. Assuming part of the radiation we register consists of mono-energetic electrons, the number of particles in the cascade will initially grow exponentially with increasing absorb thickness, until a maximum is reached, after which it will decrease to zero.

Muons exist as both positively ($\mu+$) and negatively ($\mu-$) charged particles. A muon is approximately 200 times heavier than an electron and has a half-life of 2.197μs, making it unstable. While muons behave similarly to electrons, the mass difference causes their radiation length to be approximately 40,000 times larger than that of electrons. The muons from cosmic radiation that reach sea level have an average energy of about 4 GeV. The energy loss due to ionization is relatively constant, at about 2 MeV per g/cm^2. Given that the atmosphere's thickness is approximately 1000 g/cm^2, muons must be produced with an average energy of around 6 GeV to reach the Earth's surface.

In Telescope Mode, absorbers can be placed between the GM tubes, demonstrating the extensive range of muons in solids. If measurements are taken with a fixed geometry over an extended period, a negative correlation between the count rate and barometric pressure may be observed. This effect arises because a thicker atmosphere increases the likelihood of muon decay and collisions. A similar effect can also be seen due to variations in atmospheric temperature. These factors will be the focus of the final phase of our muon research study, where we will record outdoor temperature and barometric pressure alongside other experimental parameters.

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