Measuring the Energy Loss Distribution of Cosmic Ray Muons in a Water Cherenkov Detector

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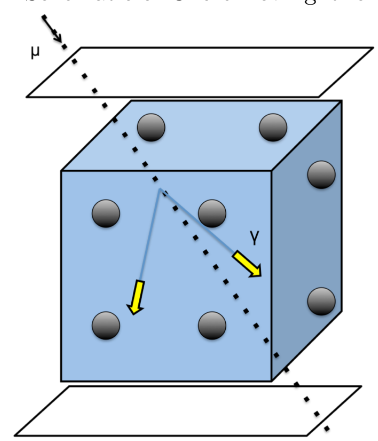
We designed a straightforward setup to measure the energy loss spectrum of the cosmic ray muons that pass through a water Cherenkov detector. We calibrated a coincidence trigger to select the signals of muon events detected independently by the three components of our detector. We recorded the signal amplitudes of muon events using a MCA/MCB setup with the MAESTRO 2002 software package. We calibrated the energy of the distribution by scaling our measured signal voltage distribution by a linear factor that we computed using the Particle Data Group's accepted value for the peak energy loss of a minimum-ionizing particle in water.

I. INTRODUCTION

Cosmic rays are of great interest to physicists and astronomers, as aspects of their origin remain ambiguous. After it interacts with the Earth's atmosphere, a cosmic ray's trajectory becomes far more mundane: primary cosmic rays (mostly protons) yield electrons, photons and muons. Most cosmic ray muons are created about 20 km above sea level. At sea level, around 75% of high energy particles are muons [1]. We measured the energy loss spectrum of cosmic ray muons using a water Cherenkov detector.

Once a cosmic ray muon (with electric charge -1) enters the detector, if its velocity is above the Cherenkov threshold in purified water (the phase velocity of light in that substance) it disturbs the electromagnetic field within the detector such that it is trailed by a shock wave of light. This Cherenkov light (generally ultraviolet) is emitted at a characteristic angle which can be calculated using the velocity of the particle and the speed of light in water. Figure 1 is a cartoon of this process. Note that the shock wave of light is drawn as being in front of the particle, in anticipation of its projection onto the PMTs (photomultiplier tubes) inside the detector. Each PMT contains a photocathode which absorbs the Cherenkov light and uses the photoelectric effect to amplify the signal using a dynode chain. The PMT outputs an inverted electric pulse with a peak roughly proportional to the original number of photoelectrons absorbed by its photocathode.

FIG. 1. Schematic of Cherenkov light formation



II. DESCRIPTION OF APPARATUS

The detector consists of three pieces: a water Cherenkov detector and two PMTs which absorb light from scintillator paddles above and below the main tank. The water Cherenkov detector, built and maintained by students and faculty of the Boston University Physics Department, is a 6.8×10^4 cm^3 light-tight aluminum case containing purified water. The detector is separated into four panels that we will call zones; each zone consists of four daisy-chained PMTs.

Figure 2 illustrates our data collection scheme. The signal from each of the four zones is sent to a fan In-Out NIM module, which outputs the sum of the four signals. This fanned-in PMTs signal is amplified 50 times and sent to a MCA (multichannel analyzer) chip in our lab computer. Our goal is to record the peak of each of these signal pulses, since the peak approximates the total charge deposited in the water Cherenkov detector for that pulse. In particular, we only want to record the peak of the signal pulses that come from the energy deposits of cosmic ray muons. So we create a trigger that prompts a gate pulse, and program the MCB (multichannel buffer) lab computer software MAESTRO 2002 to only record signal pulse heights which are contained in the gate pulse (at least half a microsecond on either side).

The idea behind the trigger is simple: we send a gate pulse to contain the signal pulse only if there is a threefold coincidence between the top PMT signal, the bottom PMT signal, and the fanned-in PMTs signal. In other words, when energy depositions occur in all three

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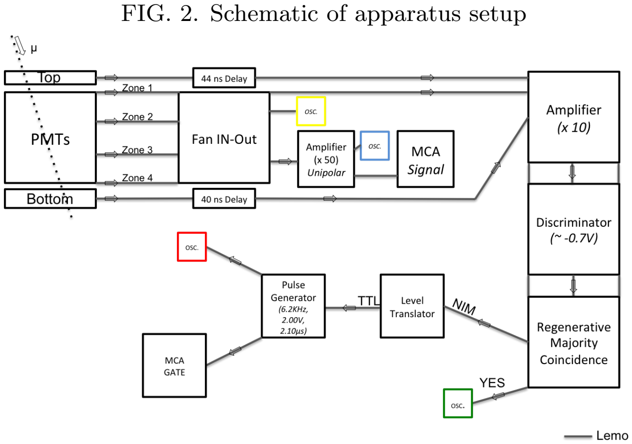
detectors in rapid succession, a cosmic ray muon has just passed through and we therefore record how much energy it deposited the water Cherenkov detector.

Implementing the coincidence trigger is also simple. We first amplify the three relevant signals (Top, Bottom and PMTs) by a factor of 10, then discriminate those pulses, only keeping those which exceed the ≈ -0.7 V threshold. We chose this threshold by inspecting the raw signals with an oscilloscope and adjusting the threshold to minimize noise contamination. Those discriminated pulses are converted into square NIM pulses (logic pulses) and sent to the coincidence NIM module which sends a trigger signal to the gate pulse generator if there is three-fold coincidence.

FIG. 2. Schematic of apparatus setup



III. SAFETY

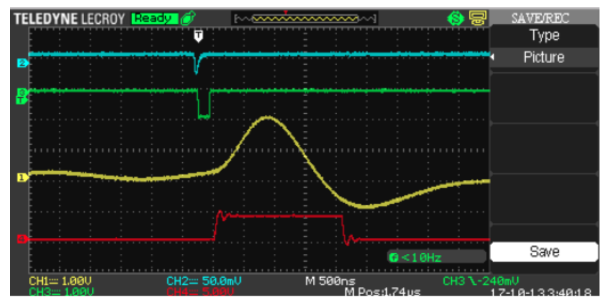
Much of the apparatus is powered by high voltage. Roughly +1.7 kV is delivered to each of the four zones of PMTs. The voltage is distributed within each zone via a daisy-chaining scheme. Independently, +2.0 kV is delivered to the top and bottom PMTs. The current delivered by the high voltage modules to the PMTs is on the order of 1 milliampere, which can give a painful shock. It is necessary to check for proper cable connections before the power is turned on, and one must make sure the high voltage is switched off before adjusting the cables. The daisy chains that distribute high voltage between the four PMTs in each zone should be handled with care. All basic safety precautions should be taken around the high voltage. It's generally a good idea not to wear conducting items of clothing (such as jewelry) since there is a risk that these will contact exposed parts of the circuitry, and also it's wise to wear shoes with rubber bottoms, which will reduce the risk of getting an electric shock.

IV. DATA ACQUISITION

Figure 3 is a typical screenshot of our oscilloscope signals. The blue pulse is the fanned-in PMTs signal, the green pulse is the coincidence signal of Top + PMTs + Bottom, the yellow pulse is the amplified fanned-in PMTs signal, and the red pulse is the gate pulse. Note that the colors match those in Figure 2. The yellow and red pulses are fed into the MCA and collected on the computer using the MAESTRO 2002 MCB software.

As the MCB collected the peak values of the (yellow) signal pulse within the (red) gate, we monitored the performance on oscilloscope.

FIG. 3. Screenshot of Oscilloscope



V. DATA ANALYSIS

A. Muon Energy Loss Distribution

The MAESTRO 2002 software as it is currently configured on the lab computer uses a specific linear scale factor to convert the amplitude of the MCA signal from volts to electronvolts. We confirmed that this conversion factor was linear by using a pulse generator to feed square pulses of varying amplitudes into the MCA, and then checking that we got the same conversion factor. The conversion factor was (1 volt/233 keV). We used this factor to recover our muon signal amplitude distribution (in V) from our histogram obtained with the MAESTRO software (in eV).

By measuring a PMT's signal with our oscilloscope while varying its high voltage, we estimated that the electrical signals emitted by our water Cherenkov detector PMTs are precise to the nearest mV. By looking at hundreds of PMT muon signals on the oscilloscope, the typical signal pulse had an amplitude of 20 mV.

According to a recent Particle Data Group publication, the accepted value for the peak energy loss for a minimum-ionizing particle in water is 1.992 MeV/cm [2]. We use this value to estimate the absolute value of the peak energy loss of a minimum-ionizing muon through our detector. In this estimate we assume that the muon is vertical and downward-going, since it is a known fact that the dominant contribution of sea-level cosmic ray muon flux comes from vertical downward-going muons [3].

$$(1.992 \text{ MeV/cm}) \times 45 \text{ cm } = 89.64 \text{ MeV}$$

Since our detector sensitivity is on the order of 1 mV, a conversion factor of (MeV/mV) implies that our detector is sensitive to muon energy loss on the order of 1 MeV. So our estimate of a linear conversion factor from mV to MeV is (90 MeV/20 mV).

Scaling our muon signal amplitude distribution by this factor, we approximate the muon energy loss distribution in our water Cherenkov detector (Figures 4 and 5). We assume a statistical Poisson error on each data point since this is a counting experiment. The run time of this distribution is approximately three days.

Excluding the small noise peak near the origin, the shape of this distribution qualitatively resembles a Landau distribution. If given more time, we wish to fit this curve to a Landau distribution and determine its goodness of fit.

FIG. 4. Muon energy loss distribution with run time of about three days (log scale).

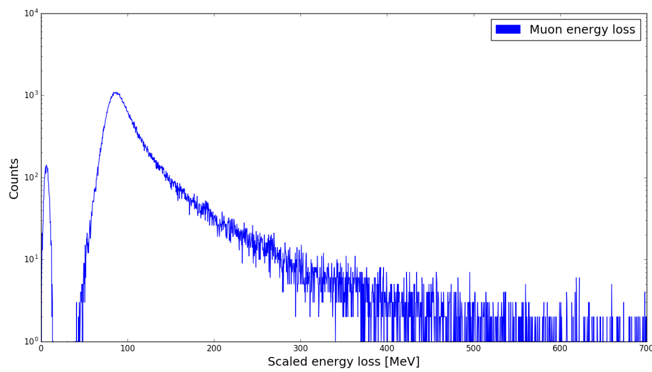
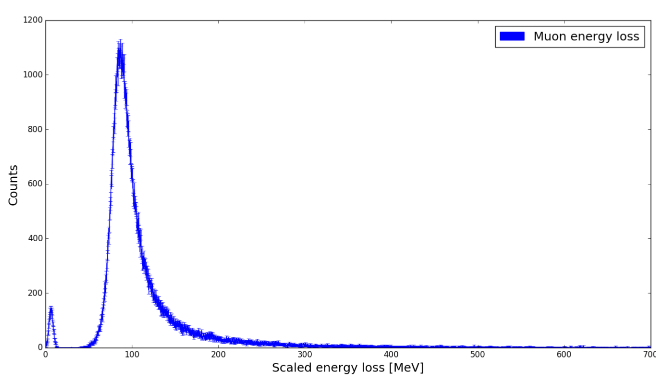


FIG. 5. Muon energy loss distribution with run time of about three days (linear scale, with statistical error bars).



B. Systematic Errors Discussion

We discuss the possible sources of systematic errors of our apparatus and data acquisition procedure, and quantify the main source of our systematic errors.

It is possible that sources of systematic error lay within the water Cherenkov detector itself. We did not check water quality or light leakage, and we only did a minimal check of each PMT's functionality. Light leakage out of the detector, damaged PMTs and poor water quality could all have contributed to our systematic errors. But any significant light leakage would have visibly distorted the lower range of our muon energy loss distribution. Similar arguments apply for the PMTs and water quality. Since we do not see such distortion in the distribution, we do not believe the detector itself contributed majorly to our experiments systematic error.

The NIM modules we used in our data acquisition flow chart were overall reliable. We confirmed this for each module by probing its signals with the oscilloscope and, in some cases, the voltmeter. So we do not include effects from these modules in our systematic error assessment.

We also reason that we need not include cable-related sources of systematic error. Cable travel time is something that our group accounted for by delaying our gate pulse to ensure that the peak of the signal pulse sent to the MAESTRO MCA fell at least 500 ns within the gate pulse. Also, all cables used were noise-resistant coaxial cables so we need not include a systematic error associated with poor electromagnetic shielding of the cables.

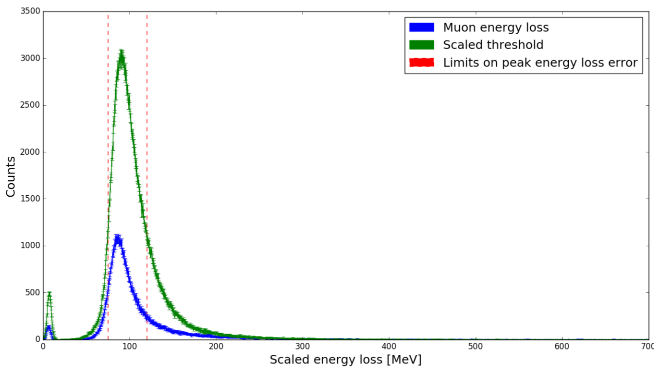
One obvious source of systematic error is the noise peak on the left side of Figures 4 and 5, which is mainly caused by amplitude-based electronic noise like RF noise. Comparing the integral of counts under this noise peak with the integral under the signal peak, we obtain the signal-to-noise ratio:

$$\frac{286619 \text{ signal counts}}{2174 \text{ noise counts}} \approx 132$$

Since the signal-to-background ratio is so large, it shows that our setup had minimal electronic noise.

A more subtle source of systematic error was the combination of our choice of PMT high voltage with our choice of PMT discriminator threshold. Delivering higher voltage to the PMTs can increase noise, and setting the threshold too low can also increase noise. To account for this, we took over three days of data where the signal pulse was counted every time the fanned-in PMTs signal was above the PMT discriminator threshold. This "above-threshold" data consists of PMT noise that had crossed the threshold, "corner-clippers" (muon events that clip the corner of the detector), other radiation above Cherenkov threshold, and the muon events which contributed to our muon energy loss distribution in Figure 1. We assume approximately constant noise, so we scale each bin by the ratio of the two run times to get a "above-threshold" distribution with the same total run time as our muon energy loss distribution. Our actual

FIG. 6. Muon energy loss distribution superimposed with the "above-threshold" signal distribution, which has been scaled to the same run time as the muon energy loss distribution.



peak energy loss could have been anywhere in the range of energies in our "above-threshold" distribution with a count at least as high as our measured peak muon energy loss. By chance, our measured peak could have had more or less counts due to PMT noise which had crossed our discriminator threshold.

By noting the lowest and highest energies in our "above-threshold" distribution with counts above the measured peak muon energy loss, we determine that

Peak scaled muon energy loss = 87 +33/-12 MeV

Then we obtain our percent error on either side of the measured peak muon energy loss.

$$\frac{|87-74|}{87} \times 100 \approx 13.8\% \text{ error to the left of the peak}$$

$$\frac{|87-120|}{87} \times 100 \approx 38.4\% \text{ error to the right of the peak}$$

Since this percent error is relatively large, it suggests that our combined choices of PMT high voltage and discriminator threshold introduced too much noise into our "above-threshold" distribution.

The method described above tends to overestimate this systematic error, since obviously not all the noise gets through during the actual experiment. Also, this method relies on counting events that happen by chance. If we had more time to collect data, we could have minimized this source of systematic error by taking data over a longer period of time than three days. For a short runtime (< 1 week), we should get a conservative estimate of the error in our measured muon energy loss peak.

VI. CONCLUSION

We measured a muon energy loss distribution with a peak value of 87 MeV, which is close to the accepted energy loss of for a vertical downward-going muon through our detector (90 MeV). Our measurement is relatively free of electronic noise, with a signal-to-noise ratio of $\approx 132/1$. We also quantify the systematic error on our choice of discriminator threshold and PMT high voltage by noting where the energy loss distribution of all signals above our discriminator threshold exceeds our peak measured muon energy loss. In the future we hope to do a more thorough study of this source of systematic error. Here we do a basic study which actually overestimates this source of systematic error. Including this error, our measured muon energy loss distribution has a peak value of 87 +33/-12 MeV.

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B. References

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