Air Fluorescence Photon Yield In Cosmic Ray Showers

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Abstract

Several cosmic ray observatories rely on fluorescence in air as a means to detect cosmic rays and measure their energy. An accurate measurement of the conversion of energy from a cosmic ray shower into fluorescence photons is key to this method. In this experiment, air fluorescence photon yield caused by the emission of electrons from a ^{90}Sr source was measured to be 3.0 ± 1.1 photons/(electron $\cdot$ m). Our goal of this measurement is for it to be a prototype for more accurate measurements of fluorescence photon yield as a function of temperature, pressure, and mixture in hope to resolve the AGASA-HiRes problem.

1 Motivation

1.1 Fluorescence Detection and Photon Yield

When a high energy cosmic ray collides with the earth's atmosphere, it initiates a shower of secondary particles (see Figure 1), including electrons and positrons, the scattering of which cause the atmosphere to fluoresce. The

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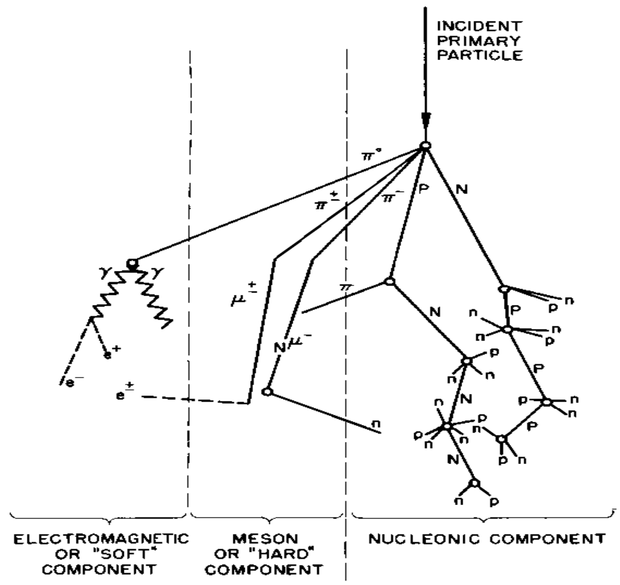

Figure 1: Cosmic ray shower composition

primary source of atmospheric fluorescence is the excitation of nitrogen molecules. One of the techniques in detecting and studying high energy cosmic rays is observing this fluorescence.

In order to measure the energy of the primary cosmic ray, the fluorescence detection method relies on the atmosphere as a calorimeter. Fluorescent light is detected by a by an apparatus of photomultiplier tubes (PMT) on clear, dark nights. The accuracy of this method depends heavily on the relationship between the path length of a given energy particle in the atmosphere and the amount of fluorescence it initiates.

> *Fluorescence photon yield* or just *fluorescence yield* is the number of photons fluoresced per unit length that a given energy electron penetrates through air.

1.2 Previous Fluorescence Yield Measurements

The first measurement of fluorescence photon yield was done by Alan Bunner[3] for his PhD thesis. He combined existing kinetic theory to predict the effect of pressure and therefore altitude dependence. His work had considerable error but remained the standard for many years for interpreting fluorescence

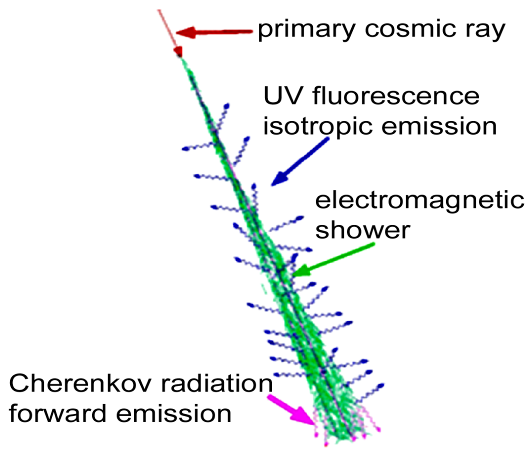

Figure 2: Fluorescence detection of cosmic ray showers

cosmic ray data. More recently Kakimoto et al.[4] did a study of the pressure dependence of fluorescence yield. Another study by Nagano et al.[5] in agreement with Kakimoto gives the currently accepted value of fluorescence yield at standard temperature and pressure to be 3.7 ± 0.148 photons/(electron$\cdot$m) with 13.2% systematic error.

1.3 The AGASA-HiRes Problem

The Akeno Giant Air Shower Array (AGASA), a ground array cosmic ray detector, and the High Resolution Fly's Eye fluorescence detector (HiRes) give disagreeing energy spectra[1] (see Figure 3). The energies in the HiRes spectrum are approximately 30% less than those of AGASA. While it is possible that AGASA's computer based reconstruction may not be precise enough, inaccuracy in the measurement of fluorescence photon yield could show HiRes's spectrum to be too low. If the accepted value of fluorescence yield is too high, then flourescence detectors like HiRes would predcit that the number of scattered particles in a cosmic ray shower is actually lower than it is in reality, underestimating the energy of the primary cosmic ray. The Pierre Auger Project[2] is a hybrid detector, using both ground array and fluorescence detection methods and is more sensitive than either AGASA or HiRes before it. This makes an accurate measurement of fluorescence photon yield even more necessary.

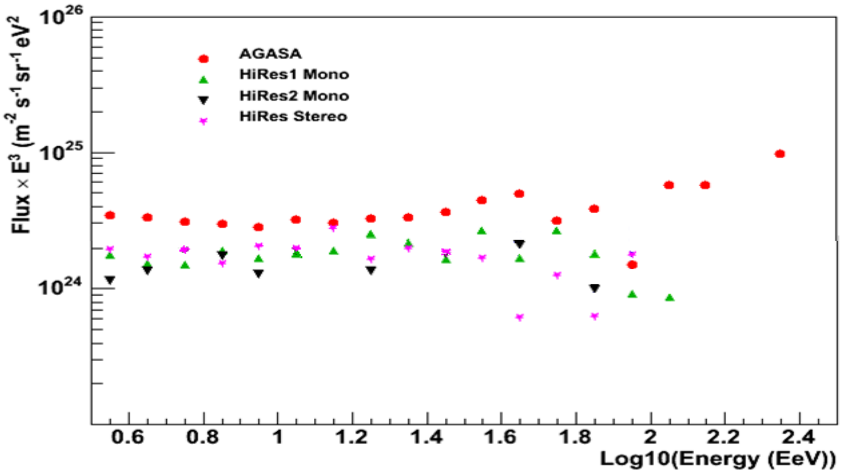

Figure 3: AGASA vs HiRes. Note that HiRes spectra are lower than AGASA's. Inaccurate knowledge of the value fluorescence yield in air could explain this discrepancy.

2 The Experiment

2.1 Theory

As defined in section 1.1, fluorescence photon yield (Y) can be expressed as:

$$Y \equiv \frac{N_\gamma}{N_e L} \tag{1}$$

where N_γ is the number of photons emitted by N_e number of electrons passing through a line of air of length L. If one uses a photomultiplier tube (PMT) to observe this fluorescence, then the number of fluorescence photons that actually produce a signal (N_{sig}) is attenuated by several factors: the fractional solid angle[1] in view of the PMT (Ω, see Figure 4), the transmission of the any filter used (f), the PMT's quantum efficiency (QE) and collection efficiency (CE), and L is now the length of electron beam in view of the PMT.

$$N_{sig} = N_\gamma \cdot \Omega \cdot f \cdot QE \cdot CE \tag{2}$$

[1] $\Omega = \frac{\Omega_{solid\ angle}}{4\pi}$

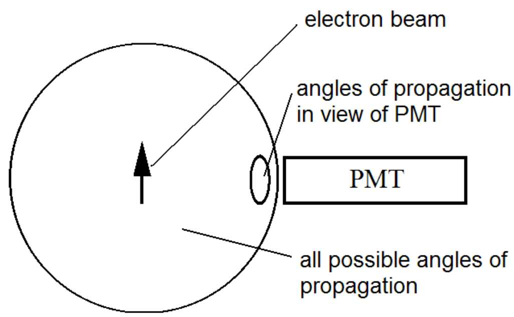

Figure 4: Fractional solid angle (Ω)

Assuming reasonable values[2] for Ω, f, QE, CE, L, and relying the [5] measurement by Nagano et al.[5] of Y as an order of magnitude estimate, the number of fluorescence events that we could expect to detect (N_{sig}/N_e) was of the order of 10^{-4}.

2.2 Setup and Procedure

We used a 1 mCi ^{90}Sr sample as a source of energetic[3] electrons. The ^{90}Sr source was placed down in a small hole drilled part way into a solid plastic cube. This collimated the emission of electrons into a vertical beam. The electron beam passed through a pair of plastic scintillators connected to PMTs, used for triggering events. The first PMT was a Hamamatsu E2624-C1 with a plastic scintillator of thickness 3 mm. The second was a Hamamatsu H1161 and had a scintillator of thickness 2 cm. A third Hamamatsu H3178 PMT (referred to as the"FD PMT") observed the region between the two trigger PMTs for fluorescence.

Because single photon counting sensitivity was necessary for this measurement, several methods were used to protect the fidelity of the FD PMT's signal. The apparatus shown in Figure 5 was entirely enclosed in a dark box. Both scintillators were covered to prevent light from being seen by the FD PMT. A wide pass UV filter (see appendix B for the spectrum) was chosen for its high transmission in the range of the nitrogen fluorescence spectrum

[2]Round the numbers in table 1 for some reasonable values.

[3]Nagano et al.[5] measured the mean energy of electrons emitted by ^{90}Sr to be 0.85 MeV.

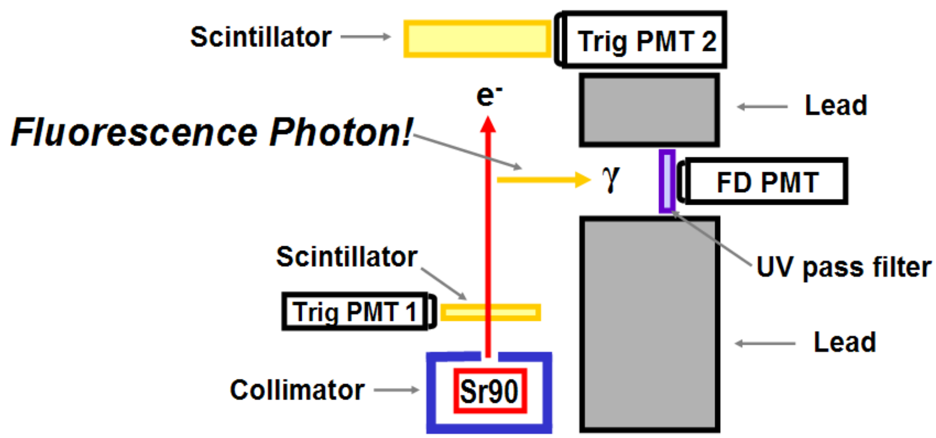

Figure 5: Experiment setup

(see appendix A). This filter helped to eliminate contamination of the signal by visible light from imperfections in the dark box. Lead bricks surrounding the the FD PMT suppressed contamination by bremsstrahlung radiation that may have been created by the electron beam scattering in the collimator or elsewhere.

We took data from the FD PMT through an LeCroy 2249W Analog to Digital Converter (ADC) using the coincidence of the two trigger PMTs as a gate with a width of 40 ns and histogramed the events. The correct timing was found by inserting an uncovered scintillator into the electron beam in view of the FD PMT, artificially making a signal[4]. Limiting our data to the coincidence of the trigger PMTs in a narrow gate further aided in suppressing non-fluorescence signal events. Because the vast majority of events were events with no signal, our histogram contained a large peak of counts referred to as the "pedestal." An amplifier for the FD PMT signal was necessary to pull the single photon fluorescence events significantly away from the pedestal so that they could be counted. A foam block was cut to fit tightly between the lead bricks and the side facing the FD PMT was covered with thick black paper. Nothing else about the experimental setup was modified and data was taken. This data was used to give a background signal that may be caused by the thermal emission of electrons in the PMT, radioactive contaminates, or the instability of the electronic equipment.

[4]We found it reasonable to assume that the time scale for scintillation in a plastic scintillator is comparable to that of fluorescence in air.

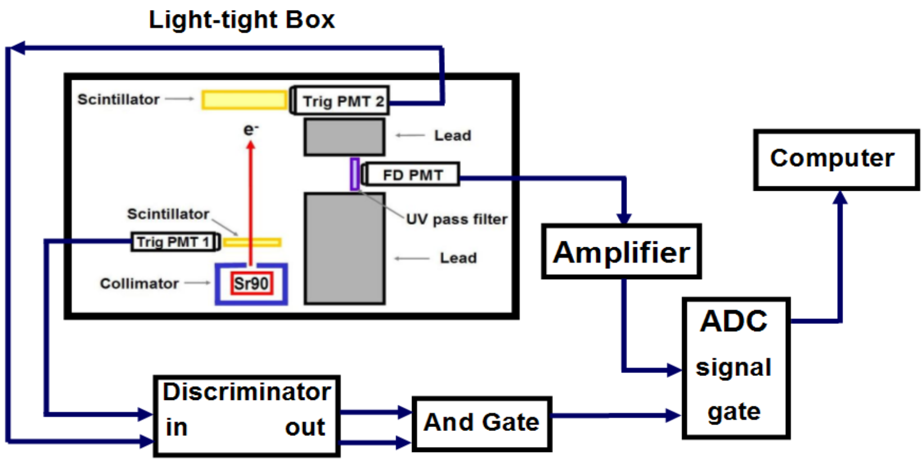

Figure 6: Data acquisition setup

3 Analysis

3.1 Data

Approximately 6 million events were recorded for both the signal and the background. This was necessary in order to collect a significant number of fluorescence events because of the many attinuation factors shown in equation 2. The two sets of data are normalized and plotted in Figure 7. Knowing the gain of the PMT, we expected a single photon signal to peak around channel 135 as it does. The low occurrence of background events in the region of the fluorescence events verifies our signal's fidelity. Subtracting the background from the signal gives a fairly clean single photon distribution as our fluorescence events (see Figure 8).

Making a cut on this distribution, the counts between channels 80 and 180 were summed to give N_{sig}. The number of triggered events (N_{trig}) selected the number of beamed electrons that were observed (see Figure 8). Therefore:

$$N_{trig} = N_e \tag{3}$$

Combining equations 1, 2, and 3 gives our equation for calculating the fluorescence photon yield:

$$Y = \frac{N_{sig}}{N_{trig} \cdot \Omega \cdot f \cdot QE \cdot CE \cdot L} \tag{4}$$

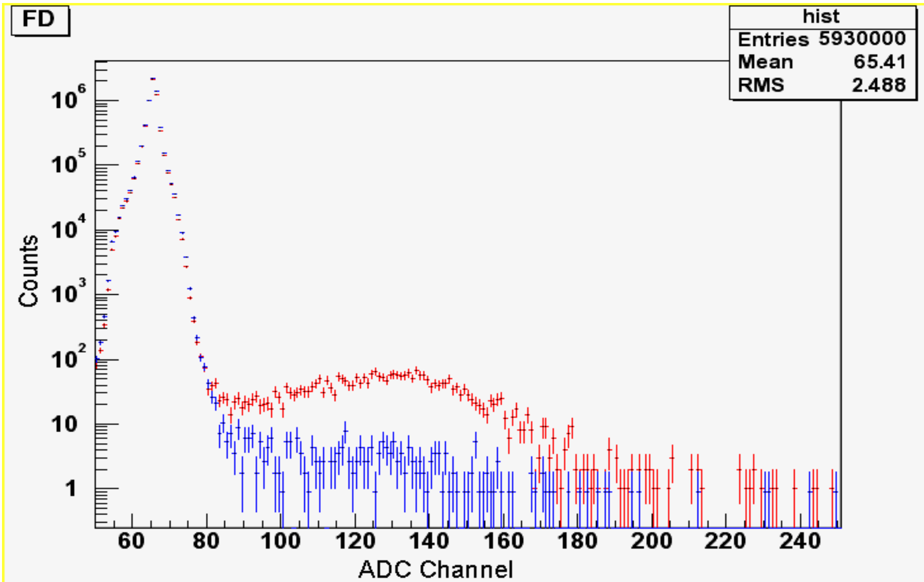

Figure 7: Fluorescence data, signal: red, background: blue

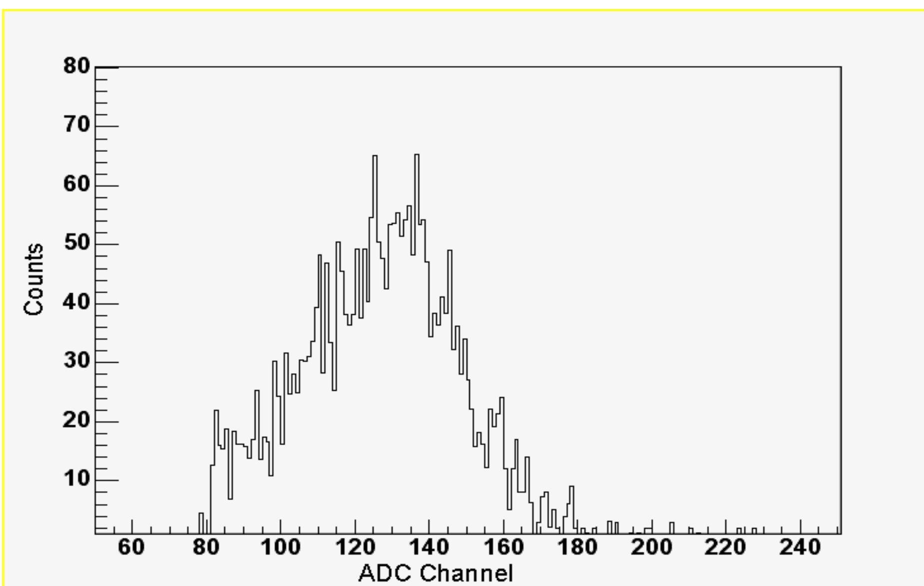

Figure 8: Signal minus background, fluorescence events. N_{sig} was recorded as the counts between channels 80 and 180.

Table 1: Data and error

Quantity	Magnitude	Error (%)
N_{sig}	2.6×10^3 photons	10
N_{trig}	5.9×10^6 electrons	0
Ω	9.7×10^{-3}	10
f	0.89	5
QE	0.25	30
CE	0.85	10
L	10 cm	5
Y	3.0 photons/(electron $\cdot$ m)	35

3.2 Error

The measured value and estimated error[5] for each quantity is displayed in table 1. Addition of errors in quadrature gives the error on the fluorescence photon yield to be approximately 35%.

4 Conclusion

4.1 Results

We measured the fluorescence photon yield of air excited by electrons from a ^{90}Sr source to be 3.0 ± 1.1 photons/(electron $\cdot$ m). As a prototype for future measurements, this experiment has been a success. The fact that this number can be produced, within range of previous measurements, by such a rough study demonstrates that a precise measurement of this number is achievable. Compare our measurement of fluorescence yield with the 3.7 photons/(electron $\cdot$ m) by Negano et al. If fluorescence yield actually is smaller than his value, this could explain the AGASA-HiRes discrepancy by shifting the HiRes spectrum up into agreement with AGASA. Further investigation into accurately measuring fluorescence photon yield is necessary in order to properly interpret data from cosmic rays detected by fluorescence. Not only could a reliable measurement of this value resolve the AGASA-

[5] A possible error not included in this analysis is that Raleigh scattered Cherenkov light created by the electron beam might contaminate the signal, but this effect was not considered.

HiRes problem, it would improve the proper calibration of the Pierre Auger Project[2].

4.2 Recommendations for Future Experiments

An experiment measuring the temperature, pressure, and mixture dependencies of fluorescence photon yield is warranted. Putting an apparatus similar to the one Figure 5 in a vacuum chamber would not only make it light-tight, but allow the ability to test variable mixtures of N_2, O_2, and CO_2 at different temperatures and pressures. This procedure could be used to simulate cosmic ray fluorescence at different altitudes.

New electronics, especially a clean amplifier and a quality PMT of high-gain, would give confidence that no irregularities could affect the data acquisition. A way of automatically alternating taking signal and background data by means of an automatic shutter would help reduce any miscomparison of the data because of instability in the pedestal.

A more sophisticated method of subtracting the background from the signal either by weighting the significance or doing some kind of curve fitting may give a more reliable result.

Quantum and collection efficiency of the FD PMT should be precisely measured. This alone, could greatly reduce the error in our measurement.

Finally, a future measurement should be capable of collecting many events. Taking events of the order of 10^7 or more would mean that several thousand fluorescence events could be observed.

5 Acknowledgments

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[2] Clay, Roger, and Bruce Dawson. **Cosmic Bullets**. Reading: Addison-Wesley, 1998.

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[5] Nagano, M. et al. "Photon Yields from Nitrogen Gas and Dry Air Excited by Electrons." arXiv:astro-ph/0303193v1. 10 Mar 2003.

A Nitrogen Spectrum

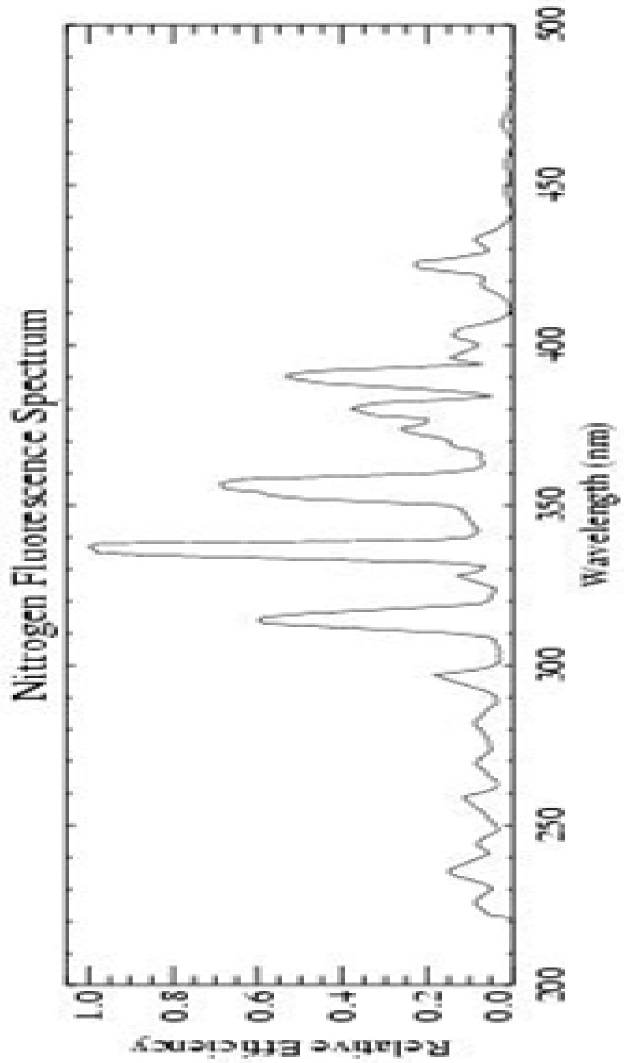

Figure 9: Nitrogen spectrum. Principal wavelengths of emission are between 300 and 400 nm.

B UV Pass Filter

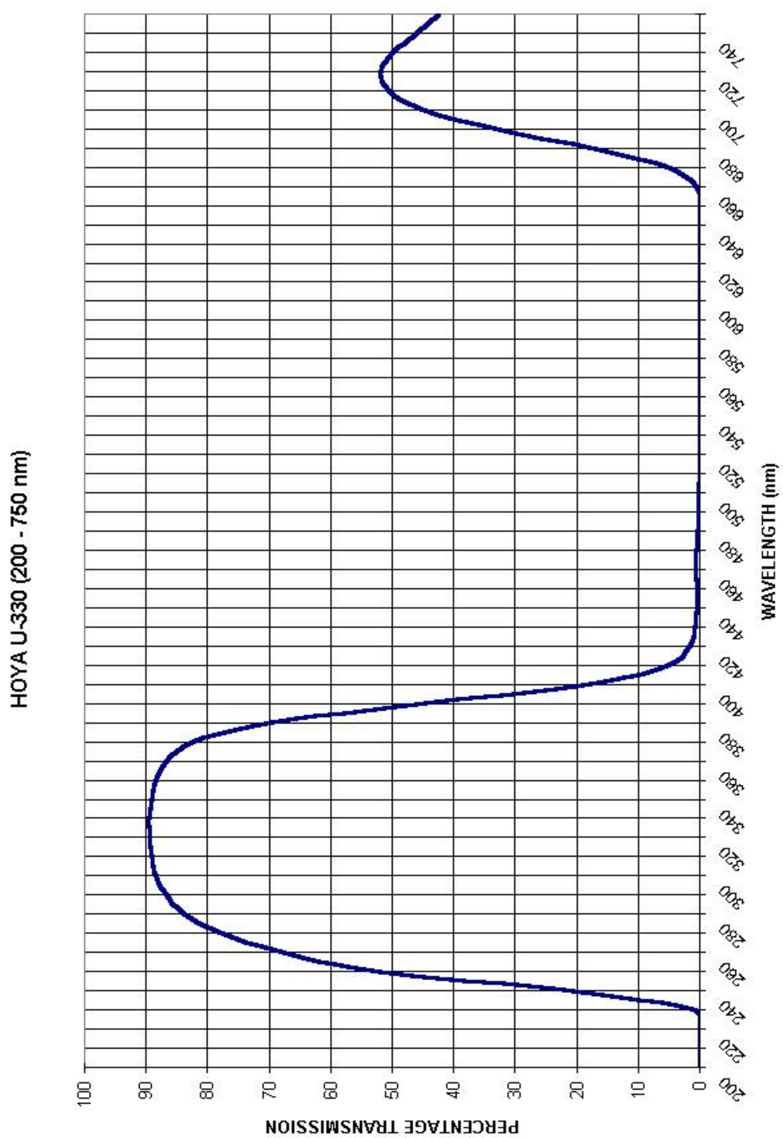

Figure 10: Hoya U-330 filter from Edmund Industrial Optics. Transmits the principal wavelengths of the nitrogen spectrum.

C Gain Plot

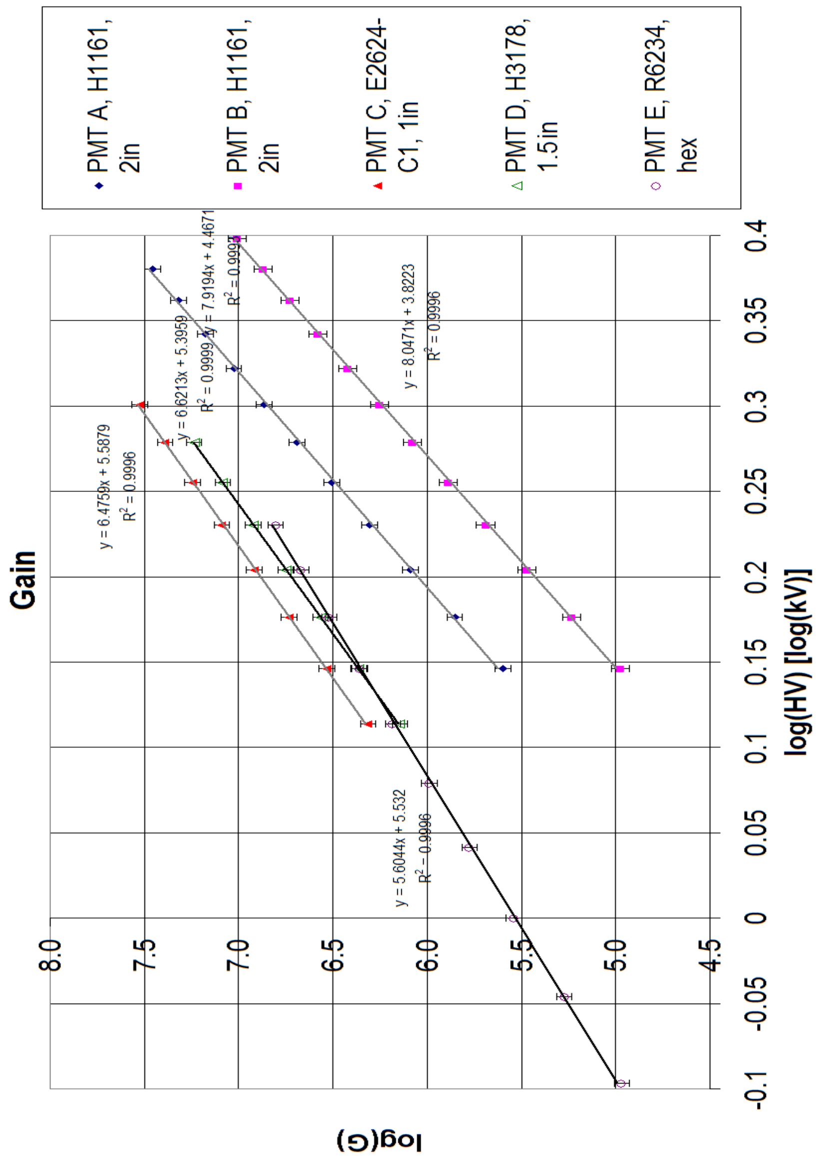

Figure 11: Trig PMT 1 in this experiments setup is PMT C on this plot. Trig PMT 2 is A and the FD PMT is D.

D ENF Plot

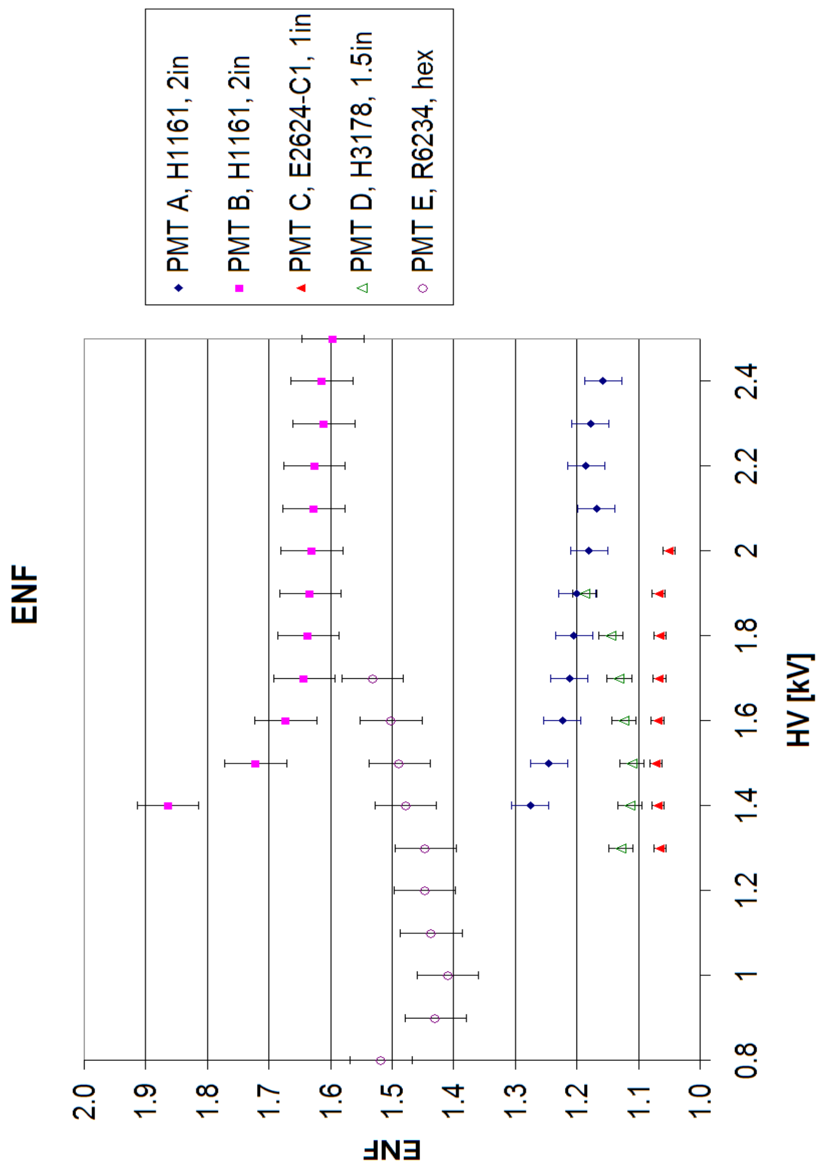

Figure 12: Trig PMT 1 in this experiments setup is PMT C on this plot. Trig PMT 2 is A and the FD PMT is D.