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## Measurement of the Air Fluorescence Yield with the AirLight Experiment

TILO WALDENMAIER[1], JOHANNES BLÜMER[2,3], DANAYS GONZALEZ[2], HANS KLAGES[2].
[1]*Bartol Research Institute, DPA, University of Delaware, Newark, DE 19716, U.S.A.*
[2]*Forschungszentrum Karlsruhe, Institut für Kernphysik, P.O.Box 3640, 76021 Karlsruhe, Germany*
[3]*Universität Karlsruhe, Institut für Experimentelle Kernphysik, P.O.Box 6980, 76128 Karlsruhe, Germany*
*tilo@bartol.udel.edu*

**Abstract:** The present uncertainties of the air fluorescence yield are the limiting factor for the energy reconstruction of ultra-high energy cosmic rays measured by fluorescence telescopes. The AirLight experiment has measured the pressure and energy dependence of the air fluorescence yield for the eight strongest nitrogen transitions with a precision of about 15 % for low energy electrons between 250 keV and 2000 keV. Furthermore the influence of water vapor has been investigated. This paper introduces the experimental method and summarizes the results.

## Introduction

The measurement of air fluorescence is used by many modern experiments (i.e. HiRes [1], Pierre Auger Observatory [2]) to detect extensive air showers (EAS), induced by ultra-high energy cosmic rays. The secondary EAS particles (mostly electrons and positrons) deposit their energy in the atmosphere by exciting or ionizing the air molecules which afterwards partially relax by emitting fluorescence photons. As pointed out by Bunner [3] most of these photons in the wavelength range between 300 nm and 400 nm originate from transitions of the second positive (2P) system of molecular nitrogen and the first negative (1N) system of molecular nitrogen ions. These faint emissions can be measured by fluorescence telescopes, allowing the observation of the longitudinal development of EAS through the atmosphere and a calorimetric determination of the primary cosmic-ray energy. The conversion factor between the deposited energy and the number of emitted fluorescence photons is the so-called fluorescence yield $Y_\lambda(p, T)$ which depends on the air pressure $p$ and temperature $T$ as well as on the wavelength $\lambda$ of the emitted photons. The fluorescence detection of EAS is considered to provide the most direct measure for the primary cosmic-ray energy, it is however limited by the present uncertainties of the fluorescence yield of about 15 % to 30 % and the lack

of knowledge about its energy dependence. In recent years this gave rise to a number of new laboratory experiments (i.e. Kakimoto et al. [4], Nagano et al. [5], AIRFLY [6], FLASH [7] or **AirLight**) aiming a precise measurement of the fluorescence yield over a wide energy, pressure and temperature range. This paper reports about the results of the **AirLight** experiment at Forschungszentrum Karlsruhe in Germany and is extracted from the Ph.D. thesis [8] of the corresponding author.

## The AirLight Experiment

The setup of the AirLight experiment is similar to the experiments done by Kakimoto and Nagano et al. [4, 5]. As is shown in Fig. 1 it consists of a cylindrical aluminum chamber in which electrons are injected along the chamber axis. The electrons are emitted from a $^{90}$Sr-source situated at the top of the chamber and are collimated by several lead rings. The electron source has an activity of 37 MBq with an end point energy of 2.3 MeV. After having traversed 10 cm of gas (dry air, pure nitrogen, or a nitrogen-oxygen mixture) the electrons are stopped in a plastic scintillator to determine their energy with an energy resolution of about 10 % at 1 MeV. The electron rate at the scintillator alters between 10 kHz and 20 kHz, depending on the pressure in the chamber which can be
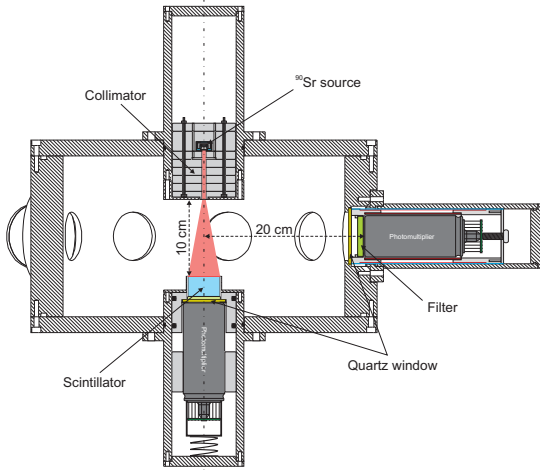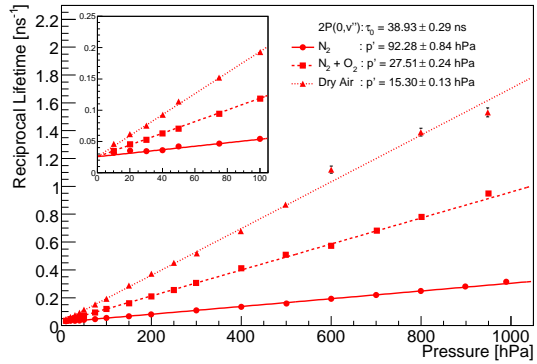
Figure 1: Sketch of the AirLight chamber.



Figure 2: Pressure dependence of the reciprocal lifetimes for the 2P(0,$v''$) transitions.

varied between 2 hPa and 1000 hPa. Seven Photonis photomultipliers (PMTs) are mounted perpendicular around the electron beam. Six of them are equipped with narrow band interference filters matched to the most prominent nitrogen bands, whereas one PMT is measuring the integral fluorescence spectrum through a broad band M-UG6 filter as it is used in the telescopes of the Pierre Auger Observatory [2]. The experiment is measuring coincidences between the electron signal in the scintillator and photon signals in any of the PMTs within a coincidence window of 120 ns.

## Fluorescence Process

The nitrogen fluorescence spectrum is a band spectrum caused by vibrational (and rotational) perturbations of the molecular energy states. All transitions of the 2P or the 1N system correspond to the same electronic transition respectively. The energy of the transitions is only modified by the different vibrational levels $v'$ and $v''$ of the initial and final electronic states. Accordingly the label 2P($v'$,$v''$) denotes a vibrational transition $v' \rightarrow v''$ within the second positive (2P) electronic system. The de-excitation of an excited electronic-vibrational state $v'$ is a competition between radiative and radiationless processes. Radiationless processes (quenching) occur via collisional energy transfer to other molecules and thus strongly depend on the pressure and the temperature of the air. Instead of this

the transition probabilities for radiative transitions $v' \rightarrow v''$ are constant. This causes the nitrogen fluorescence spectrum to be assembled of several sub-spectra for each vibrational level $v'$. The intensity ratios between transitions within a sub-spectrum are always constant but the absolute intensities of the individual sub-spectra vary differently with pressure and temperature according to the different strength of the quenching. The quenching strength is directly related to the lifetime $\tau_{v'}(p,T)$ of an excited state $v'$ which decreases the faster with increasing $p$ and $T$ the stronger the quenching. In the absence of collisional quenching the lifetime $\tau_{v'}(p,T)$ is constant and equals to the intrinsic lifetime $\tau_{v'}^0$ of the electronic-vibrational state. The probability for radiative transition can be expressed as the fraction of the lifetime $\tau_{v'}(p,T)$ at given $p$ and $T$ to the intrinsic lifetime $\tau_{v'}^0$. All these general relations are taken into account by the following approach for the fluorescence yield $Y_{v',v''}(p,T)$ for a transition $v' \rightarrow v''$:

$$Y_{v',v''}(p,T) = Y_{v'}^0 \cdot R_{v',v''} \cdot \frac{\tau_{v'}(p,T)}{\tau_{v'}^0} \qquad (1)$$

In this expression the intensity ratios $R_{v',v''}$ are defined with respect the most intensive transition, the so-called main transition, of the electronic-vibrational system. In this work the main transitions are 2P(0,0), 2P(1,0) and 1N(0,0). The intrinsic yield $Y_{v'}^0$ corresponds to the fluorescence yield of the main transition in the absence of collisional quenching where $\tau_{v'}(p,T) = \tau_{v'}^0$.

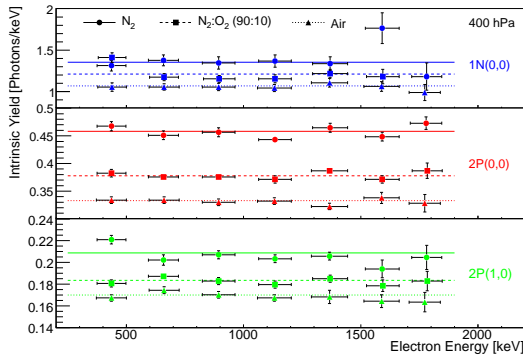The pressure and temperature dependence of the lifetime $\tau_{v'}(p,T)$ can be derived using kinetic gas

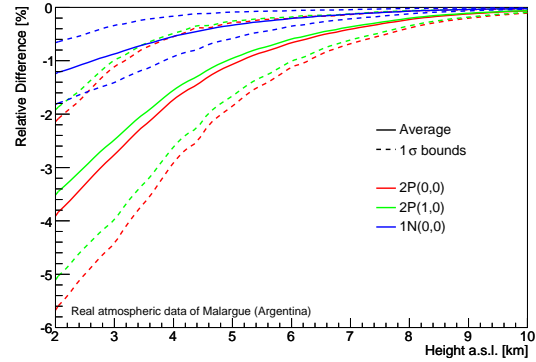Figure 3: Energy dependence of the intrinsic fluorescence yield.



Figure 4: Relative differences between the fluorescence yield of the main transitions with and without taking into account the water vapor in the atmosphere. $1\sigma$-bands correspond to daily humidity variations.

theory [8]. In first order the reciprocal lifetime behaves like

$$\frac{1}{\tau_{v'}(p,T)} = \frac{1}{\tau_{v'}^0} + \frac{p}{kT} \cdot \sum_i f_i \cdot Q_i^{v'}(T) \quad , \quad (2)$$

where the sum goes over all gas constituents $i$ with fractions $f_i = p_i/p$. For air the fractions $f_{N_2} = 0.78$ and $f_{O_2} = 0.21$ have been used. The water vapor fraction $f_{H_2O}$ has been individually derived from its partial pressure $p_{H_2O}$. The quenching of Argon and other trace gases turned out to be negligible. The quenching strength of each constituent is characterized by the quenching rate constants $Q_i^{v'}(T)$ which are proportional to $\sqrt{T}$ if the collisional cross-sections are assumed to be constant.

## Measurement & Data Analysis

The dataset used for this analysis consists of about 50 measurements in dry air, pure nitrogen and a nitrogen-oxygen mixture (90:10) performed between August and November 2005. The study of different nitrogen-mixtures is a useful cross-check for the quantitative understanding of the quenching process. In addition several runs with pure nitrogen plus a variable amount of water vapor have been carried out in order to study humidity effects. The measurements were done at room temperature at pressures ranging from 3 hPa to 990 hPa. One single run lasted between 12 and 30 hours, depending on type and pressure of the gas.

The data analysis is based on the investigation of the time difference spectra between the elec-

tron and photon signals in individual filter channels. The fluorescence signals can be statistically distinguished from uncorrelated background by their exponential time distribution. A Gaussian-convoluted exponential fit to the time spectra results in the lifetime $\tau_{v'}$ and the number of fluorescence photons. In general there are additional contributions of other nitrogen bands in one filter channel, and the measured time spectra are a superposition of several nitrogen transitions. In order to break up the different contributions a global $\chi^2$-fit to the complete dataset (all channels and runs) has been applied. A good relative calibration of the individual filter channels is essential for this procedure [8]. The fit was constrained by the physical relations between the lifetimes and the intensities as explained in the previous section. An example for the pressure dependence of the reciprocal lifetimes in the three gas mixtures is given in Fig. 2 for the $2P(0,v'')$-system. The single data points result from a global fit which was only constraint by equation (1) whereas the lines correspond to the results obtained by further constraining the fit by relation (2). Both fits agree with each other but only the latter one results in a minimal and consistent set of parameters which are summarized in Table 1. Since the quenching does not depend on the excitation process, the above fitting procedure was applied on the whole usable energy range from 250 keV to 2000 keV in order to maximize statistics. To study the energy dependence of the

| Band | $\lambda$ [nm] | $Y_{v'}^0$ [Ph./keV] | $R_{v',v''}$ | $\tau_{v'}^0$ [ns] | $Q_{N_2}^{v'}$ | $Q_{O_2}^{v'}$ | $Q_{H_2O}^{v'}$ |
|---|---|---|---|---|---|---|---|
| 2P(0,0)* | 337.1 | $0.338 \pm 0.001$ | 1.00 | $38.9 \pm 0.3$ | $0.11 \pm 0.00$ | $2.76 \pm 0.01$ | $5.43 \pm 0.12$ |
| 2P(0,1) | 357.7 | | 0.69 | | | | |
| 2P(0,2) | 380.5 | | 0.29 | | | | |
| 2P(1,0)* | 315.9 | $0.172 \pm 0.001$ | 1.00 | $32.9 \pm 0.5$ | $0.29 \pm 0.00$ | $2.70 \pm 0.03$ | $5.78 \pm 0.17$ |
| 2P(1,2) | 353.7 | | 0.33 | | | | |
| 2P(1,3) | 375.5 | | 0.34 | | | | |
| 2P(1,4) | 399.8 | | 0.46 | | | | |
| 1N(0,0)* | 391.4 | $1.048 \pm 0.007$ | 1.00 | $65.2 \pm 18.7$ | $5.00 \pm 0.17$ | $5.24 \pm 0.79$ | $16.02 \pm 1.09$ |

Table 1: Parameters for the eight strongest nitrogen transitions. Transitions from the same vibrational state $v'$ have the same values for $Y_{v'}^0$, $\tau_{v'}^0$ and $Q_i^{v'}$ as their main transitions marked with an $^*$. The quenching rate constants $Q_i^{v'} \propto \sqrt{T}$ are given for $T = 20°C$ in $[10^{-10}$ cm$^3$ s$^{-3}]$. All quoted errors are statistical only.

fluorescence yield the fit was repeated on seven sub-samples with an energy binning of 250 keV. It turned out that in the investigated energy range the intrinsic yield $Y_{v'}^0$ does not depend on the energy of the exciting electrons as is shown in Fig. 3. In order to derive these values the detection efficiencies for the individual bands as well as the energy deposit in the chamber have been carefully determined using GEANT4 simulations as described in [8].

The quenching of water vapor has been investigated by adding different concentrations of water vapor to 30 hPa of pure nitrogen. The quenching rate constants $Q_{H_2O}$ have been determined by a linear fit of expression (2) to the reciprocal lifetimes versus the water vapor partial pressure as described in [8]. The water vapor quenching turned out to be rather strong especially for the 1N-system where it is 3 times stronger than for oxygen as can be seen in Table 1. However due to the relatively small amount of water vapor in the atmosphere the net effect on the fluorescence yield is in the order of a few per cent as is illustrated in Fig. 4 for real atmospheric profiles measured at the Auger site [9].

## Results & Conclusions

The analysis procedure described above leads to a consistent description of the fluorescence process with a minimal set of parameters. These parameters have been determined for the 8 strongest nitrogen bands and are summarized in Table 1. It has been shown elsewhere [8] that the contribution of neglected nitrogen bands to the total fluorescence yield is less than 4 %. Using the values

of Table 1 the fluorescence yield in dry and humid air can be calculated for any atmospheric pressure and temperature by means of equation (1) and (2) with a systematic uncertainty of about 15 %. This error can be further reduced to less than 10 % by an end-to-end calibration of the whole setup using Rayleigh-scattering of a nitrogen laser beam [10]. Water vapor in the lower atmosphere further reduces the fluorescence yield by about 4 % at the Auger site. Currently this effect is still concealed by the systematic uncertainties of the fluorescence yield but might become an issue when these uncertainties are further reduced.

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