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## Temperature and humidity dependence of air fluorescence yield measured by AIRFLY

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### ABSTRACT

The fluorescence detection of ultra high energy cosmic rays requires a detailed knowledge of the fluorescence light emission from nitrogen molecules over a wide range of atmospheric parameters, corresponding to altitudes typical of the cosmic ray shower development in the atmosphere. We have studied the temperature and humidity dependence of the fluorescence light spectrum excited by MeV electrons in air. Results for the 313.6, 337.1, 353.7 and 391.4 nm bands are reported in this paper. We found that the temperature and humidity dependence of the quenching process changes the fluorescence yield by a sizeable amount (up to 20% for the temperature dependence in the 391.4 nm band) and its effect must be included for a precise estimation of the energy of ultra high energy cosmic rays.

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### 1. Introduction

The detection of ultra high energy ( $\gtrsim 10^{18}$  eV) cosmic rays using nitrogen fluorescence light emission from extensive air showers (EAS) is a well-established technique, used by the Fly's Eye [1], HiRes [2], and Pierre Auger Observatory [3] experiments, and for the Telescope Array [4] under construction. It has also been proposed for the satellite-based EUSO and OWL projects. Excitation of atmospheric nitrogen by EAS charged particles induces fluorescence emission, mostly in the wavelength range between 300 and 430 nm. Information on the longitudinal EAS development can be obtained

by fluorescence telescopes by recording the light intensity as a function of time and incoming direction. However, the fluorescence light yield from EAS charged particles must be well known at each point within the shower, and corrections must be applied for atmospheric effects between the shower and the telescope for an accurate primary energy determination. Thus, the intensities of the fluorescence bands should be measured over a range of air pressures and temperatures corresponding to altitudes up to about 16 km, the typical elevation of EAS development in the atmosphere. The presence of humidity will also affect the fluorescence yield, the effect being more important for satellite experiments which will detect showers over the oceans.

The AIRFLY (AIR Fluorescence Yield) collaboration is pursuing an extensive measurement program of the fluorescence light yield with significantly improved precision with respect to previous experiments [5]. A precise measurement of the pressure

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dependence of the air fluorescence band intensities has been published [6], and is summarized in Ref. [7]. Measurements of the fluorescence yield dependence on the electron kinetic energy from keV to GeV are presented in Ref. [8]. The status of the AIRFLY measurement of the absolute fluorescence yield is presented in Ref. [9]. The data reported here address the measurement of the fluorescence yield spectrum dependence on air temperature and humidity.

The fluorescence yield of a band of wavelength  $\lambda$  at a given pressure  $p$  and temperature  $T$  can be written as [6]

$$Y_{\text{air}}(\lambda, p, T) = Y_{\text{air}}(337, p_0, T_0) \cdot I_{\lambda}(p_0, T_0) \times \frac{1 + \frac{p_0}{p'_{\text{air}}(\lambda, T_0)}}{1 + \frac{p}{p'_{\text{air}}(\lambda, T_0) \sqrt{\frac{T H_{\lambda}(T_0)}{T_0 H_{\lambda}(T)}}}} \quad (1)$$

where  $Y_{\text{air}}(337, p_0, T_0)$  is the absolute yield of the 337 nm band at pressure  $p_0$  and temperature  $T_0$  (in photons emitted per MeV of energy deposited),  $I_{\lambda}(p_0, T_0)$  is the  $\lambda$  band intensity relative to the 337 nm band and  $p'_{\text{air}}(\lambda, T_0)$  is the band quenching reference pressure.  $H_{\lambda}(T)$  has been introduced to take into account a possible temperature dependence of the collisional cross-sections.

The effect of humidity in the fluorescence yield can be introduced by substituting in Eq. (1):

$$\frac{1}{p_{\text{air}}} \rightarrow \frac{1}{p'_{\text{air}}} \left(1 - \frac{p_h}{p}\right) + \frac{1}{p'_{\text{H}_2\text{O}}} \frac{p_h}{p} \quad (2)$$

where  $p_h$  is the water vapor partial pressure and  $p'_{\text{H}_2\text{O}}$  is the water vapor collisional quenching pressure.

The experimental method used for the measurement of the temperature and humidity dependence is described in Section 2. The results obtained for the humidity and temperature dependence of four major fluorescence bands (313.6, 337.1, 353.7 and 391.4 nm) are presented in Sections 3 and 4, respectively. Implications for the energy determination of ultra high energy cosmic rays of the AIRFLY measurements reported in this paper are discussed in Section 5. Conclusions are given in Section 6.

## 2. Experimental method

Measurements of both the humidity and temperature dependence of the fluorescence light yield were performed at the Argonne National Laboratory Chemistry Division's Van de Graaff

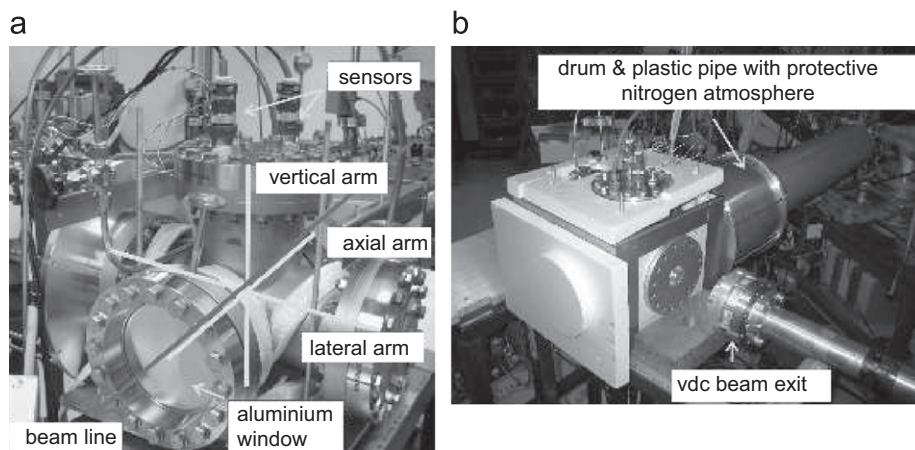
(VdG) electron accelerator [10,11]. It was operated in the DC current mode with typical beam currents of approximately 10  $\mu\text{A}$  and nominal beam kinetic energy of 3.0 MeV. After a 30° bend in an electromagnet, the beam was focused near the exit from the accelerator vacuum, which consisted of a 35 mm diameter and 0.152 mm thick dura-aluminum window. For beam tuning, the beam spot of about 6 mm diameter was viewed with a quartz plate and mirror close to the exit window, and a camera. The quartz plate and mirror were removed during data collection. For each humidity or temperature measurement, spectra from 284 to 429 nm were recorded with a spectrograph. The beam current was also measured by a Faraday cup located in the accelerator vacuum.

### 2.1. Humidity measurements

The humidity measurements occurred in the same setup shown in Fig. 1 of Ref. [6]. The electron beam entered the pressure chamber through a 0.50 mm thick beryllium window, traversed 378 mm of gas, and left through a 0.1 mm thick aluminum window. Fluorescence light produced in the gas left the pressure chamber through a quartz window; it was collected by a 10 m long, 1.5 mm diameter pure silica core optical fiber, which brought the light to a spectrograph. The aluminum spherical mirror in Ref. [6] was not used for these measurements. The spectrograph was located behind a concrete block wall with additional lead shielding to protect it from radiation produced by the VdG.

A remotely controlled vacuum and gas handling system was used with the pressure chamber. A dry scroll vacuum pump [12] was used, and the chamber pressure [13] and relative humidity (rH) (Sensorika probe HTP-9511533 [14]) were measured at the pump-out port. A high purity dry gas (78.0% nitrogen, 21.0% oxygen, 1.0% argon) passed through a bubbler containing high purity water before entering the pressure chamber. The measurements were performed at atmospheric pressure.

Air fluorescence spectra were recorded by an Oriel MS257™ spectrograph [15], described in detail in Ref. [6]. Calibrations with a mercury pencil lamp (Oriel no. 60635) and a quartz tungsten halogen lamp (Oriel no. 63350) were performed. In a fluorescence run the spectrograph collected data first in the wavelength range 284–369 nm and then in the range 344–429 nm. For each range, 50 spectra of 1 s integration time were taken in an automated sequence. The beam current from the Faraday cup was recorded before and after each sequence of spectra collected, with an uncertainty of 2% estimated from the reproducibility of the results.



**Fig. 1.** The temperature chamber at the Van de Graaff: (a) the chamber on the beam line as it appear before mounting the polystyrene box, (b) the chamber inside the polystyrene box, with the protective drum and pipe also in place.

## 2.2. Temperature measurements

A special temperature chamber was constructed for the temperature measurements; see Fig. 1. It consisted of a stainless steel pipe with two horizontal arms and one vertical arm. The electron beam entered and exited the chamber through 100  $\mu\text{m}$  thick aluminum windows. One horizontal arm had a stainless steel plate blankoff, and the other had the same quartz window as the pressure chamber. The gas length traversed by the electron beam in the temperature chamber was approximately 220 mm.

The vertical arm of the temperature chamber contained feed-thrus for five sensors: two relative humidity (moisture) sensors (Sensorika HS 2Ta [14]), a pressure sensor (Sensortech BT/PTU7000 [16]), and two temperature sensors (Sensorika Pt 10000 [14]). The humidity and pressure sensors were located near the vacuum flange with the feed-thrus, about 120 mm above the beam line. One temperature sensor was near beam height, but offset perpendicular to the beam and away from the quartz window about 3 cm, and the other was approximately 70 mm above beam height. Signals from all sensors were collected in a portable data acquisition system including a calibrated signal converter, and then sent to a PC to monitor the chamber conditions.

The temperature chamber body was enclosed in a polystyrene box with aluminum supporting structure. The box was filled with dry ice ( $\text{CO}_2$ ) for cooling of the chamber down to  $-40^\circ\text{C}$ . A 2 m long strip heater (48 V, 325 W) wrapped around the chamber body was used to regulate the temperature inside.

In order to avoid buildup of frost on the quartz window, a protective drum and pipe were added to the temperature chamber. These covered the window and end of the optical fiber. Boil-off gas from a liquid nitrogen dewar was continuously fed through the protective drum and pipe system.

The same remotely controlled vacuum and gas handling system, silica core optical fiber, Faraday cup, and spectrograph were used as for the humidity measurements.

Measurements were performed by filling the chamber at room temperature with  $\approx 1000$  hPa of dry air. The temperature was changed after sealing the chamber, thus keeping the air density constant. We checked that the pressure and temperature were indeed proportional during the measurements. An uncertainty of 2% on the beam current also applies to the temperature dependence measurements.

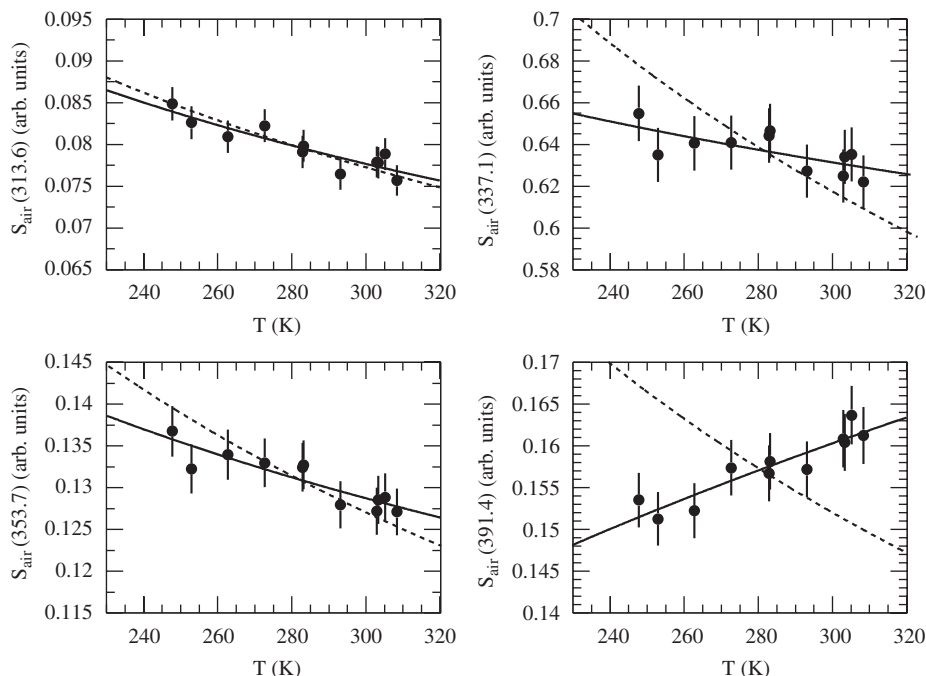
## 3. Temperature dependence

Fluorescence yield measurements were performed in the temperature range between 240 and 310 K in dry air. After allowing for temperature to stabilize in the chamber, a fluorescence spectrum was taken. The fluorescence band intensities were estimated by integrating the CCD counts in a wavelength interval around each band. A detailed account of the procedure can be found in Ref. [6]. For each fluorescence band  $\lambda$ , the corresponding fluorescence signal  $S_{\text{air}}(\lambda)$  was obtained from the ratio of the number of counts in the band interval to the beam current.

The temperature dependence of the fluorescence signal of the 313.6, 337.1, 353.7 and 391.4 nm bands is shown in Fig. 2, together with the result of a fit to the data (full lines) with the following ansatz in Eq. (1):

$$\frac{H_\lambda(T)}{H_\lambda(T_0)} = \left(\frac{T}{T_0}\right)^{\alpha_\lambda}. \quad (3)$$

The  $\chi^2/\text{ndf}$  of the fits was around 0.5. The dashed lines in Fig. 2 represent the expectations for  $\alpha_\lambda = 0$ , that is no temperature dependence of the collisional cross-sections, which has been so far assumed in the application of fluorescence yield measurements to fluorescence detection of ultra high energy cosmic rays. The fitted values of  $\alpha_\lambda$  are reported in Table 1. The AIRFLY measurements show a sizable temperature dependence of the fluorescence yield, contrary to the usual assumption. Also, the



**Fig. 2.** Temperature dependence of the air fluorescence signal for the 313.6, 337.1, 353.7 and 391.4 nm bands. Uncertainties are given by the quadrature sum of the statistical uncertainty on the fluorescence signal with the uncertainty on the beam current. Full lines are the result of a fit with a temperature dependence model for the collisional cross-sections, while dashed lines are the expectations for no temperature dependence of the collisional cross-sections.

value of  $\alpha_\lambda$  appears to depend on the wavelength band, with the 391.4 nm band being significantly different from the others.

#### 4. Humidity dependence

Fluorescence yield measurements were performed for relative humidity ranging from 0% to almost 100% corresponding to water vapor partial pressures  $p_h$  up to about 25 hPa. After allowing humidity to stabilize in the chamber, a fluorescence spectrum was taken. For each fluorescence band  $\lambda$ , the corresponding fluorescence signal  $S_{\text{air}}(\lambda)$  was obtained from the ratio of the number of counts in the band interval to the beam current. The beam current was measured several times during the run with a Faraday cup placed inside the beam pipe. The measured fluorescence signal as a function of the water vapor partial pressure  $p_h$  for the 313.6, 337.1, 353.7 and 391.4 nm bands is shown in Fig. 3, together with the result of a fit to the data using Eq. (2). The fitted values of the water vapor collisional quenching pressure  $p'_{\text{H}_2\text{O}}$  are reported in Table 1. Notice that the quenching effect of water vapor is not negligible, resulting in about 20% decrease of the fluorescence yield for RH = 100%.

**Table 1**  
Summary of measured temperature and humidity dependence parameters for a selected group of air fluorescence bands

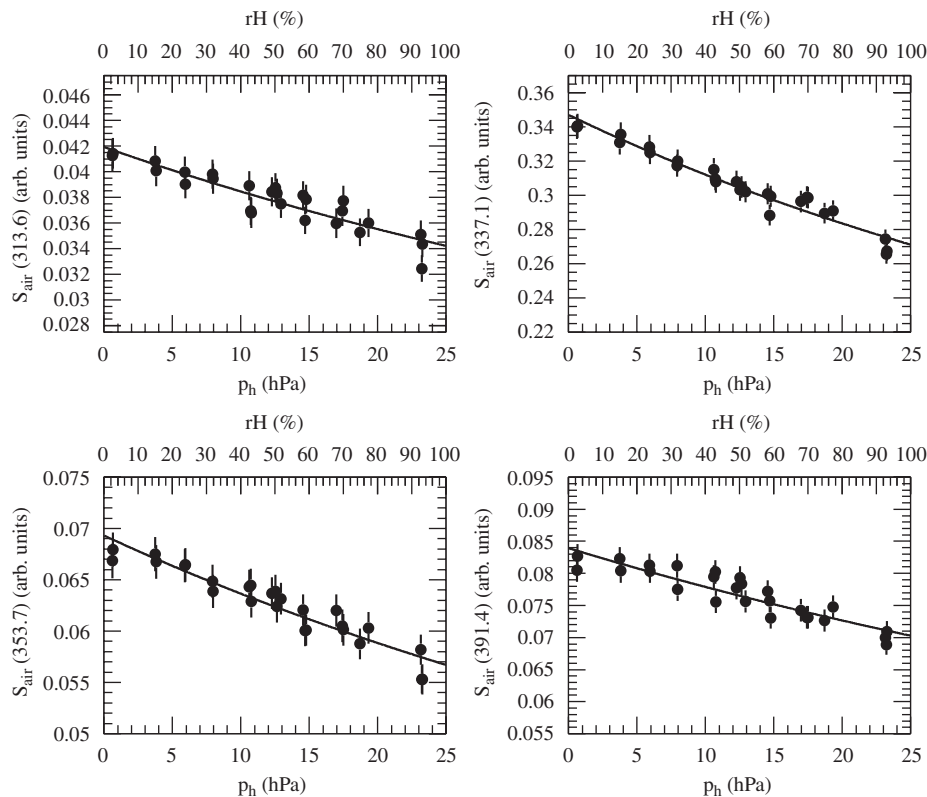
$\lambda$ (nm)	$\alpha_\lambda$	$p'_{\text{H}_2\text{O}}$ (hPa)
313.6	$-0.09 \pm 0.10$	$1.21 \pm 0.13$
337.1	$-0.36 \pm 0.08$	$1.28 \pm 0.08$
353.7	$-0.21 \pm 0.09$	$1.27 \pm 0.12$
391.4	$-0.80 \pm 0.09$	$0.33 \pm 0.03$

#### 5. Implications for the fluorescence detection of ultra high energy cosmic rays

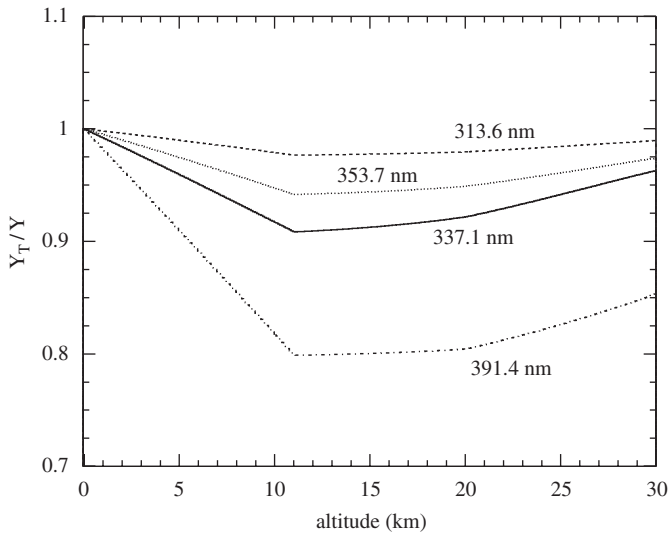
Experiments employing the fluorescence technique for the detection of ultra high energy cosmic rays have so far assumed  $\alpha_\lambda = p_h = 0$  in the treatment of fluorescence yield. The AIRFLY results presented in Sections 3 and 4 do not support this assumption. In fact, neglecting temperature and humidity effects on the fluorescence yield introduces a sizeable bias in the energy estimation of EAS. In Fig. 4, the ratio of the fluorescence yield with  $\alpha_\lambda$  from Table 1 to the one with  $\alpha_\lambda = 0$  is shown as a function of altitude. All yields were normalized to have the same value at ground level, and the U.S. 1976 Standard Atmosphere [17] was used to calculate the pressure and temperature at a given altitude. It appears from Fig. 4 that neglecting the temperature dependence results in an overestimation of the fluorescence yield by an amount going up to  $\approx 20\%$  for the 391.4 nm band.

We also investigated the bias introduced by neglecting the humidity effect on the fluorescence yield. We expect the effect to be more important for satellite experiments which will detect showers over the oceans. In Fig. 5, the ratio of the fluorescence yield with  $p'_{\text{H}_2\text{O}}$  from Table 1 to the one with  $p_h = 0$  is shown as a function of altitude, assuming a humidity profile over oceans as given in Ref. [18]. The effect of humidity is sizeable up to about 5 km altitude.

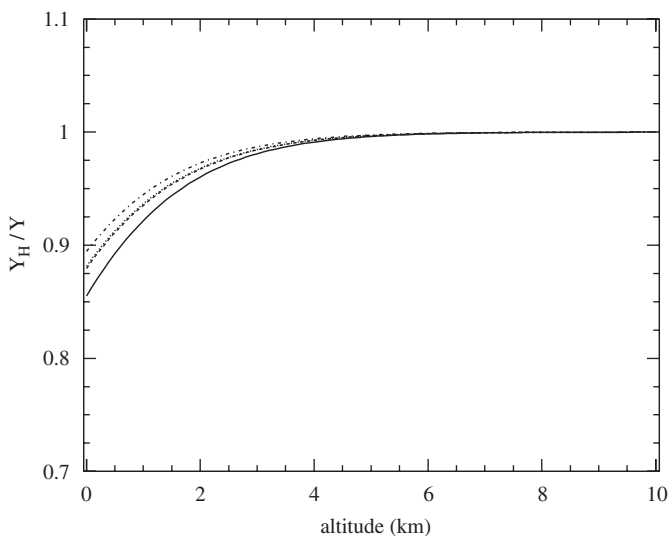
A full estimate of the effect of neglecting temperature and humidity in the fluorescence yield on the EAS energy measurement would need a detailed study, including the EAS energy deposit as a function of altitude, the wavelength dependent attenuation of the emitted fluorescence light in the atmosphere and the sensitivity of the fluorescence detectors. This goes beyond the scope of this paper. On the other hand, the experimental accuracy on the energy estimation of EAS with the fluorescence detection technique asks for a systematic uncertainty on the



**Fig. 3.** Air fluorescence signal as a function of water vapor partial pressure (relative humidity on the top axis) for the 313.6, 337.1, 353.7 and 391.4 nm bands.



**Fig. 4.** Ratio of fluorescence yield with measured  $\alpha_i$  to the one with  $\alpha_i = 0$ : dashed line 313.6 nm; full line 337.1 nm; dotted line 353.7 nm; dashed-dotted 391.4 nm.



**Fig. 5.** Ratio of fluorescence yield with measured  $p'_{\text{H}_2\text{O}}$  to the one with  $p_{\text{H}_2\text{O}} = 0$ : dashed line 313.6 nm; full line 337.1 nm; dotted line 353.7 nm; dashed-dotted 391.4 nm.

knowledge of the fluorescence yield better than 10%. Thus, biases of the order of 10%, as seen in Figs. 4 and 5, should not be neglected.

## 6. Conclusions

The measurement of the EAS energy with the fluorescence detection technique requires a detailed knowledge of the air

fluorescence emission as a function of pressure, temperature and humidity. The AIRFLY experiment has performed precise measurements of the fluorescence light spectrum excited by MeV electrons in dry air. The relative intensities of 34 fluorescence bands as well as their pressure dependence have been fully reported [6], and are summarized in a contribution to this workshop [7]. In this paper, we reported measurements of the temperature and humidity dependence of the 313.6, 337.1, 353.7 and 391.4 nm fluorescence bands in air. Our data show that collisional cross-sections are temperature dependent, contrary to the assumption so far made in the UHECR community. We also measured the quenching effect of water vapor, resulting in about 20% decrease in the fluorescence yield for RH = 100%. The effect of the temperature and humidity dependence of the fluorescence yield on the energy estimation of EAS was studied, and we found that it should not be neglected. A full analysis of the AIRFLY data, with the measurement of the temperature and humidity dependence of 34 fluorescence bands, is in preparation.

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