Experimental Physics 3: Experiment IV
The Rate of Cosmic Rays and its Dependence on Height and Zenith Angle

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Abstract

The aim of this experiment is to show that the detection of muons depends on the height and the angle of the instrument and that the counts of muons follows a Poisson distribution. We use a CAEN Cosmic Hunter SP5620CH kit with plastic scintillating detectors to measure the rate of cosmic rays. We first measure the efficiency of the detectors however the efficiency is found to be around 96% for all of the three detectors. Additionally a very low difference whether light is present or not goes to show that our detectors are in proper working order. We measure the rate of muons at different heights and show that the rate increases with the height. We are uncertain if this part of the experiment is ruined by the fact that all measurements are taken indoors, and that we actually show the dependency of how much muons decay through concrete and other building materials. We measure the angle dependency at a constant height, and show that the rate of muons follows a $\cos^2$-function within a 95% confidence interval. This result lies close to the edge of the interval and the theory might be disproved if one were to collect more data during this experiment. We have taken a 5-day measurement to show that the rate of the cosmic rays follows a Poisson distribution with a p-value of 0.90.

1 Introduction

Cosmic rays are very interesting to look into. It is believed that cosmic rays played a key role in the evolution of life on Earth, as it is ionizing radiation that can lead to mutations in early species[1]. Especially since cosmic rays are high energy particles where the most common energy is in the order of 10^8eV, but can reach upwards of 10^{20}eV. By far most of the high energy cosmic rays are actually particles and most of these particles are protons that is to say hydrogen nuclei. It is therefore essential for early life to avoid these high energy particles to survive. As the cosmic rays hit the molecules and atoms in the atmosphere they are converted into different particles, for instance muons, but they have a lot less energy than the original high energy cosmic rays, making them not as dangerous to different organisms [2].

Firstly, it will be determined if there are any light leaks in the detectors. Thereafter it will be determined if the rate of coincidence between two detectors is Poisson distributed. The detection efficiency of the three detectors will also be investigated. Additionally, the zenith dependence of cosmic rays will be examined. Furthermore, it is interesting to measure the height dependency of the cosmic rays as more and more people frequently fly around the world and spend more time over 3 km above the ground. This could lead to an increased exposure to ionizing radiation that could lead to further health and reproduction issues.

2 Theory

Ever since the first observations of cosmic rays, the topic has been widely discussed and is still very open to interpretation. At the moment, cosmic rays are believed to be radiation originating from way outside our own solar system. It is believed that cosmic rays are not directly correlated with solar activity, but is on the other hand connected, since increased solar activity results in a greater magnetic field from the sun, shielding the solar system from the high energy particles from space. We are not looking into the effects of solar activity, but this raises the possibility of solar activity interfering with our experiment. The Sun's activity has been correlated to the amount of sun-spots on the solar surface. These have been measured since the 1880's and are shown to fluctuate with a period of around 11 years. All of the experiments in this report are on a significantly smaller time scale, as they range from minutes to a couple of days of collecting. Also every experiment is performed within 3 weeks, so the solar activity will not vary much during the data collection.[3]

2.1 Relativistic effects for muons

Muons are a charged particle from the second lepton family. They are made from primary cosmic rays in the atmosphere. Primary cosmic rays are the particles coming directly from outer space, while secondary cosomic rays are products of the interactions in the atmosphere [4]. Since the cosmic rays are high energy particles with energy values typically at around 300MeV and can be much higher, the muons are often created with relativistic velocities [2]. The muons can decay by the weak interaction

$$\mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu$$

Or by the similar process for the anti particle obeying lepton number conservation. Its lifetime in the rest frame is $t = 2.2\mu s$. Since they are typically created at around 10km up in the atmosphere the only reason why we see so many on Earth is due to time dilation. The mean travel distance is namely at around only 1km in its rest frame and therefore the ratio of muons present 10km above sea level and the number of muons at sea level would be much different if the relativistic effects had not existed [5].

2.2 The Cosmic Hunter Detectors

The Cosmic Hunter uses plastic scintillating tiles made of a polystyrene compound where cosmic rays can hit the scintillating material in the detector. This excites the scintillating material, which then emits light. The scintillator needs charged particles to function for instance muons. They can also detect photons, but this is due to the different ways photons can interact with matter for instance pair production, which creates two charged particles. The light from the scintillating material is picked up by a photodetector and the energy is proportional to the energy of the original high energy particle. The photodetector converts the light into an electronic signal and sends the signal to the main unit. The main unit then knows that this plate has a count [6] [7]. If you choose to set the detector to only count coincidences between multiple plates, an incident is then only counted if the plates register an event within a certain time interval, set by the company making the detector [8].

2.3 Detector efficiency

In some of the experiments we need two detectors, but are given three. Because we need to use two, we want to use the most efficient detectors. The efficiency of a detector can be written as

$$\epsilon = \frac{N_0}{N}, \tag{1}$$

where ϵ is the efficiency, N is the number of detected particles and N_0 is the total number of particles going into the detector. When we send particles through multiple detectors, we would expect a coincidence count, where a coincidence is when both (or all) detectors register a particle at effectively the same time,

$$N_{ABC...} = N_0(\epsilon_A \cdot \epsilon_B \cdot \ldots) \tag{2}$$

So for our three detectors (A,B,C) we can write

$$N_{ABC} = \epsilon_A \epsilon_B \epsilon_C N_0 \tag{3}$$

and

$$N_{BC} = \epsilon_B \epsilon_C N_0 \tag{4}$$

then

$$\frac{N_{ABC}}{N_{BC}} = \frac{\epsilon_A \epsilon_B \epsilon_C}{\epsilon_B \epsilon_C} \frac{N_0}{N_0} = \epsilon_A \tag{5}$$

This can be done for all combinations of detectors [9].

2.4 Zenith Dependency

We want to determine if the cosmic rays really come from above and not just from Earth. And if they do come from above what would their zenith angle dependency be. A sketch of the zenith angle can be seen on figure 1.

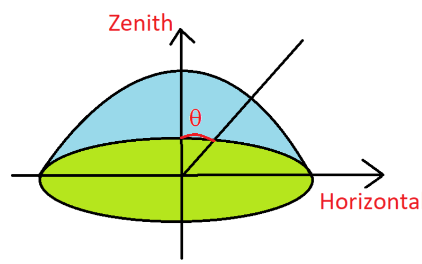

Figure 1: The zenith angle θ. If the cosmic rays come from space we would expect more counts when the angle is $\theta = 0°$ and fewest when $\theta = 90°$.

If we measure with one detector, and assume that the muons only come down from above, our measurements would be proportional to the areal projection of the area of the detector, on to the plane from where the muons come. So, if the area of the detector is denoted by A and the detector is assumed to be infinitely thin, then the counts would follow

$$N \propto \cos(\theta), \tag{6}$$

where θ is the angle from zenith, see figure 1, and N is the number of counts. If we use two detectors, we have to multiply the two projections together to get the combined projection. This gives us

$$N \propto \cos(\theta)\cos(\theta) = \cos^2(\theta). \tag{7}$$

If the counts follow this function, we would show that the cosmic rays are indeed cosmic, and not generated here on earth [9].

2.5 Height Dependency

When cosmic rays bombard the atmosphere they interact with molecules and generate showers of secondary particles, including muons. These showers are created around 10km above the Earth's surface. Since the muons are created at slightly different heights and their decay times are varying, (muons has an exponential decay-rate), we would expect that the further we go towards the source, the more flux we will get. This effect would be blurred by anything above the detectors, such as concrete, since muons as well as many other particles has a much larger decay rate in denser materials [5][2].

2.6 Poisson distribution

The Poisson distribution is a probability distribution given by

$$P(N;\bar{N}) = \frac{\exp(-\bar{N})\bar{N}^N}{N!}$$

Where P is the probability of measuring N counts in a given time interval where the mean count rate is $\bar{N}$. The Poisson distribution often works well to describe the data when the counts are rare, the events are independent of each other, and when the mean does not change over the period [10]. Therefore one should expect that the count rate of the muons would follow a Poisson distribution given the three parameters really holds true for the experiment.

3 Experimental setup

The experiment was conducted by using the cosmic hunter equipment from CAEN to detect cosmic rays. The setup consists of a coincidence box and three scintillator tiles coupled to silicon photo-multipliers. Two of the scintillator tiles can be mounted on a device with a fixed distance of 40 cm with an adjustable zenith angle. This is all placed on a movable wagon as seen on figure 2.

The coincidence box can be put into different modes depending on which tiles are needed to have a coincidence to get a "real" count. This mode is changed depending on the experiment. Additionally the integration time of the coincidence box was set to 10 min. throughout the whole experiment.

3.1 Light Leak Setup

Firstly a measurement is needed to determine if there might be light leaks in the detectors. To do this a black blanket was placed on top of all of the three detectors. Additionally the light was turned off inside the room in case the blanket was not completely light proof. This measurements lasted for 10 min. After, another measurement was made which also lasted 10 min., but this measurement was without the blanket and with the light on.

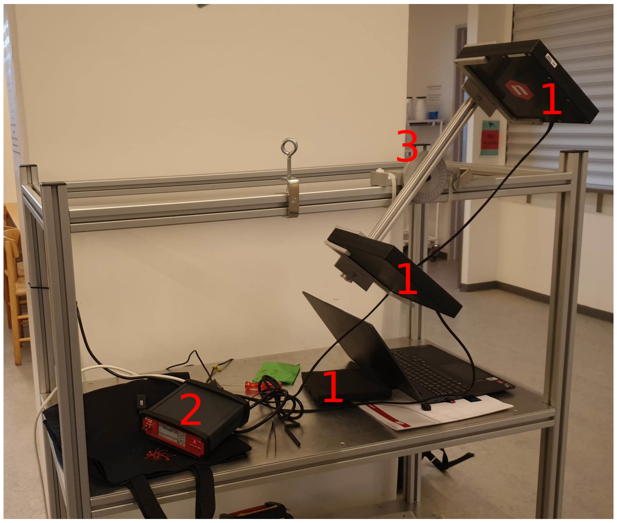

Figure 2: The cosmic hunter detecting cosmic rays. (1) are the scintillator tiles connected to the coincidence box (2). Two of the scintillator tiles are mounted on a device (3) with a fixed distance between the tiles. The device also have a protractor to measure the angle with respect to zenith.

3.2 Poisson Distribution Setup

It was also necessary to make a very long measurement to determine if the rate of coincidences are Poisson distributed. How the tiles are placed with respect to each other and where the wagon with the tiles were placed does not matter as long as the measurement is long enough. The measurement therefore lasted for about 5 days and the wagon was placed in the basement.

3.3 Detector Efficiency Setup

To determine the detection efficiency of the three tiles several measurements were needed. All of the measurements lasted 10 min. To calculate the efficiency a measurement was needed of all the tiles together and a measurement of the two other tiles for each of the detectors. Note that it is very important to only have the two detectors of interest stacked and the one not in use put away from the others. This ensures that the conditions for the different measurements are identical.

3.4 Zenith Angle Dependency Setup

Penultimately measurements were needed to determine the zenith dependence of the cosmic flux. Two of the tiles were mounted on the device as seen on figure 2 to keep the distance between them constant as well as being able to tell the angle. The two detectors should be the two with the highest efficiency to ensure as many counts as possible, but since they were all at almost the same efficiency we decided to use A and C since B looked a little suspicious with the many counts see section 4.3. These measurements all lasted 10 min. The measurements were taken at $0°$, $20°$, $40°$, $60°$, and $80°$.

3.5 Altitude Dependency Setup

Finally, the altitude dependence needed to be determined. This was done by taking a measurement at every second level of the eight level building at IFA at Aarhus University, so at level 0, 2, 4, 6, and 8. These measurements lasted for 20 min. each. In these measurements, the tiles simply lay on top of each other on the wagon. Tile B was once again not used.

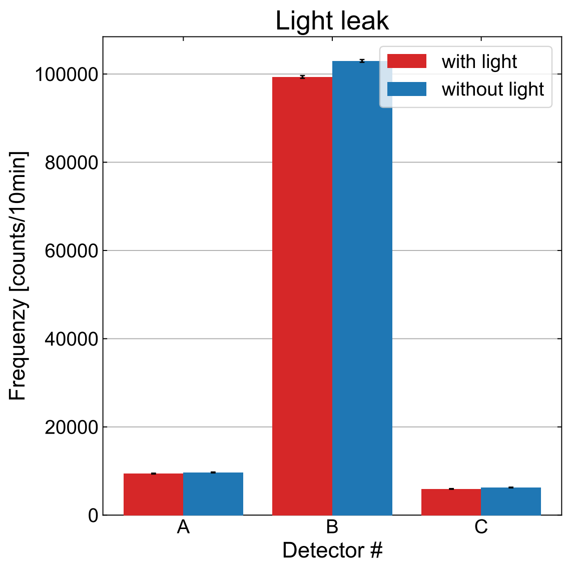

Figure 3: The difference between with and without light is very small, however there were more counts when the light was off compared to when the light was on in all three tiles. There is a significant difference between the measured counts of the three tiles as tile B had about 10 times as many counts as the other two detectors. As the uncertainty is $\sqrt{N}$, the error bars are too small to be seen.

4 Data

4.1 Light Leak

The results of the counts in the three detectors with and without light is seen in figure 3. Surprisingly it was the measurements with the light off that had the most counts.

As seen in figure 3 and table 1 the difference between having the light on and off was very small.

#	Percentage
A	97.3 ± 1.4
B	96.5 ± 0.4
C	95.5 ± 1.7

Table 1: The number of counts when the light was on compared to when the light was off seen in figure 3. It makes little difference whether the light is on or off.

4.2 Poisson Distribution

The data points and the fitted Poisson distribution is plotted in figure 4. The fit gave the mean value $\bar{N} = (94.4 \pm 9.7)(10\text{min})^{-1}$ where the detector was placed on the zeroth floor for almost 5 days.

It is seen to match very well with the Poisson distribution with approximately $\frac{1}{5}$ of the data points lying outside one σ. The χ^2 value was calculated by collecting the data points in bins with a width such that the expected number of counts in that bin is $E_i > 5$ as recommended by [10]. From this it is possible to calculate the χ^2- and the p-value given the number of degrees of freedom. This gave the results in table 2.

χ^2	ν	χ^2/ν	p
30	41	0.73	0.90

Table 2: ν is the number of degrees of freedom given by the number data point subtracted by the number of fit parameters. The p value represents the probability of getting a χ^2 greater than 30 given that the Poisson distribution is the true one.

Since $p = 0.90$ we are not rejecting that the Poisson distribution is the true distribution. The time dependence of the count rate was seen to

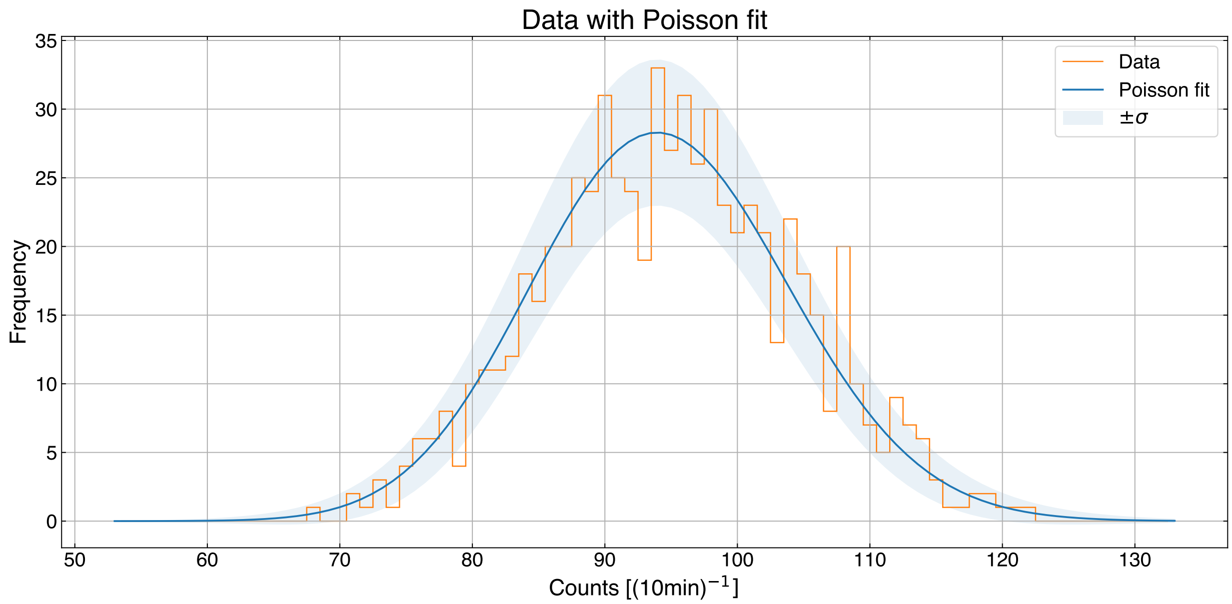

Figure 4: The data is seen to match very well with a Poisson distribution. Most of the bins are within one σ of the Poisson fit.

very constant as seen in figure 5 and there was no significant periodicity of the fluctuations.

4.3 Detector Efficiency

The efficiency of each of the three detectors can be calculated by equation 5 by comparing the measured coincidences for all of the tiles with the measured counts for two of the tiles. The results can be seen in table 3.

#	Efficiency
ϵ_A	0.720 ± 0.033
ϵ_B	0.737 ± 0.033
ϵ_C	0.733 ± 0.033

Table 3: The efficiency of the three detectors is seen to be almost the same at around $72\% - 74\%$.

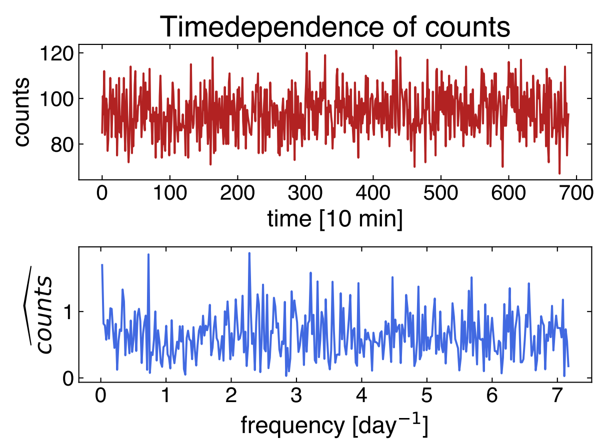

Figure 5: The count rate (upper) fluctuates randomly around the mean, and the Fourier transform (lower) reveals no systematic periodicity in the signal.

Interestingly, the tiles have almost the same efficiency, even though the count rates in the individual tiles are very different as seen in figure 3.

4.4 Zenith Dependency

When measuring the zenith angle dependency, we get a coincidence count for each angle. We have measured at 0, 20, 40, 60 and 80 degrees. This data is shown in figure 6. There we have fitted and tested a $\cos^2$-function and found a χ^2 value of 6.58 and a p-value of 0.09 which means that our data lies within a 95% confidence interval (or within 2σ) of the theoretical $\cos^2$-function given by $f(\theta) = (0.195 \pm 0.02)cos^2([0.91 \pm 0.05]\theta)$.

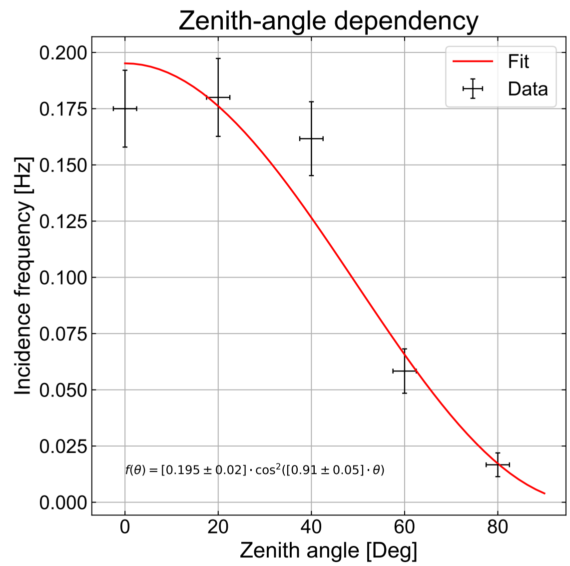

Figure 6: The black data points is the frequency of the incidents counted by the detector. As the detector counts for 10 minutes, it is simply $N/10min$. The angle in degrees is on the x-axis. The red line is our fitted $f(\theta) = A\cos^2(\omega\theta)$ function.

4.5 Altitude Dependency

We have taken data from separate floors in the highest building at our faculty, where we measured the frequency of the cosmic rays at different levels. This is shown in figure 7, which shows that the higher up the detector is, the more cosmic rays are detected.

5 Discussion

5.1 Poisson fit

The data follows a Poisson distribution very well as seen on figure 4. Most of the data lies within one standard deviation from the Poisson fit. Furthermore the p-value was $p = 90\%$ so it is very likely that the data points were actually drawn from a Poisson distribution. The reason for this is that the three conditions for the Poisson distribution seem to hold for the experiment. Of course the counts are independent of each other and the events are relatively rare. However, we could not have been sure that the average count rate would not change over the scale of the measurement at 5 days. For example one might expect a periodic feature of the mean with period of 1 day as the sun could affect many things such as a difference in temperature or a change in the air humidity between night and day. But the Fourier transform did not find a peak at this frequency. We must therefore conclude that the mechanisms controlling the muon flux at the surface of the Earth are not controlled by night and day. As a bonus we can hereby also conclude that the

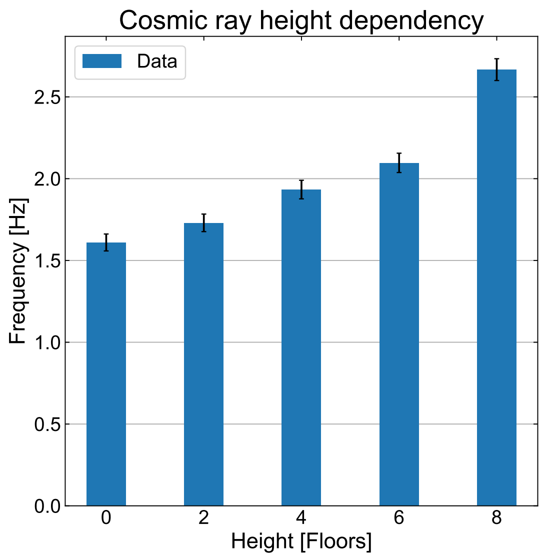

Figure 7: The frequency of detected muons on different floors of the university building. Every floor is separated by approx. 4m, but the goal is to show that the rate of muons are increasing with altitude.

detected muons are mainly made from cosmic radiation from outer space and not from the sun. One could, on the other hand, argue that there actually are peaks at 0.7 and 2.3 cycles/day. But these are not significant and since there should not be an obvious reason for a periodicity at these lengths, it must be characterized as noise.

5.2 Detector Efficiency

As we saw in table 3, the efficiencies of the detectors were close to each other. However the individual counts varied a lot across the three detectors. This can be verified by looking at the individual counts from the light leak experiment and figure 3. So since ϵ_B is not much greater than the other tiles we can conclude that the count rate in B is around $R_B \simeq 167\mathrm{s}^{-1}$. And in order to have the above fulfilled one must therefore have $R_B^{-1} \simeq 0.006s \gg \tau$, where τ is the tolerated time dilation between two measurements to classify it as a coincidence. However this is not a problem at all for the experiment since one can easily hold τ fixed and still have $\tau \gg \Delta t$, where Δt is the travel distance for the muon. These are namely moving at relativistic velocities [5] such that Δt should be in the interval of approximately $0.1 - 1$ns depending on the distance between the plates. The distance between the plated varied from being just their thickness to around 40cm depending on the experiment.

5.3 Light leaks

The result in table 1 shows that the rate of counts increases with less light in the room. This is a very confusing result as we cannot find any reason as to why this should be the case. We do to think that the values are so close that the difference with and without light can be neglected. We checked the weather data to see if this could have had an effect, and both wind speed, temperature, and humidity changed a little between the two measurements. But since we do not know the precise effect of these forces, we will not conclude anything from this. If the experiment should be performed again one should definitely try to investigate this strange result closer, to see whether the result could be reproduced. Nonetheless this was a small effect, which justifies that it was no problem that we measured with lights on during the rest of the experiment.

5.4 Zenith angle dependency

In this part of the experiment we found that the data fits the model within a 95% confidence interval. This is fine, but the model still does not fit as well as we would like. If we were to do the experiment again we would like to do more measurements at more different angles. As there are some points in figure 6 that lie away from the function, we would like to get more data points to show that these might just be a statistical fluctuation, or maybe to show that the theory does not fit after all, as it is difficult do determine from the few data points.

5.5 Altitude dependency

For this experiment we think that we are more likely to have measured the amount of concrete above the detector rather than the height dependency of the cosmic rays. We think that since the muons have travelled 15km through the atmosphere then the last 20-or so meters are not going to make the big difference for their decay. Though we do believe that the muons might decay faster in the concrete, and that we therefore have found a concrete-dependence rather than a height dependence. If we were to do this again we might do the experiment on the side of a mountain or outside at different heights. Here we would be able to do measurements with small time intervals and we could travel up and down, with little change in the atmosphere above the detector.

6 Conclusion

We first investigated the light dependence of the count rates and the efficiency of each tile. Surprisingly we found the count rates to be higher when the light was off which we could not explain. However this effect was small so we measured with the light on. This strange result should also be investigated if one should perform the experiment again to see if the effect just was due to statistical errors. The efficiencies were found to be almost the same for the three tiles at around $\epsilon = 0.73 \pm 0.03$ which showed that it did not really matter which tiles we used. We have shown that the detection rate as a function of zenith angle varies as a $\cos^2$-function with a p-value of 0.08 which is within the 95% confidence interval. However this was not not as convincing as the Poisson fit to the count rates. That data followed the distribution very well and gave a p-value of $p = 0.90$. With great confidence we can therefore conclude that the count rate follows a Poisson distribution which indirectly indicates that the mean count rate did not vary over the 5 day measurement. This statement were supported by the investigation of the time dependence of the count rate that showed no trends apart from random noise. We have also shown that the rate of muons has a height dependency such that it increases with the height. However it is still unclear whether this effect was mainly due to the amount of concrete above the detector as all measurements were done inside, or it actually was the shorter distance to the outer atmosphere itself that was the course of the effect.

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