Laser Calibration of the Air Fluorescence Yield Experiment AirLight

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Abstract: The relative fluorescence efficiency for MeV electrons in nitrogen and air has been measured with high precision by the AirLight experiment [1]. The range from 300 nm to 400 nm was spanned using a 300 nm to 400 nm broad-band (M-UG6) filter and 5 narrow-band filters. Fluorescence photons were detected by seven 2-inch PMTs in coincidence with the signals of a plastic scintillator, which stopped the collimated beam from a ^{90}Sr electron source. The main source of error for the absolute scale of the fluorescence yield is the uncertainty of the efficiency of the PMTs for single photon detection in the UV domain. Therefore, using the original AirLight setup, the ^{90}Sr electron beam was substituted by a pulsed N2 laser beam with a wavelength of 337 nm and similar geometry. The scintillator at the beam stop was replaced by a calibrated energy probe to measure the laser energy in each pulse. The beam intensity is reduced by a stepped density filter to achieve count rates from the Rayleigh scattering similar to the fluorescence measurements. A narrow-band filter (337 nm), a M-UG6 broad-band filter, and a quartz window will be applied to three original PMTs of the fluorescence measurements. The experimental procedures and first results are discussed.

Introduction

Ultra high energy cosmic rays (UHECR) are comprised of elementary particles, nuclei, and electromagnetic radiation of extraterrestrial origin, with energies of 10^{18} eV or higher. When UHECR enters the Earth's atmosphere, they generate a correlated cascade of secondary particles, also called extensive air showers (EAS). The passage of these charged particles through the atmosphere results in the ionization and excitation of air molecules, inducing fluorescence in nitrogen molecules. Important parameters of an EAS are: its longitudinal development, i.e., the number of particles in the shower depending on the amount of materials penetrated by the shower at a given point in its development (slant depth); and the amount of photons per deposited energy. Accordingly, there are several experimental setups (AIRFLY, AirLight, FLASH, MACFLY, among others), where the fluorescence yield is measured accurately for different electron beam energies.

The AirLight Experiment at Forschungszentrum Karlsruhe was created to measure the fluorescence yield of electrons in nitrogen and air under atmospheric conditions as they appear in extensive air showers [1]. Electrons emitted from ^{90}Sr-source, with usable energies from 250 keV to 2000 keV, produce fluorescence light in nitrogen and air. This fluorescence is measured by photon detectors around the electron beam. Measurements of the absolute fluorescence yield between 300 nm and 400 nm for MeV electrons have been performed with high precision, the results are described in another paper presented at this conference [2].

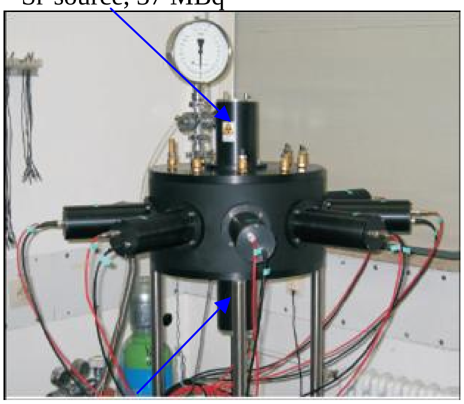
The aim of the absolute calibration for the AirLight Experiment is to improve the absolute accuracies obtained for the single nitrogen bands from the current 15% to values in the order of 10% or below, by decreasing the uncertainty of the efficiency of the photomultiplier tubes (PMTs) for single photon detection in the UV domain. The PMT efficiencies will be measured by comparison to an energy meter with accuracy of ±5% (NIST calibrated UV LaserProbe RjP465

Silicon Energy Probe). The experimental setup and the method used for the absolute calibration will be described in the following sections.

Experimental setup for the AirLight Absolute Calibration

As shown in Figure 1, using the original AirLight setup, the electron beam from the ^{90}Sr-source was substituted by a pulsed nitrogen laser beam with a wavelength of 337.1 nm and similar geometry. The scintillator at the beam's end was replaced by a photodiode calibrated at NIST, to measure the laser energy in each pulse.

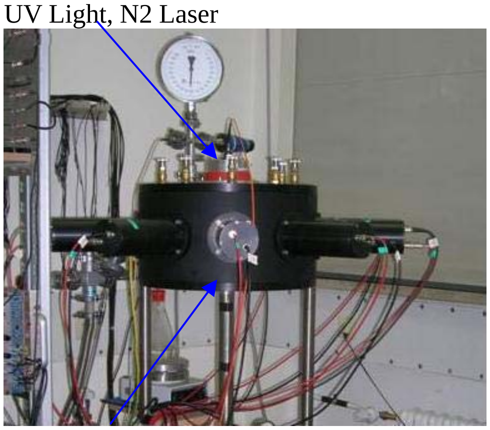
^{90}Sr-source, 37 MBq



Electron detector-Plastic Scintillator

Figure 1a: AirLight

UV Light, N2 Laser



Laser probe-Silicon Energy Probe

Figure 1: The original AirLight setup (a) and the absolute calibration setup, showing the original and the new beam sources as well as the original and the new detectors at the beam stop

The absolute calibration is done by using the Rayleigh scattering of a nitrogen laser beam. An optical fiber is used to guide the laser beam to the top of the chamber. A detailed schematic representation of the experiment is illustrated in Figure 2. The laser output energy of 120 µJ is reduced by a stepped density filter to achieve count rates around 1 p.e., then the laser beam is splitted into two beams. One of the beams is guided with an optical fiber to a Photonis XP 2262 PMT, which is used as the trigger PMT. The other beam is guided by an optical fiber to a box, in which the laser beam is collimated and then converted from an inherently depolarized light into a circularly polarized light. The purpose is to have the same amount of scattered light in the direction of all PMTs. The light then enters the chamber through a quartz window, passing another collimator (black tube), which ensures that there will be no Rayleigh scattered light before the desired distance from the center of the chamber. This collimator tube prevents the PMTs from 'seeing' the quartz window. There are seven PMTs, placed symmetrically, around the beam. The photodiode is located inside the chamber, with a small aperture of the same diameter as that one of the collimator tube. The distances, from the end of the collimator tube to the center and from the center to the photodiode, are equal.

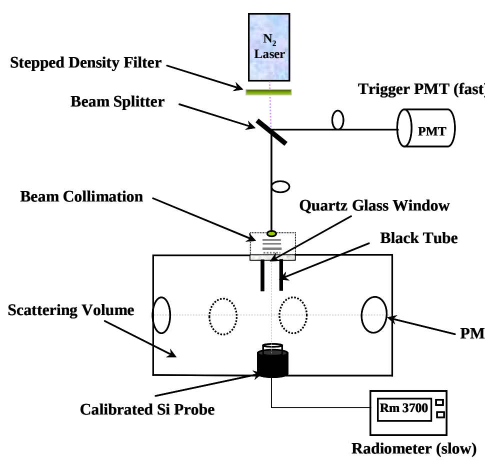


Figure 2: Schematic representation of the absolute calibration setup. In addition to the beam collima-

tor, there are 2 linear polarizers, one λ/4 plate and another linear polarizer used for crosschecking.

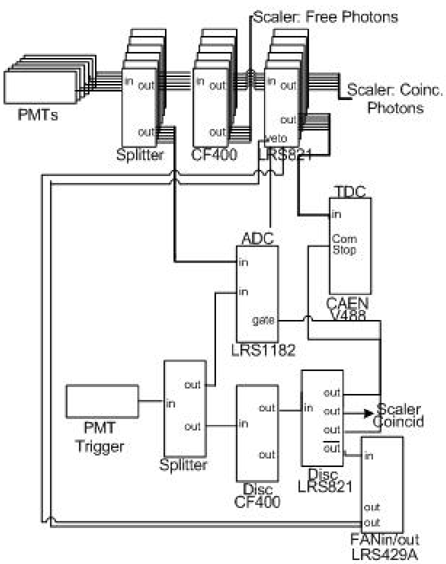


Figure 3: Simplified NIM-logic of the data acquisition system, including the trigger PMT

The photodiode is triggered externally with a frequency of about 10 Hz and 20 µs later the laser is triggered. A simplified NIM-Logic of the data acquisition system, triggered by the PMT, is shown in Figure 3. The signal of the trigger PMT, as well as the signals of the other seven PMTs, are recorded with an ADC and readout by a computer. Simultaneously with the PMTs signals, the silicon probe, coupled to the radiometer, measures the energy of each laser pulse. The pressure and temperature inside the chamber are recorded as well. The data acquisition software is written in LabView 5.1.1, from National Instruments, following the data acquisition system of the AirLight experiment [1].

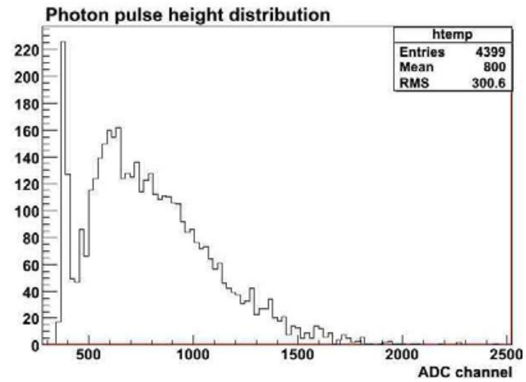


Figure 4a: ADC-histogram, showing the pedestal of the PMT and the p.e. distribution

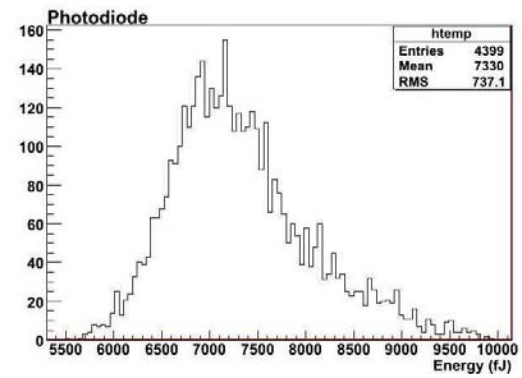


Figure 4b: Energy distribution per laser pulse

Figure 4 shows the pulse height distribution of one of the PMTs and the corresponding energy distribution per laser pulse, detected by a calibrated silicon probe. As can be seen in Figure 4, the pulse height distribution of the PMT obtained under the present laser setting does not correspond to that of a single photoelectron distribution. This is due to the fact that the second, and perhaps even the third, p.e-peak are still visible. This means that the intensity of the laser is still too high and must be reduced in future measurements.

Calculation of the number of photons reaching the iris of the PMT

Once the Rayleigh scattering is well understood [3,4,5], it can be used for the calculation of the precise number of Rayleigh scattering photons, and then for the absolute calibration of the PMTs for the AirLight setup [6]. The number of scattered photons (N_{photon}) reaching the iris of the PMT is:

$$N_{photon} = N_L \sigma_{tot} N_{mol} A$$

where, N_L is the number of photons in each laser pulse and N_{mol} is the molecular number density. The total Rayleigh scattering cross section ($\sigma_{\tau o \tau}$) was calculated from Bucholtz [4]:

$$\sigma(\lambda) = \frac{24\pi^3}{\lambda^4 N_s^2} \frac{\left(n_s^2 - 1\right)^2}{\left(n_s^2 + 2\right)^2} \left(\frac{6 + 3p_n}{6 - 7p_n}\right)$$

where, λ is the wavelength (in cm), N_s is the molecular number density for stp N_2, n_s is the refractive index for stp N_2 and p_n is the depolarization factor.
For a preliminary estimate, an isotropic scattering was considered. This way, it is possible to take into consideration only the geometry of the experiment, and to use the value of the acceptance calculated in [1], A = 0.25%. A precise calculation of the total hypothetical number of photons Rayleigh scattered from the beam axis will be performed by means of a Geant4 simulation. The estimated value for N_{photon} was 5.0115 x 10^6. Using this value the energy needed for 1p.e is approximately 20 pJ/pulse.

Summary

Preliminary results obtained with the experimental setup for the absolute calibration of the AirLight Experiment, using Rayleigh scattered light are presented. The measurements that are ongoing (without filters) will be compared with results previously obtained by the AirLight experiment [1]. There will be additional measurements of the PMTs with a M-UG6 broad-band filter, with the narrow-band filter (337nm) and with the quartz window. The calibration measurements must be performed at various pressures, from near vacuum until ambient pressure. As mentioned before, the Geant4 simulation for the calculation of the total hypothetical number of photons Rayleigh scattered from the beam axis is still necessary.

Acknowledgements

The authors are grateful to Guenter Woerner, who constructed the mechanical structure for the laser calibration bench, and provided useful and helpful assistance.

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