Fabrication of Cosmic Ray Detector Systems

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Abstract:

When a cosmic ray interacts with the atmosphere of Earth, the cosmic ray emits Cherenkov radiation along with a barrage of particles, called an air shower. The main interest of this research project is the composition of the cosmic ray. By measuring rates and amplitudes of this emitted Cherenkov radiation and determining the quantity of Cherenkov particles per meter; the composition of these particles should be able to be determined. In order to study these interests my objective was to fabricate a cosmic ray detecting prototype. This prototype consists of three triggering units, which were constructed using a photomultiplier tubes (PMT) attached to scintillation panels, along with coincidence electronics, and the main Cherenkov light detector PMT Cone. Ultimately, this detector will be deployed to collect data on the Cherenkov radiation and compared against Monte Carlo simulations.
Introduction:

In High Energy Astrophysics, one of the leading topics in research is high energy cosmic rays. The questions being asked about these rays are how they are produced, where they are being produced, and what the ray’s composition is (The Pierre Auger Collaboration). The research group I am working with is especially interested in the composition of high energy cosmic rays.

The composition of cosmic rays is believed to range from single protons to iron nuclei. The method we are going to use involves the fact that when a particle from a cosmic ray enters Earth’s atmosphere, it emits Cherenkov radiation and also a particle shower (Sundaresan 94). Keeping these facts in mind, the research group has devised a method in which the particles from the air shower will be used to set off a triggering mechanism of photomultiplier tubes attached to scintillation panels. When these triggers go off simultaneously, the main photomultiplier tube will record the amplitude of the Cherenkov radiation and the rate the rays occur will also be recorded.

My objective was to construct a prototype of this Cosmic Ray Detector System. It consists of three triggering mechanisms
and one Cherenkov radiation cone. This prototype is necessary in order to ensure the system works properly and is cost effective before a large scale cosmic ray detector system is administered.

**Background:**

The Earth is frequently bombarded by high-energy particles. These particles are called cosmic rays. As an example of the frequency of cosmic rays striking Earth, 10,000 relatively low-energy rays, around 1 GeV, hit a square meter of ground every second. However, the frequency quickly decreases for higher energy rays. For cosmic rays of energy around $10^{12}$ GeV, only a single particle strikes a square meter of ground every second (Pierre Auger Observatory).

Curiosity of Cosmic ray origins, productions, and compositions have lead to many investigations.
Review of Previous Work:

Much research has taken place about high energy cosmic rays. The topics investigated about these phenomena range from how energetic cosmic rays can be, the origins of the cosmic rays, how gamma-ray bursts propagate, and how the average chemical composition compares to the energy of the cosmic rays.

In order to measure the energy of ultra high energy cosmic rays, rays which exceed $10^{18}$ eV, cosmic ray observations are made indirectly through the air showers they produce (Cronin). Similarly attempting to determine the origin of a cosmic ray was also dependent on ground based research (O.Saavedra) as well as the research done in trying to determine the average chemical composition vs. energy (Springer).

The fact that all these investigations use ground based air shower detectors as their means of data collection establishes that constructing a ground based Cherenkov light detector is a credible method for researching cosmic ray composition. However the triggering mechanisms for data collections used previously are rather large ($10 \text{ m}^2 \times 1.2\text{m}$ deep) water tanks at the Pierre Auger Observatory (Cronin). The scintillation panels being used in the prototype being proposed are only $2 \text{ ft} \times 2 \text{ ft}$ (Covault,
Cherenkov Tasks) which could enable more triggers to be placed at expectedly a lower cost.

All of the questions posed by the researches mentioned are still open ended with only the discovery that as of yet no limit to the energy of a cosmic ray has been determined (Cronin). Thus further research of cosmic rays is necessary and developing a more cost effective detector system with smaller triggering units can lower the cost and ease construction of future high energy cosmic ray researches.

**The Pierre Auger Observatory:**

The Auger Observatory has already implemented a large scale cosmic ray detector in Argentina. The detector covers an area of 3000 square kilometers and consists of 1600 particle detectors for air showers and 24 Cherenkov radiation measuring telescopes.

The Auger Observatory also wants to implement another large scale cosmic ray detector in Colorado. This will allow coverage of the entire night sky and the collection of data of more events. Before this project begins, a prototype of a cost efficient cosmic ray detector system must be constructed and tested for desired results.
**Theory:**

When a Cosmic Ray strikes Earth’s Atmosphere, two things occur. Cherenkov radiation is emitted and a particle shower spreads many secondary particles down to, and through, Earth’s surface.

Cherenkov radiation is emitted when a particle travels through a medium at a velocity which is faster than the speed of light in that medium. This is because of the variations in dipole polarization of the medium from the particle.

The emission of light as Cherenkov radiation is especially high in mediums which have refractive indexes close to 1. Examples of which are gases like nitrogen, carbon dioxide, and oxygen (Sundaresan 80). Due to the fact that Nitrogen, Carbon Dioxide, and Oxygen make up the majority of Earth’s atmosphere; and, cosmic rays usually have energies in the range of $10^9$ eV to $10^{20}$ eV (Brancus 362) the emission of Cherenkov radiation is clearly capable of happening as cosmic rays hit the atmosphere.

The air shower produced by the ray is initiated as the cosmic ray particle interacts with an atmospheric nucleus. After the initial interaction, the particle loses some energy due to multi-particle production but continues to interact with
other atmospheric nuclei as it travels to the ground. (Brancus 362).

The particles created are mainly pions and kaons, but also antiprotons and other more exotic particles. The neutral pions decay into photons, while the kaons and charged pions often times decay into muons and neutrinos. While these productions occur, the reduced energy cosmic ray particle continues to interact with more atmospheric nuclei and more multi-particle productions ensue (Brancus 363).

**Theory of Cosmic Ray Composition:**

By studying variations in the density and radius of an air shower, it is possible to predict what the initial particle interacting with the atmosphere was. It is believed that the
density of the particle shower will give insight to the composition of the cosmic ray particle causing the radiation. The range of expected particles goes from a single proton up to the much larger, yet stable, iron nuclei. Due to iron nuclei’s larger quantity of particles the possibility of it interacting with Earth’s atmosphere is increased, and therefore a denser particle shower should occur. These expectations have been recreated using computer simulations (Covault, Personal Meeting).

Nuclear interactions are a primary causes of air showers due to the fact that Earth’s atmosphere is full of hadrons such as nitrogen, oxygen, and carbon nuclei. Therefore the nuclear interaction length, $\lambda_{\text{int}}$, plays a role in the dimensions of the shower (Wigmans 78). “The nuclear interaction length of an absorber medium is defined as the average distance a high-energy hadron has to travel inside that medium before a nuclear interaction occurs” (Wigmans 78). The probability $P$ of a particle traveling a distance $d$ without having a nuclear interaction is (Wigmans 78)

$$P = e^{-\frac{d}{\lambda_{\text{int}}}}$$

From this equation, the probability of the particle interacting with a hadron of the medium, such as the atmosphere,
increases with a smaller value for the nuclear interaction length.

However, the nuclear interaction length is not only dependent on the medium, but is also dependent on the size of the particle passing through the medium. As an example, the Nuclear interaction length of the smallest hadrons, the pions, through a specific medium is much larger than the nuclear interaction length of a proton through the same medium (Wigmans 79).

Therefore the larger a particle is that strikes earth’s atmosphere, the shorter the distance it travels between interactions. As a result large hadrons have many more interactions with the atmosphere and create a larger density of particles in the air shower. Also, the larger hadrons will react higher in the atmosphere creating a larger spread air shower (Huang 378).

Due to nuclear action lengths varying by the size of the passing particle, an iron nuclei striking the Earth’s atmosphere yields a higher muon density and a larger deflection angle of the muons than a proton would yield (Huang 377). These differences are being used by such research teams as the Mosco State University Extensive Air Shower Experiment (MSU EAS) and
the HEGRA-CRT experiment to attempt to discover what the composition of cosmic rays are.

Another insight into why larger particles interact at shorter distance in the atmosphere is the nuclear collision length, which is the mean free path a particle travels before having a nuclear reaction in a medium (Groom). Mediums composed of larger particles have larger nuclear collision lengths. For example the nuclear collision length of lithium is only 52.2 g/(cm²) while iron’s collision length is 81.7 g/(cm²) (Groom). However lighter particles that pass through a medium have larger nuclear collision lengths than larger particles in the same medium. So protons can travel further than heavier nuclei like iron through the atmosphere.

Both the nuclear interaction and collision lengths decrease as the mass of the particle increases. This shortens the distance between reactions. As a result, when a cosmic ray particle is heavier, it initially interacts higher in the atmosphere than lighter ray particles creating a larger spread air shower than the lighter rays (Haungs 378).
Apparatus:

In order to construct a prototype of the cosmic ray detector system I had to synthesize apparatuses from past undergraduate research projects. This includes the scintillation panels with mounted photomultiplier tubes constructed by Yvette Cendes (Covault, Cherenkov Tasks). These devices will serve as the triggering mechanism for the main...
photomultiplier tube to begin recording data of the amplitude of Cherenkov light.

Along with these triggers, coincidence circuitry and a cone mounted to another photomultiplier tube, which will be used to measure the Cherenkov radiation, are the other key portions of the apparatus.

The prototype works in the following manner: In order to measure the Cherenkov radiation of a cosmic ray, the Cherenkov radiation cone must be activated to record data as the ray is interacting. The activation of the cone is initiated when the triggers scintillate simultaneously. This is because although particles randomly pass through Earth frequently, when particles pass through the triggers simultaneously it is likely due to a particle shower formed by a cosmic ray.

Every time a trigger detects the scintillation of a passing particle, a signal is sent to the coincidence circuitry.
circuitry. When multiple signals are received by the coincidence circuitry at the same time, a particle shower is being detected. As a result the simultaneous signals cause the coincidence circuitry to activate the Cherenkov radiation cone to measure the amplitude of the radiation.

**Triggers:**

The triggers are constructed of photomultiplier tubes attached to scintillation panels using vacuum grease. Originally these devices were attached using optical cement.

Using the cement proved to lead to issues in the apparatus. If a trigger was not functioning properly, the PMT could not be removed to check its performance. To allow easier access to the bare PMTs, optical grease replaced the cement.

The scintillation panels are wrapped in sheet rubber to insure no light leaks will occur which could inaccurately cause a trigger to detect a scintillation.

Each trigger also has its own high-voltage power supply (−2000 Volts) and discriminator (−20 Volts).
Cherenkov Radiation Cone:

The Cherenkov light cone consists of an aluminum cone attached to a base. A photomultiplier tube has a convex lens attached to it using vacuum grease and placed in the base of the cone.

The cone was made by machining out the shape from a solid piece of aluminum.
The photomultiplier tube was attached to the base using sheet rubber and electrical tape.

Figure 7: Cherenkov Light Cone Top View
Methods:

Testing the Spacing of Triggers:

Determining the proper spacing of the triggering units is a very important process. Higher energy cosmic rays cause wider spread particle showers. Therefore in order to collect data on the highest energy cosmic rays possible, the triggering units must be placed as far apart as possible (Covault, Personal Meeting). However; the higher the energy of the cosmic rays, the less frequently they occur. Therefore determining the distance which will result in the desired rate of data collections while still obtaining the data from as high an energy cosmic ray as possible is crucial. Professor Covault expects that a coincidence rate of 1 coincidence per hour will suffice to collect enough data over a time span of a few nights to test the prototype, and also record cosmic rays of high enough energy (approximately 10 GeV) to be able to measure the amplitude of the emitted Cherenkov radiation.

Measuring the coincidence rates of the prototype was conducted by using the three triggers, along with their respective discriminators and power supplies, and the coincidence circuitry.
With the exclusion of the Cherenkov radiation cone, these devices were set up as they would for the fully built prototype atop the roof of the A.W. Smith Chemical Engineering Building at Case Western Reserve University. The triggers were placed at a distance of 0, 1, and 2 meters apart and the coincidences were recorded every hour.

Figure 8: Picture of testing Trigger Spacing
Testing PMT’s for Cherenkov Radiation Cone:

In order to build a Cherenkov radiation cone consisting of a PMT and an aluminum cone, a functioning photomultiplier tube is clearly needed.

Testing of PMTs to be used for the cone was conducted using a dark box. The dark box was a wooden box painted black. It had a felt lining around the hinged door to insure it was void of light penetrating the box which would affect the testing of the PMTs.

During the test, an LED is placed in the dark box along with a PMT that is secured with a heavy frame.

A pulse generator sends a signal to both the LED and a nearby Oscilloscope. The photomultiplier tube’s signal is sent to a different channel of the oscilloscope. The signal created by the pulse generator is
then compared to the signal emitted by the PMT on the oscilloscope to see if the PMT is responding.

**Results and Discussion:**

**Trigger Spacing Results:**

<table>
<thead>
<tr>
<th>Distance Between Triggers</th>
<th>Coincidences/Hour</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 meters</td>
<td>11.6 ± 3.9</td>
</tr>
<tr>
<td>1 meter</td>
<td>9.6 ± 2.3</td>
</tr>
<tr>
<td>2 meters</td>
<td>13.3 ± 3.0</td>
</tr>
</tbody>
</table>

*Table 1: Coincidence Rates for varied distances between Triggers*

From the tests for finding the proper distance between triggers, the distances of 0, 1, and 2 meters all yield a coincidence rate of approximately 12 coincidences per hour. The desired rate of only 1 coincidence per hour must occur when the triggers are positioned much further apart than the largest distance tested of 2 meters. Dr. Covault expects that the rate of a single coincidence per hour will occur when the triggers are placed a distance of around 10 meters apart.

The reasoning behind why larger distances were not tested is that the roof top used for the experiment has limited space,
and having the triggers equidistant from each other would not allow for much further separation.

**PMT Testing for Cherenkov Radiation Cone Results:**

<table>
<thead>
<tr>
<th>PMT</th>
<th>Pulse Period, Width, Amplitude</th>
<th>Signal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trigger #2</td>
<td>10 ms, 1μs, 3V</td>
<td>-30 mV</td>
</tr>
<tr>
<td>(Working)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PMT W</td>
<td>10 ms, 1μs, 3V</td>
<td>-20 mV</td>
</tr>
<tr>
<td>(Used for Cone)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Yvette’s Tube</td>
<td>10 ms, 1μs, 3V</td>
<td>No response</td>
</tr>
</tbody>
</table>

**Table 2: Signal of Various PMTs vs. Pulse Generator Signal**

From the testing for suitable photomultiplier tubes for the Cherenkov radiation cone, a suitable PMT (PMT W) was found to respond well enough to be attached to the cone.

This was determined by using the PMT of trigger #2, which is known to work and respond accurately through the consistent response it yields through others portions of the project. Many
PMTs were tested, and PMT W had by far the strongest signal of all possible tubes in the lab. Although it still is showing 10mV less of amplitude in the signal than the trigger #2’s PMT, it should still prove successful in the prototype. If it is decided to be unsuitable for the cone, at the least it can serve for a test deployment of the entire cosmic ray detector prototype. This meaning making sure the coincidence circuitry activates the Cherenkov radiation cone to collect data after a coincidence occurs.

**Future Plans for Project:**

The future plans for this project are to deploy the prototype in an area of low light pollution to collect data on the Cherenkov radiation amplitude and the rate of air showers per hour.

Although it is unnecessary for the prototype to function, a fourth triggering unit should be constructed. This will enable the data collected by the prototype to be compared to the Monte Carlo simulations of cosmic rays of varying compositions and ultimately test if the prototype yields the desired results for the large scale cosmic ray detector implementation by the Pierre Auger Observatory.
**Conclusion:**

When a cosmic ray interacts with the atmosphere of Earth, particles from the cosmic ray emit Cherenkov radiation. The main interests of the radiation in this experiment are the rates and amplitudes of this emitted light and ultimately determining the quantity of Cherenkov particles per meter and the composition of these particles. In order to study these interests three triggers were constructed using a photomultiplier tube (PMT) attached to a scintillation panel for each trigger along with coincidence electronics and the main Cherenkov radiation detecting cone. In the Future this detector will be deployed to collect data on the Cherenkov radiation and rates of air showers and then compared against computer simulations.

**Acknowledgements:**

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References:


