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Precise measurement of the absolute yield of fluorescence photons in atmospheric gases

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Abstract: We present final results of the AIRFLY experiment on the absolute yield of fluorescence emission in atmospheric gases. Measurements were performed at the Fermilab Test Beam Facility with a variety of beam particles and gases. Absolute calibration of the fluorescence yield to 4 % level was achieved by comparison with two known light sources - the Cherenkov light emitted by the beam particles, and a calibrated nitrogen laser. The uncertainty of the energy scale of current Ultra-High Energy Cosmic Ray experiments will be significantly improved by the AIRFLY result.

Keywords: Ultra-High Energy Cosmic Rays, Fluorescence detection

1 Introduction

The fluorescence technique has been used as a method of detection of Ultra-High Energy Cosmic Rays for the past 30 years. Secondary particles of extensive air showers excite nitrogen molecules in the atmosphere, which then de-excite emitting photons mostly in the range of 300 to 400 nm. The amount of fluorescence light emitted is proportional to the energy deposited by the shower particles, therefore the fluorescence telescopes provide a nearly calorimetric measurement of the primary energy. Moreover, the fluorescence telescopes record directly the longitudinal profile of the shower allowing an accurate determination of the depth of the shower maximum. The key parameter of the technique is the absolute air fluorescence yield and its dependence on the thermodynamic conditions along the shower development. The relative band intensities need to be known in order to correctly account for the propagation of the light through the bulk of the atmosphere from the emission point to the detector.

Properties of air fluorescence emission have been studied by several experiments. A detailed account of the recent progress in the field can be found in [1]. The AIRFLY (AIR FLuorescence Yield) experiment has performed precise measurements of the fluorescence yield dependence on pressure, temperature and humidity and also its relative emission spectrum [2, 3]. AIRFLY has also verified the proportionality of the fluorescence yield to the deposited energy in a wide energy range (keV to GeV) [4]. These measurements have minimized the systematic uncertainty on the energy scale of Ultra-high Energy Cosmic Rays due to atmospheric effects. However, the uncertainty due to the

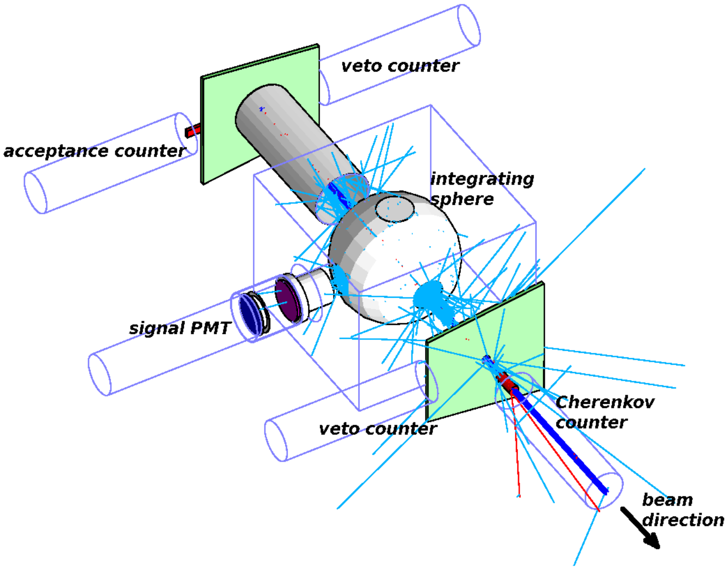

Figure 1: Experimental setup in the fluorescence mode.

absolute fluorescence yield still remains a major contribution [5].

We report results of our measurements of the absolute fluorescence yield of the 337 nm emission band with a systematic uncertainty of $\approx 4\,\%$. Measurements were realized at the Test Beam Facility of the Fermi National Laboratory, USA using several types of particles and gases. A precise calibration of the apparatus was performed using two different photon sources - Cherenkov radiation from the particles of the beam and a 337 nm laser.

2 Experimental apparatus

A drawing of the experimental setup used for the absolute yield measurement is shown in Fig. 1. The 3 mm thick stainless-steel pressure chamber encloses the integrating sphere lined with highly diffusive coating. The beam passes through the center of the sphere and produces fluorescence inside the sphere. Acceptance and veto counters are placed upstream and downstream of the chamber allowing to select beam particles with a well defined geometry. The photon detector - Hamamatsu H7195P photomultiplier tube (PMT) with a good single photoelectron resolution is placed perpendicularly to the beam direction viewing one of the sphere ports. A 337 nm narrow band interference filter is placed in front of the PMT acting also as a gas-tight window.

The integrating sphere collects light from $\approx 4\pi$ sr and provides a Lambertian light distribution at the output ports. In the fluorescence mode the sphere exit port is open so that the Cherenkov radiation from the beam particles can exit and be absorbed on the UV-absorbing material lining the chamber and only the fluorescence photons reach the PMT. In the Cherenkov mode the exit port is closed with a diffusive cover so that both fluorescence and Cherenkov photons produced by the beam particles are detected. The top port has to be open in this mode for the reflective area (and hence the efficiency) of the sphere to remain constant in both modes. Interchanging of the sphere ports, the gas filling and evacuation, and the mechanical shutter for the background measurements were remotely controlled.

A Cherenkov radiator, 30 mm long and 10 mm in diameter made of UV-transparent acrylic placed at the end of the setup provided a very good single particle resolution and a fast response. The signal of the Cherenkov counter is shown in Fig. 2. The beam profile monitoring was provided by wire chambers placed upstream and downstream of the AIRFLY apparatus inside the experimental hall.

The trigger and data acquisition system were designed according to the time structure of the beam. A typical beam intensity of 2×10^5 particles was arranged in a train of bunches within a 4 second spill. The train separation and the bunch separation was 10 μs and 19 ns, respectively.

The trigger logic was given by the coincidence of the train trigger gate and the single particle trigger gate, both provided by the Test Beam Facility. Each time a trigger was issued, the signals from the acceptance counters and the signal PMT were digitized by 12-bit 500MHz FADC and the entire train of bunches was recorded into the FADC internal memory. The data were read out and copied to an external hard drive during the 56 s separating the spills. A typical run lasted 30 spills ($\sim$ half an hour) and several runs were performed in each configuration to check for consistency and to accumulate sufficient statistics.

The primary proton beam of 120 GeV from the Fermilab Main Injector was used for most of the measurements. Secondary pions of 32 GeV and 8 GeV positrons were also used providing a crosscheck of the energy deposit mod-

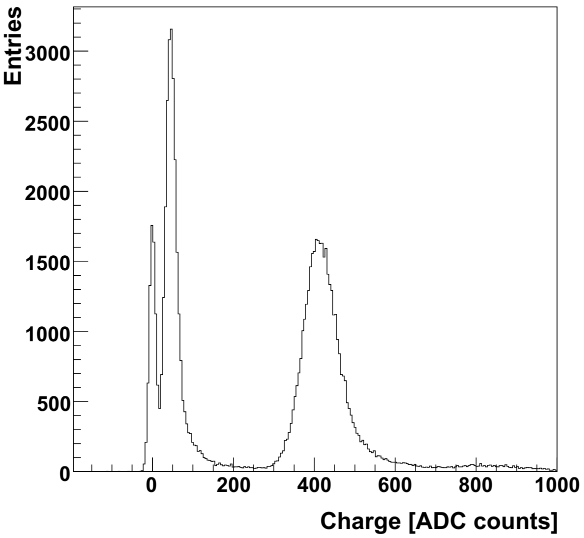

Figure 2: Spectrum of the Cherenkov counter signal. The peak at 0 ADC counts represents the pedestal. The peak at ~ 50 ADC counts corresponds to particles passing through the glass window of the PMT,while the peak at $\sim$ 420 ADC counts corresponds to particles passing through the Cherenkov radiator material. The small peak at around 800 ADC counts denotes two particles passing the counter simultaneously.

el. The measurement of fluorescence and Cherenkov light was performed in pure nitrogen and in a dry air gas mixture. Non-fluorescing gases (helium, argon) were also used to study the background. The nitrogen measurement was used to derive the final air fluorescence yield as this allows to maximize the collected statistics.

Calibration by a pulsed 337 nm nitrogen laser was also performed regularly, typically during the period when no beam was delivered. The laser power output was measured by a NIST calibrated silicon probe with 5 % uncertainty. The laser light was attenuated by a second integrating sphere to a level measurable by the signal PMT.

3 Data analysis and results

Data were selected during offline analysis by asking for a single particle in the beam passing the geometry requirements, i.e. a single particle signal both, in the Cherenkov radiator and in the acceptance counter upstream, and no signal in any of the veto scintillators within ± 80 ns of the candidate particle. A single photoelectron signal was searched for in the PMT in a 30 ns window after the beam particle arrival time. An example of the PMT response is presented in Fig. 3. Counting the number of photons gives the signal S measured in units of photons per beam particle (pbp). The measured signal in the fluorescence mode consists of the 337 nm fluorescence signal and the background

$$S_F^{gas}(meas) = S_F^{gas} + B_F^{gas}. \tag{1}$$

The difference between the measured signal in pure nitrogen and air can then be expressed as

$$\Delta S_F = S_F^{N_2} - S_F^{air} + B_F^{N_2} - B_F^{air}. \tag{2}$$

The beam related background and secondary particle production are practically the same so that the backgrounds of (2) cancel and the expression can be rewritten as

$$\Delta S_F = S_F^{N_2}\left(1 - \frac{1}{r_{N_2}}\right), \tag{3}$$

where r_{N_2} is the nitrogen to air fluorescence ratio at the 337 nm band measured previously by AIRFLY [2]. It was verified in the current setup using an ^{241}Am radioactive source yielding $r_{N_2} = 7.45 \pm 0.07$ at 1000 hPa. From the measured signal $\Delta S_F = (16.83 \pm 0.13)10^{-4}$ pbp and (3) we derive the fluorescence signal

$$S_F^{N_2} = (19.44 \pm 0.15)10^{-4}\,\text{pbp}. \tag{4}$$

The background amounts to

$$B_F^{N_2} = (0.61 \pm 0.07)10^{-4}\,\text{pbp}. \tag{5}$$

In the Cherenkov mode both the Cherenkov and fluorescence emissions contribute to the detected signal.

$$S_C^{gas}(meas) = S_C^{gas} + S_F^{gas} + B_C^{gas} + B_F^{gas}, \tag{6}$$

where B_C accounts for the background related to beam particle interactions with the diffusive material of the exit port cover (independent of the gas filling). Series of measurements with the evacuated chamber and the chamber filled with non-fluorescing gases converged to the value $B_C = (2.57 \pm 0.13)10^{-4}$ pbp. From the measured signal in the Cherenkov mode $S_C^{N_2}(meas) = (32.89 \pm 0.15)10^{-4}$ pbp we derive

$$S_C^{N_2} = (10.27 \pm 0.23)10^{-4}\,\text{pbp} \tag{7}$$

and the ratio of fluorescence to Cherenkov photons of the 337 nm band produced inside the chamber becomes

$$R^{N_2}(meas) = \frac{S_F^{N_2}}{S_C^{N_2}} = 1.893 \pm 0.049. \tag{8}$$

A full Monte Carlo simulation of the experimental setup was developed using the GEANT4 package. The simulation incorporated the results of dedicated measurements of the integrating sphere efficiency, the 337 nm filter transmission as a function of angle and the PMT quantum efficiency. The signal in the fluorescence mode was simulated including a nominal fluorescence yield $Y_F^{air}(sim.)$ and the published AIRFLY fluorescence spectrum. Thus the ratio $R^{air}(sim.)$ of fluorescence to Cherenkov was predicted. Comparing $R^{air}(sim.)$ with the measured ratio

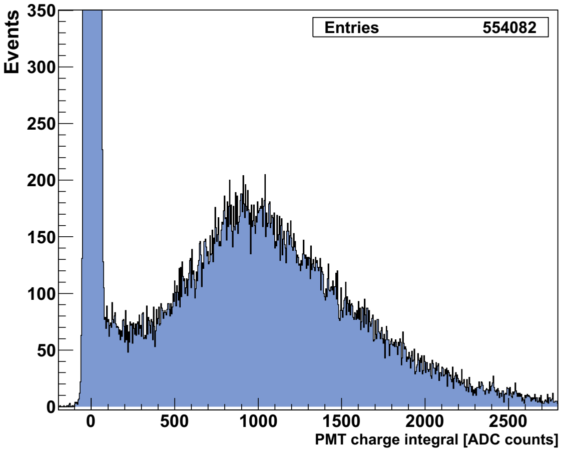

Figure 3: Spectrum of the AIRFLY signal PMT. The single photoelectron peak around 900 ADC counts is well separated from the pedestal.

$R^{air}(meas.) = R^{N_2}(meas.)/r_{N_2}$ the absolute fluorescence yield in units of photons per MeV deposited at the 337 nm line is obtained

$$Y_F^{air}(Chere) = 5.64 \pm 0.12(stat.)\,\mathrm{p}_{337}/\mathrm{MeV}. \quad (9)$$

Relative systematic uncertainties are reported in Tab. 1 and amount to a total of 4 %. The dominant contribution are the 337 nm filter transmission due to the different spectral distribution of the fluorescence and Cherenkov light and the model for energy deposit used in the simulation.

The measurement of the fluorescence to Cherenkov ratio was also performed in a modified setup, substituting the diffuser exit ports with a thin aluminized Mylar. In this way, the background due to the diffusive material of the sphere ports was eliminated. The absolute yield of the 337 nm band was found to be

$$Y_F^{air}(Mylar) = 5.48 \pm 0.25(stat.)\,\mathrm{p}_{337}/\mathrm{MeV}, \quad (10)$$

with a relative systematic uncertainty of 4 %, in a good agreement with the diffuser measurement.

The fluorescence emission was also calibrated by a 337 nm nitrogen laser. The ratio of fluorescence to laser was measured and compared to the ratio derived from the simulation. The measured yield was

$$Y_F^{air}(Laser) = 5.73 \pm 0.08(stat.)\,\mathrm{p}_{337}/\mathrm{MeV} \quad (11)$$

with a relative systematic uncertainty of 6 %, dominated by the 5 % uncertainty of the laser probe absolute calibration. Relative systematic uncertainties of this measurement are summarized in Tab. 2.

The two methods have different systematic effects yet the resulting fluorescence yields are in agreement, which gives us confidence in the reliability of the measurement.

sphere efficiency	1.0%
PMT quantum efficiency	1.0%
Monte Carlo statistics	1.0%
N_2/Air ratio	1.0%
sphere wavelength dependence	1.0%
background subtraction	1.0%
energy deposit	2.0%
filter transmittance	2.0%
Total	3.7%

Table 1: Systematic effects of the Cherenkov calibration method.

laser probe calibration	5.0%
calibration sphere transmission	0.8%
integrating sphere efficiency	0.9%
Monte Carlo statistics	1.0%
N_2/Air ratio	1.0%
background subtraction	1.0%
geometry	0.3%
energy deposit	2.0%
Total	5.8%

Table 2: Systematic effects of the laser calibration method.

Our best estimate for the absolute fluorescence yield of the 337 nm band, obtained by averaging the measurements (9), (10) and (11), taking into account the correlated systematic uncertainties yields

$$Y_F^{air} = 5.61 \pm 0.06(stat.) \pm 0.21(sys.)\,\mathrm{p}_{337}/\mathrm{MeV} \quad (12)$$

valid at 1013 hPa and 293 K. With a total uncertainty of only 4%, our measurement will significantly reduce the current uncertainty on the energy scale of Ultra-High Energy Cosmic Ray experiments.

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References

[1] Proceedings of the 5th Fluorescence Workshop, El Escorial 2007 F. Arqueros, J.R. Hörandel, B. Keilhauer editors, Nucl. Instr. and Meth., 2008, **A 597**.

[2] M. Ave et al. [AIRFLY Collaboration], Astropart. Phys., 2007, **28**: 41, [arXiv:astro-ph/0703132].

[3] M. Ave et al. [AIRFLY Collaboration], Nucl. Instrum. Meth. A, 2008, **597**: 50, [arXiv:0711.4583 [astro-ph]].

[4] M. Ave et al. [AIRFLY Collaboration], Nucl. Instrum. Meth. A, 2008, **597**: 46.

[5] J. A. Abraham et al. [The Pierre Auger Collaboration], Phys. Lett. B, 2010, **685**: 239.