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Air fluorescence yield dependence on atmospheric parameters

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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 made a precise measurement of the fluorescence light spectrum excited by MeV electrons in air. The relative intensities of the fluorescence bands and their pressure, temperature and humidity dependence are reported.

Introduction

The detection of ultra high energy ($\gtrapprox 10^{18}$ 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 to 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 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 pressure and temperature 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]. Measurements of the fluorescence yield dependence on the electron kinetic energy from keV to GeV are presented in [6]. The data reported here address the measurement of the fluorescence yield spectrum and its dependence on air pressure, temperature and humidity.

The fluorescence yield of a band of wavelength λ at a given pressure p and temperature T can be written as [7]:

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

where $Y_{air}(337, p_0, T_0)$ 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 λ band intensity relative to the 337 nm band and $p'_{air}(\lambda, T_0)$ 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):

$$\frac{1}{p'_{air}} \rightarrow \frac{1}{p'_{air}}\left(1 - \frac{p_h}{p}\right) + \frac{1}{p'_{\mathrm{H_2O}}}\frac{p_h}{p}, \quad (2)$$

where p_h is the water vapour partial pressure and $p'_{\mathrm{H_2O}}$ is the water vapour collisional quenching pressure.

The fluorescence yield measurements reported here were mainly performed at the Chemistry Division Van de Graaff (VdG) accelerator of the Argonne National Laboratory. The VdG was operated in DC current mode with typical electron beam currents of $\sim 10\ \mu A$, and nominal beam kinetic energy of 3.0 MeV.

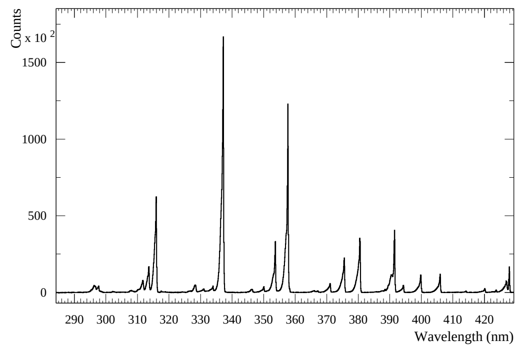

Figure 1: Measured fluorescence spectrum in dry air at 800 hPa and 293 K.

Pressure dependence

A detailed account of the AIRFLY measurement of the pressure dependence of the air fluorescence yield can be found in [7]. In this Section we briefly summarize the results achieved. The pressure chamber was constructed of an aluminum tube with various flanges welded to it for windows, gauges, gas inlet, and pump-out. The chamber length is about 38 cm along the beam axis. Electrons entered the chamber through a 0.50 mm thick beryllium window. A remotely-controlled gas handling and vacuum system was used with the pressure chamber. Fluorescence light produced in the gas was focused by an aluminum spherical mirror onto the end of a pure silica core optical fiber, which brought the light to a high resolution spectrograph. The optical fiber was placed outside the pressure chamber, and light reached the fiber end passing through a quartz window.

The measured fluorescence spectrum in dry air at $p_0 = 800$ hPa and $T_0 = 293$ K is shown in Fig. 1. The relative intensities $I_\lambda(p_0, T_0)$ of the major fluorescence bands are reported in Table 1. The high resolution spectrograph allowed the measurement of the relative intensities of 34 fluorescence bands over the wavelength range 284 - 429 nm [7]. The 2P and 1N systems of molecular nitrogen were found to dominate the fluorescence emission, while a group of weaker bands was found to be consistent with the Gaydon-Herman bands. The relative intensities of bands corresponding to transitions from a common upper level were in good agreement with theoretical expectations based on the ratio of Einstein coefficients.

We measured the collisional quenching reference pressure of the 337 nm band, p'_{air}(337), by studying the ratio of fluorescence emission in nitrogen and air. With this method, we eliminated the bias from undetected light due to secondary electrons escaping the detector's field of view at low pressures. This measurement was performed at a 14 MeV LINAC electron beam (Argonne Wakefield Accelerator) with a different set-up which included a narrow band optical filter and a photomultiplier tube, taking advantage of much better stability of the beam position, a small spot size and reduced multiple scattering effects compared to the 3 MeV beam. The collisional quenching reference pressures of the other fluorescence bands were obtained from the pressure dependence of their relative intensities, measured from a few hPa up to atmospheric pressure at the VdG, using p'_{air}(337) as normalization. A full description of the method and the values of 25 measured p'_{air} can be found in [7]. The measured values of the collisional quenching reference pressures for the 313.6 nm, 337.1 nm, 353.7 nm and 391.4 nm bands are reported in Table 1.

Temperature dependence

A dedicated chamber was used to measure the temperature dependence of the fluorescence yield. The chamber consisted of a six-way stainless steel cross, about 30 cm long. The beam entered and exited the chamber through 100 μm thick aluminum windows. Two Pt1000 temperature sensors were located in different places inside the chamber, allowing a check of the temperature uniformity. Humidity and pressure sensors were also installed. Fluorescence light produced in the chamber was collected by a pure silica core optical fiber, and measured by the spectrograph. The optical fiber was placed outside the pressure chamber, and light reached the fiber end passing through a quartz window. To avoid water condensation on the quartz window from air outside the chamber, the fiber and the quartz window were contained in a cylinder where dry nitrogen was flushed. The chamber body was placed in a metal plate box with polystyrene walls. The chamber cooling was performed by filling the box with about 5 kg of dry ice. The core temperature of the dry ice is -79 °C, which allowed the chamber to cool down to about -40 °C. Temperature regulation was achieved by a 2 m long strip heater 48V-325W wrapped around the chamber body.

Fluorescence yield measurements were performed in the temperature range between 240 K and 310 K in dry air. After allowing for temperature to stabilize in the chamber, a fluorescence spectrum was taken. For each fluorescence band λ , the corresponding fluorescence signal $S_{air}(\lambda)$ 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 temperature dependence of the fluorescence signal of the 313.6 nm, 337.1 nm, 353.7 nm and 391.4 nm bands is shown in Fig. 2, together with the result of a fit to the data with the following ansantz in Eq. (1):

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

The fitted values of α_λ are reported in Table 1. Notice that $\alpha_\lambda = 0$ indicates that collisional cross sections have no temperature dependence, which has been so far assumed in the application of fluorescence yield measurements to fluorescence detection of ultra high energy cosmic rays. The AIRFLY measurements show a sizable deviation of the temperature dependence of the fluorescence yield from this usual assumption. Also, the value of α_λ appear to depend on the wavelength band, with the 391.4 nm band being significantly different from the others.

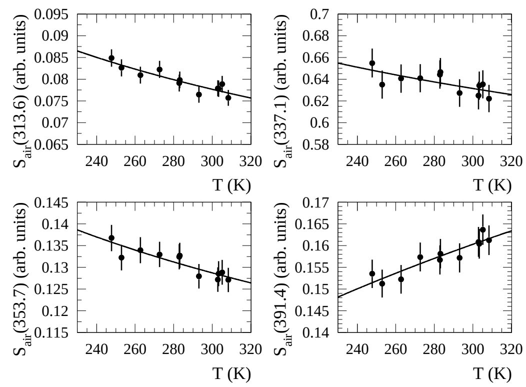

Figure 2: Temperature dependence of the air fluorescence signal for the 313.6 nm, 337.1 nm, 353.7 nm and 391.4 nm bands

Humidity dependence

Measurements of the humidity dependence of the fluorescence yield were performed with the experimental set-up used for the pressure dependence measurement. Water vapour was allowed in the chamber by flushing dry air in a bubbler filled with pure water. The relative humidity (rH) of the gas was measured by a humidity sensor placed inside the chamber.

Fluorescence yield measurements were performed for relative humidity ranging from 0 to almost 100% corresponding to water vapour partial pressures p_h up to about 25 hPa. After allowing for humidity to stabilize in the chamber, a fluorescence spectrum was taken. For each fluorescence band λ , the corresponding fluorescence signal $S_{air}(\lambda)$ 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 vapour partial pressure p_h for the 313.6 nm, 337.1 nm, 353.7 nm 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 vapour collisional quenching pressure $p'_{\mathrm{H_2O}}$ are reported in Table 1. Notice that the quenching effect of water vapour is not negligible,

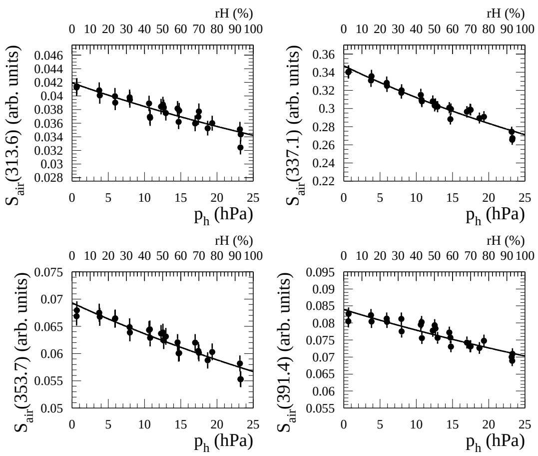

Figure 3: Air fluorescence signal as a function of water vapour partial pressure (relative humidity on the top axis) for the 313.6 nm, 337.1 nm, 353.7 nm and 391.4 nm bands.

resulting in about 20% decrease of the fluorescence yield for rH=100%.

λ (nm)	I_λ (%)	p'_{air} (hPa)
313.6	11.05 ± 0.41	12.3 ± 1.0
337.1	100.00	15.89 ± 0.73
353.7	21.35 ± 0.76	12.70 ± 0.72
391.4	28.0 ± 1.0	2.94 ± 0.66
λ (nm)	α_λ	p'_{H_2O} (hPa)
313.6	-0.09 ± 0.10	1.21 ± 0.13
337.1	-0.36 ± 0.08	1.28 ± 0.08
353.7	-0.21 ± 0.09	1.27 ± 0.12
391.4	-0.80 ± 0.09	0.33 ± 0.03

Table 1: Summary of measured pressure, temperature and humidity dependence parameters for a selected group of air fluorescence bands.

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Conclusions

The fluorescence detection of ultra high energy cosmic rays requires a detailed knowledge of the fluorescence light emission from nitrogen molecules, which are excited by the cosmic ray shower particles along their path in the atmosphere. We have made a precise measurement of the fluorescence light spectrum excited by MeV electrons in dry air. We measured the relative intensities of 34 fluorescence bands in the wavelength range from 284 to 429 nm with a high resolution spectrograph. The pressure dependence of the fluorescence spectrum has also been measured for most bands, and results have been fully reported [7]. We presented measurements of the temperature and humidity dependence of the 313.6 nm, 337.1 nm, 353.7 nm and 391.4 nm fluorescence bands. Our data show that collisional cross sections are temperature dependent, contrary to the assumption so far made in the UHECR community. We have also shown that the quenching effect of water vapour is not negligible, resulting in about 20% decrease of the fluorescence yield for rH=100%. A detailed account of the AIRFLY measurements of temperature and humidity dependence of the fluorescence yield is in preparation [8].

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