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Experimental Details and Calibration of The FLASH Thin Target Experiment

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Abstract: The thin target mode of the FLASH (Fluorescence in Air from Showers) experiment was conducted at SLAC. The aim was to measure the total and spectrally resolved fluorescence yield of charged particles traveling through air to better than 10%. The setup consisted of a 15.24 cm thick gas volume which was viewed by two PMT detectors each equipped with 15 remotely interchangeable narrow band filters to measure the fluorescence spectrum between 300 and 430 nm. Final results of the FLASH experiment will be presented in a talk at this conference. The calibration of the experimental setup is crucial in minimizing the systematic uncertainty of the measurement. We will describe how the physics of Rayleigh scattering is used to derive an absolute end-to-end calibration of the experiment from first principles. In addition, a method for a relative calibration is presented using a setup with a mercury lamp, a monochromator and a NIST calibrated photo diode in a light sealed black box. Finally, the toroid measuring the beam charge had to be calibrated. The combination of all three measurement uncertainties provided an absolute calibration of the FLASH experiment.

Introduction

The FLASH experiment [1] was one of many experiments in the past few years conducted to measure the fluorescence yield with a much higher precision [2, 3, 4, 5, 6, 7, 8]. Experiments like HiRes, Auger, and TA rely on understanding the fluorescence yield of charged particles in extended air showers when measuring the energy of cosmic ray primaries. Pinning down their energy scale with a high level of accuracy is crucial in order to confirm or refute the existence of the GZK cut-off and in order to measure where it occurs [9, 10, 11]. FLASH was conducted in the Final Focus Test Beam (FFTB) of the Stanford Linear Accelerator Center (SLAC) during three run periods, which is described elsewhere in these proceedings [12]. The objective of the FLASH experiment was a precise measurement of the fluorescence yield between 300 and 430 nm integrally and spectrally resolved. The fluorescence yield is commonly expressed in units of number of photons N_γ per number of electrons N_e per distance d traveled by the electron:

$$Y = \frac{N_\gamma}{N_e \cdot d}. \qquad (1)$$

The number of electrons per beam was measured with a toroid installed upstream of the thin and thick target. The toroid device was calibrated at SLAC after data taking with a precision charge coupled to the toroid and by charge injection at the front end amplifier input [13]. In order to translate the measured fluorescence signal in units of ADC counts into units of photons per unit length the experimental setup of the thin target was calibrated at the University of Utah after data taking. In comparison with previous fluorescence yield measurements [14, 15, 2], which corrected their data based on piece-by-piece calibrations, for FLASH a new method of an end-to-end calibration of the entire setup is applied making use of Rayleigh scattering of a nitrogen laser beam injected in the thin target chamber through the beam ports. The absolute uncertainties of previous yield measurements [15, 2, 6] were larger than 10%. With its end-to-end calibration the FLASH experiment aimed to reduce the uncertainty to below 10%. Since a nitrogen laser was used, the end-to-end calibration only determined the number of photons per unit length at a wavelength 337 nm. To extend the calibration to the entire wavelength range between 300 and 430 nm, in a second step the detector assembly is calibrated against a silicon photo diode using a high pressure mercury arc lamp monochromator combination as light source.

End-to-End Calibration Using Rayleigh Scattering of Laser Light

A schematic of the experimental set-up of the end-to-end calibration was shown in [16]. The thin target chamber (fully assembled) was installed in an environmental chamber. Using a temperature controller the temperature in the environmental chamber was kept at 29°C, which was the average temperature measured in the FFTB tunnel at SLAC. A nitrogen laser was mounted at a distance of approximately 2 m from the chamber. It injected a beam of 337 nm photons into the chamber along the electron beam axis. The light beam intensity was decreased by an aperture which was mounted on the beam port facing the laser. Thus the laser beam was confined to the center of the chamber. The scattered light passed through the baffled detector arms, was reflected by the UV enhanced aluminum coated mirror, passed through a filter in the filter wheel, and finally reached the PMT. The signal of the two photo multiplier tubes, which were named North and South PMT according to their position with respect to the beam line, was recorded with a LeCroy ADC and read out by a computer. Simultaneously with the PMT signal, the energy of the outgoing laser beam was measured by a pyroelectric energy probe installed on the opposite side of the chamber. The pressure inside the chamber was recorded as well. Based on Rayleigh scattering calculations as discussed in [17, 18, 19] and taking into account that fluorescence light is emitted isotropically, it then was possible to calculate the number ADC counts per emitted 337 nm fluorescence photon per meter, G. In order to be able to take measurements at different pressures inside the chamber coated glass windows with close to 100% transmission efficiency in the UV range are attached to both beam ports. The thin target chamber was connected to a vacuum pump and a pressure gauge. Data were taken at several different pressures between vacuum and atmospheric pressure, and a linear fit,

$$\Rightarrow \quad \frac{N_{ADC}-N_{ped}}{E} = G \cdot F \frac{SP}{T} + k_0 \qquad (2)$$

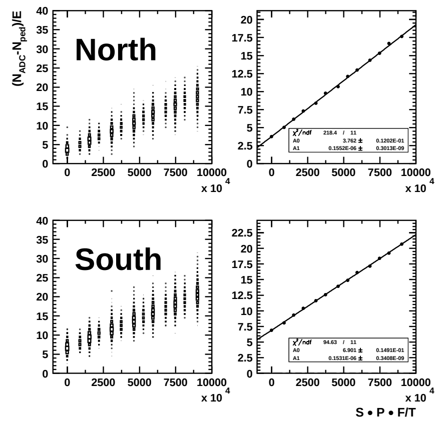

Figure 1: Plots representing equation (2). The plots are based on data taken with the setup described in [16] for the no-filter position. The left column shows the scattering of the data during each of the 12 different pressure runs. The right column shows the fits to the mean values of each run.

was performed to the data, varying the fit parameters G and k_0. Here, N_{ADC} is the signal counts recorded for each PMT, N_{ped} is the number of pedestal counts measured in the respective signal channel, F is the transmission efficiency of the selected filter, P, and T are the pressure and temperature measured in the chamber, and k_0 accounts for the light background from scattering of the laser beam with the chamber material. After the χ^2minimization, G represents the calibrated number of ADC counts per isotropically emitted photon per meter. Data taken at twelve different pressure points with the setup described above and in more detail in [16] for the NO-FILTER position is displayed in Figure 1. The values of G resulting from the fit are also shown in Figure 1 as parameter $A1$.

Relative Calibration Using Two Silicon Photo Diodes

Figure 9 of [3] shows a schematic of the experimental set-up of the relative calibration. It consists of a dark box containing one of the two silicon photo diodes, which were used for the calibration, and either the North or South PMT. In contrast to the set-up in [3] however, the silicon photo diode was installed at the close end of the dark box with respect to the mercury lamp, whereas the PMTs were installed at the far end in a distance of 1.8 m from the mercury lamp. The set-up was modified because the PMTs were much more sensitive to light than the Si photo diodes, and is possible since only a relative calibration was needed. During a measurement the computer controlled monochromator, which has an accuracy of 0.5 nm, scanned through a pre-defined set of wavelength going back to the 337.13 nm position - the wavelength of the Rayleigh calibration measurement - between each measured wavelength. The PMT and the silicon photo diode were connected to a Keithley picoampmeter each and read out simultaneously. In between every light measurement the shutter of the monochromator was closed to take a background measurement. Each measure point was derived as the mean of one hundred current measurement. The responsivity curve in Figure 2 is based on the analysis of two data sets collected with the North PMT. Two data sets were taken with two different silicon photo diodes for each PMT in the no-filter position. The measured Si photo diode currents were convoluted with the respective absolute NIST measured photo diode responsivity by this getting the number of photons hitting the photo diode, $(\frac{\gamma}{t})^{SI}$. The number of photons hitting the diode are related to the number of photons hitting the PMT by a geometrical factor k, so that the responsivity of the PMT expressed in units of charge per photon is given by

$$(Q/\gamma)^{PMT} = \frac{I^{PMT}}{k \cdot (\frac{\gamma}{t})^{SI}} \quad (3)$$

where I^{PMT} is the background-subtracted PMT current. Normalizing the responsivity to the responsivity at 337.13 nm cancels the geometrical factor k. The normalized responsivity, QE/QE337, calculated like this, is plotted in Figure 2.

Resulting Systematic Uncertainties

Systematic studies have been performed to estimate the systematic uncertainties of the two cali-

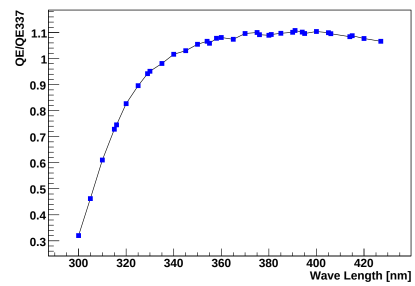

Figure 2: Relative responsivity of the North PMT.

brations. The largest uncertainty of end-to-end calibration originates from the uncertainty of the energy probe of 5%. Smaller contributions were derived from a comparison of calibration values calculated separately based on the Bucholtz [17] and Bhodaine [18] publications, from excluding the lowest pressure points from the fit shown in Figure 1, from measurements which were performed for different temperatures ($29° \pm 2°$) in the environmental chamber and for different filters in front of the PMT. The quadratic sum of all these contributions is listed as end-to-end uncertainty in Table 1. The dE/dx uncertainty listed in Table 1 is derived from a Monte Carlo study and takes into account the broad spread of the energy deposit from the electron beam. The uncertainty listed as ADC transfer takes into account the transfer uncertainty from SLAC, where the experiment was conducted, to Utah, where the experiment was calibrated. The uncertainties from the relative calibration range between 0.5 and 2% depending on the wavelength. Adding all contributions in quadrature, including the error of the beam charge from the toroid measurement, which is also listed in Table 1, a total systematic uncertainty on the fluorescence yield as measured by FLASH of 7.6-7.9% is derived.

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Source	Uncertainty in %
End-to-End	5.4
dE/dx	2.0
ADC Transfer	4.2
Relative Calibration	0.5-2.0
Toroid	2.7
Total	7.6-7.9

Table 1: Systematic uncertainties of the FLASH experiment. See text for details.

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