The Cosmic Ray Telescope

Senior Lab

Brian A. Raue

FIU Physics

January 19, 2004

1 Cosmic Ray Flux

The Earth is constantly bombarded by energetic particles from outer space at the rate of about 1 per cm^2 per second. The vast majority of the cosmic rays are muons produced in the Earth's upper atmosphere. They have a lifetime of 2.2 μs, which, considering their velocity, is long enough that there is a good probability for them to reach the earth before they decay. These muons are the cosmic rays that we observe with our detector.

We will be using a cosmic-ray telescope to measure the angular distribution of the cosmic-ray flux. According to the Particle Data Book,[1] the flux of cosmic rays per unit solid angle per unit horizontal area relative to the vertical direction is

$$j(\theta = 0) = 110 \text{ m}^{-2}\text{sec}^{-1}\text{sr}^{-1}.$$

(You may find that converting this to units of cm^2 and minutes is more particle due to small detector sizes and low counting rates.) This is true for zenith angles of $0 < \theta < \pi/2$. Beyond $\pi/2$ the presence of the Earth stops the cosmics. This flux is not a constant over the face of the earth and can vary up to about 10% depending latitude and altitude. ϕ is the azimuthal angle around the vertical direction.

The flux of cosmic rays drops off as the incident angle increases. It will be your job to determine the angular dependence of the *integrated* flux ($J(\theta)$ in equation below) by measuring the flux at several angles. So I want you to determine the functional form of $J(\theta)$ and determine the constants within the function. I also want you to explain why the flux drops off at larger angles. The explanation is well known so all you have to do is a little bit of literature searching for the answer.

The total rate through a horizontal unit area per unit time is the rate integrated over θ and ϕ:

$$J(\theta) = \int j(\theta)\cos\theta d\Omega = \int_{\theta=0}^{\pi/2}\int_{\phi=0}^{2\pi} j(\theta)\cos\theta\sin\theta d\theta d\phi \qquad (1)$$

The extra $\cos\theta$ comes from the fact that a cosmic ray coming in with an angle of θ sees a horizontal detector area foreshortened by $\cos\theta$.

If you want to determine the direction of a cosmic ray you will need two detectors separated by some distance d and oriented at an angle with respect to the vertical (see figure below). The two detectors are operated in "coincidence mode" meaning that we count a cosmic ray only when both detectors are hit. Given the width, w, and length, l, of the detectors, we can calculate a solid angle.

Let's first consider the easy case where the detectors are in the zero-degree orientation and assume that d is big. If we consider rays that pass through the

[1] See Physical Review **D66**, 010001 (2003) or the Particle Data Group website at `pdg.lbl.gov`.

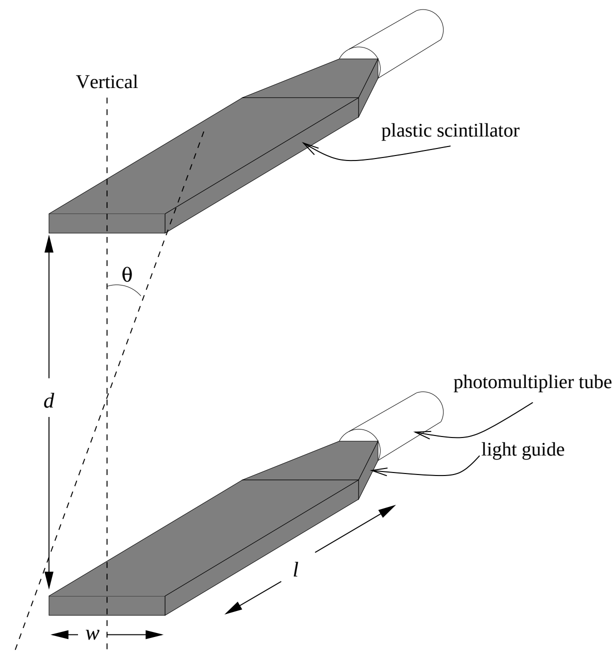

Figure 1: Basic scintillation detectors in "zero-degree" orientation.

top detector, the bottom detector covers a *solid-angle*, $d\Omega = \sin\theta d\theta d\phi$. This is the fraction of a spherical surface of radius d covered by the detector. Since the area of a sphere is $4\pi d$ and the area covered by the detector is lw, then the solid angle is approximately the ratio of these two factors or

$$\Delta\Omega \approx \frac{lw}{d^2}.$$

This is really only good if $d \gg w, l$ since the flat rectangular area covers more than lw of the curved spherical surface. Furthermore, the top detector is not a point detector so there will be distances of travel between the detectors greater than d. With these approximations, the integrated flux now becomes

$$\int j(\theta)\cos\theta d\Omega \approx 110\Delta\Omega \text{ m}^{-2}\text{sec}^{-1}.$$

Now what about angles other than zero? Except for a horizontal orientation, $\theta = 90°$, the solid-angle approximation isn't too bad. The flux through the top panel, however, must be recomputed for non-zero angles because the angular foreshortening is no longer just $\cos\theta$. We now need the dot product of the direction of the cosmic ray $\hat{\mathbf{p}}$, and the normal to the area $\hat{\mathbf{A}}$. If we tilt the panel around the x-axis, then $\hat{\mathbf{p}}$ and $\hat{\mathbf{A}}$ are:

$$\begin{aligned}\hat{\mathbf{p}} &= (\sin\theta\cos\phi, \sin\theta\sin\phi, \cos\theta) \\ \hat{\mathbf{A}} &= (0, \sin\alpha, \cos\alpha)\end{aligned}$$

where α is the angle of inclination of the panel. The resulting dot product is

$$\hat{\mathbf{p}} \cdot \hat{\mathbf{A}} = \sin\theta\sin\phi\sin\alpha + \cos\theta\cos\alpha.$$

We see that for α=0 this reduces $\cos\theta$ and we will get back our previous flux integral. So for non-zero α, the flux is given by

$$\int j(\theta)\hat{\mathbf{p}} \cdot \hat{\mathbf{A}} d\Omega = \int j(\theta)|\sin\theta\sin\phi\sin\alpha + \cos\theta\cos\phi| d\Omega.$$

(The absolute value is needed to account for particles coming from both directions through the top panel.) Unfortunately, this integral cannot be done analytically because of the absolute value in the integrand. We can make further approximations to get out of this dilemma. If we tilt the setup over an angle α about the x-axis, and assume that d is large, then only those cosmics that hit the top panel roughly perpendicularly will make it to the bottom panel. That is, the top panel is not very foreshortened and the factor $\hat{\mathbf{p}} \cdot \hat{\mathbf{A}} \approx 1$. So now we have

$$J(\theta) = \int j(\theta \sim \alpha, \phi)|\hat{\mathbf{p}} \cdot \hat{\mathbf{A}}| d\Omega \approx f(\theta)\alpha\Delta\Omega.$$

So, you need to find $f(\theta)$ with your experiment. Once you have it, you can, in principle, predict muon flux for our detector system in any orientation.

2 Apparatus

The apparatus we use consists of a pair of detectors and some signal-processing electronics. These components are similar to the devices used in accelerator-based nuclear and high-energy physics experiments, only on a much smaller scale. We will discuss each of these components separately.

Detectors

The adjustable-angle cosmic-ray telescope that we use is pretty simple. The individual detectors (shown in the previous figure) each consist of a rectangular piece of plastic scintillator, a plastic light guide, a photomultiplier tube (PMT), and a

PMT base (not shown). Materials which "scintillate" produce light when charged particles–like our muons–pass through. This is due to excitation of atomic electrons through an electromagnetic interaction with the passing charged particle. When the atoms de-excite, they produce light. The amount of light produced is proportional to the energy left behind by the passing particle. The light then passes through the light guide on its way to the PMT. Both the scintillator and the light guide are wrapped in a shiny material (aluminum foil or aluminized mylar) and black paper so that no light gets out or in.

Once at the PMT, the light signal is processed and turned into an electrical signal. The one thing that I am going to tell you about the PMTs that we will be using is how to use them. I would like for you to find references on the functioning of PMTs and include it in your writeup. The signal from the PMT is readout through the PMT base. The base also has a connection for the high voltage needed to operate the PMT. The HV is supplied by a separate HV module and should be limited to less than -2400 V for the tubes we use.

The negative PMT signal typically ranges in size from a few millivolts (mV) to a few volts. When using plastic scintillator, the signal has a rise time of a few nanoseconds and a fall time of a few tens of nanoseconds. Other types of scintillator–such as NaI crystals–produce somewhat longer rise and fall times. You should apply the voltage and look at some signals on an oscilloscope. You will need a source of ionization, so use the ^{90}Sr beta source located in the source cabinet.

Electronics

The processing of the PMT signals is done with a number of NIM electronics modules. These include a linear fan in/fan out (FIFO), a threshold discriminator, a coincidence logic module, and a scaler. The FIFO just takes the signal and produces exact copies–useful for when you are setting up the electronics. A discriminator produces a "NIM true" signal whenever the pulse height (PH) of the input signal exceeds a certain threshold. A NIM true signal is between -500 mV and -1 V. The threshold and output width of the discriminator are adjustable on the front panel. The threshold should be set above the "noise level" of the PMT and the width should be set to about 50 ns. A coincidence logic module will produce a NIM true signal if multiple input signals are present at the same time. So you will uses the logic module to tell that both scintillators fired at the same time and, therefore, you most likely had a single particle passing through the telescope. This signal is fed into the scaler which simply increments the numerical display every time a coincidence is detected.

3 The Experiment

Once you have your electronics set up, you should accumulate data at several angle settings. Your rate is the number of events you detected divided by the time you were counting: $R = N/t$. You should then plot your results–with error bars–as a function of detector-angle setting. Hopefully, you be able to identify the form of the angle dependence of $J(\theta)$.

Counting Statistics

One thing you need to properly account for is uncertainties due counting statistics. You need to make sure that you get enough data at every point so that your measurements are statistically significant. So how much is enough? If I have N counts, over a period of time t, there is an uncertainty of $\Delta N = \pm\sqrt{N}$ associated with these N counts. For example, if I have 100 counts, I have an uncertainty of ± 10 counts. This is a *relative* uncertainty of $\Delta N/N = 0.10 = 10\%$. On the other hand, 10000 counts gives me a relative uncertainty of 1%. The uncertainty in the rate is just $\Delta R = \Delta N/t$. Shoot for something better than 10% but you probably can't get 1% at all settings. You can estimate how long you need to run at each angle setting by applying the integrated-flux equation from above.