



Experimental Emulation of Air Fluorescence and Study of its Yield at Low Pressure Electrical Discharges

S. MALTEZOS¹, E. DRAKAKIS⁴, E. FOKITIS¹, A. GERANIOS², V. GIKA¹, D. KARABOURNIOTIS³, N. ANTONAKAKIS SPYROPOYLOS¹

¹National Technical University of Athens (NTUA)

²University of Athens, Athens (UoA)

³University of Crete, Heraklion (UC)

⁴Technological Educational Institute (TEI) of Crete, Heraklion
maltezosl@central.ntua.gr

Abstract: The study of high-resolution UV spectra, similar to these produced from EAS fluorescence, emulated experimentally could confront the problem of calibration of fluorescence detector telescopes. Therefore, we are conducting measurements of air fluorescence spectra using discharge lamps with possibility to modify parameters such as pressure and temperature. We develop and use a variety of spectrographs in order to find the most suitable for dedicated fluorescence yield experiments in electron beam accelerators. In this work we present data from 3-meters and also from 0.25-meters focal length spectrographs. The high-resolution data can provide a detailed database of nitrogen emission lines which can be compared with absorption lines of various atmospheric constituents in the troposphere and in the ionosphere as well. This high-resolution spectrograph as well as another one of 1-m focal length, already constructed, is presented.

Introduction

The fluorescence yield at high resolution is important if one considers the absorption of nitrogen fluorescence radiation, which happens due to resonance phenomena with ionized and excited N₂ molecules that mostly reside at the ionospheric heights. These phenomena may lead to appreciable corrections of the signal to be recorded by orbital Extensive Air Showers (EAS) telescopes such as EUSO experiments, etc. In particular, we expect that the attenuation factors for the various EAS induced nitrogen fluorescence lines will be proportional to the corresponding concentration of excited N₂ molecules and ions residing in ionosphere. The mechanism of resonance absorption, which leads to the attenuation of the EAS fluorescence signal, to be detected from EUSO, will be better understood if we have high resolution spectra from electrical discharges of N₂ in conditions approximating the EAS fluorescence. There has been some previous work using high resolution spectroscopy to measure air-fluorescence spectra

in a spectral lamp with air [1], but now we are able to extend such measurements to higher spectral resolution, while covering a greater number of the UV nitrogen spectral lines.

We have chosen to prepare some facility that generates air discharge spectra with aim to compare them with these taken in accelerator facilities, which study the measurements of the air fluorescence yield using electron beams at selected energies. Recent widespread international studies, such as the AIRLIGHT Collaboration [2] have led to the minimization of the uncertainty in the air fluorescence yield. One of the most unexplored aspects of these measurements is the air fluorescence yield in high resolution. Ideally, this should be measured so that one can select the electron energy in a range from few keV to several TeV. However, the expected signal to noise ratio (SNR) is too small to be measured with the current experimental techniques when the resolution is a fraction of 1 Å. The aim of the present work is to develop the technique of measuring and analyzing data of air-fluorescence yield at

this level of resolution using as experimental emulator of fluorescence electrical discharge in air at reduced pressures. By optimizing the design of such spectrometers we aim to use some optical components, which improve significantly the sensitivity. In the next paragraph we discuss some issues concerning the molecular excitation and de-excitation.

The N_2 fluorescence spectrum is characterized by an electronic band system. Light is emitted isotropically in the wavelength region of interest (from 300 to 400 nm). There are 19 strong separated emission bands, while 18 of them are belonging to the second positive (2P) system and the other to the first negative system (1N). Nitrogen molecules are excited mainly by electrons (and positrons) in extensive air showers. During de-excitation some non-radiative processes have to be taken into account. Therefore, the quantum efficiency of fluorescence is defined as the rate of de-excitation via radiation over the total rate of de-excitation, where the rate of de-excitation is proportional to the reciprocal of the life time.

In Section 2, we describe measurements with 3-meters spectrometer, in Section 3, the design and preliminary tests of medium resolution and portable spectrograph developed is presented, while we conclude this work in Section 4.

Measurements with high-resolution spectrometer

The development of appropriate compact light sources for studying air-fluorescence is useful because it can give inputs in simulation programs, which are used for determining the attenuation of air-fluorescence yield in various atmospheric conditions. The light source used was based on around 100 Torr air pressure according to the manufacturer's information. The lamp can be operated in different temperature and pressure close in order to simulate to the conditions during an EAS fluorescence emission at various atmospheric depths. This lamp can be supplied by a DC high voltage, which in our case was adjusted at 1300 V. A high-resolution grating spectrometer THR 1500 from Jobin Yvon, Czerny-Turner type, installed at Physics Department of University of Crete. The optical grating has 2400 g/mm while the focal length is 3 m using a double-pass beam. The grating rotation mechanism is controlled by a

PC-type computer. The detector is a CCD with 375 pixels horizontally of 23 μm width. The total number of 375 pixels corresponds to a total wavelength range as follows:

$\Delta\lambda = 375 \times (1.2 \times 10^{-3} \text{ \AA}/\mu\text{m}) \times 23 \mu\text{m} = 11.2 \text{ \AA} = 1.2 \text{ nm}$, which is not sufficient to record the required spectrum.

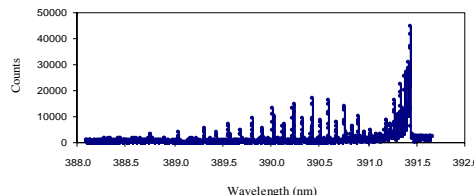


Figure 1: Spectrum of first negative band (around the line 391.44 nm), obtained experimentally by a 3 m focal length monochromator.

Therefore, we recorded totally four such spectra and the whole spectrum was obtained after contexture accomplishing a range of 4.8 nm. The resolving power of the spectrometer is $\lambda / \delta\lambda = 300000$ and the corresponding resolution has been measured experimentally using the isotopic lines of the line 546.1 of Hg, which found to be $\delta\lambda = 1.5 \times 10^{-3} \text{ nm}$.

The discharge lamp equipped with a quartz lens of focal length equal to 400 mm was located in front of the 20 μm wide entrance slit of the spectrometer. Each of the four spectra was recorded with an exposure time of 240 s. The background was recorded just after each spectrum and was subtracted in the off-line data analysis.

The data revealed the well-known fine structure due to molecular rotation. In addition, they indicate that the ionized nitrogen molecules emitting this spectral line are almost in thermal equilibrium. The apparent width of each peak is mainly related with three factors: The first two relate with the Doppler and pressure broadening, while the third one is due to the instrumental resolution, mainly depending on the entrance slit size. The efficiency of the transitions is proportional to the Franck Condon factors, available through the reference [3]. The above data may be useful in considering the degree of absorption of fluorescence radiation produced in the troposphere when it is propagated throughout the ionospheric re-

gions. It is not trivial to either compute or determine experimentally this absorption factor. Apparently, the absorption factor depends on the temperature and pressure during the emission of the EAS photon and the temperature and pressure at the ionospheric volume. Therefore, it may be of interest to extract the temperature information from the above data. This is feasible, given the excellent resolution of the spectrograph, which allows following the method described in [4].

Design of portable spectrographs

In the frame of our prospect to study the fluorescence yield caused by accelerator electron beam, we designed two portable spectrographs. The first is a relative simple and low cost spectrograph, which uses a holographic concave grating with reciprocal linear dispersion (RLD) about 4.5 nm/mm and a dSLR CCD camera, model D40 of Nikon as a detector. According to camera's specifications CCD size is 23.7 mm x 15.6 mm, while the pixel size is about 7.8 μm x 7.8 μm. Using the maximum width of the camera we are able to cover the whole visible region in only three frames. For handling the data recorded by the pixels array we used the common shared software IRIS and Visual Spec. This spectrograph, because of its higher sensitivity, is appropriate for measuring the N₂ fluorescence yield in a range of 100 nm, namely from 300-400 nm in UV region. This spectrograph can be easily located near an accelerator electron beam using reasonable quantities of exposure times. Some first spectra of the N₂ discharged lamp have been taken in the Laboratory over an extended spectral range and are shown in Fig. 2 and Fig. 3.

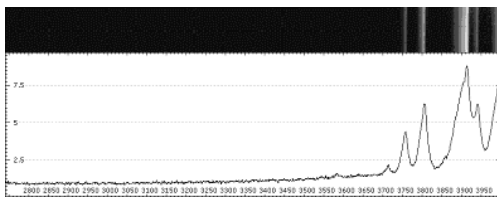


Figure 2: Nitrogen spectrum in the range 280-400 nm (UV). On the top of the plot we illustrate the corresponding recorded image in black and white. The lower cut-off of the grating efficiency combined with CCD quantum efficiency is around 365 nm and thus there is no signal recorded.

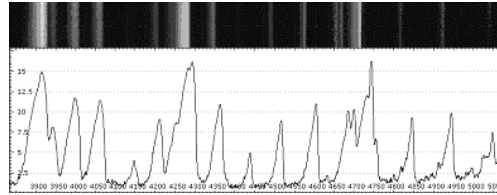


Figure 3: Nitrogen spectrum in the range 385-505 nm (visible) where the overall efficiency is large.

We also constructed a Czerny-Turner type spectrograph with focal length of around 1 m (more precisely 0.914 m) operating mostly in the UV wavelength range, namely from 300 to 400 nm. This spectrograph has been designed in order to obtain the N₂ spectra under various pressure and temperature conditions with a sufficient spectral resolution and thus to study their effect on the fluorescence yield. Its diffraction grating has 1800 grooves/mm and can be substituted alternatively by a 2400 grooves/mm with a minor movement of one of the mirror. The optical configuration is shown below in Fig. 4.

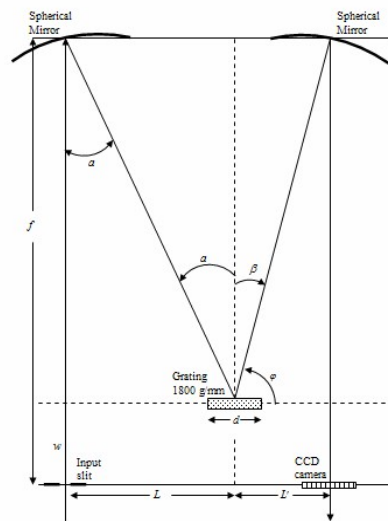


Figure 4: An optical configuration of the 1 m focal length spectrograph designed for recording the N₂ de-excitation UV light. The distances L , L' and w are geometrical design parameters, which have been appropriately selected for the UV range with a central wavelength of 350 nm.

The “plate factor” $R_d = dx/d\lambda$ is expressed by:

$$R_d = \frac{mNf}{\sqrt{1 - (mN\lambda - \sin\theta_m)^2}},$$
 where m is the diffraction

order, θ_m is the incidence angle, f the focal length and N the groove density. For $\lambda_0 = 350$ nm and assuming first order of diffraction ($m = 1$) we obtain $R_d = 1.74$ mm/nm, which leads to a wavelength resolution $\delta\lambda = 1.4 \times 10^{-2}$ nm using an entrance slit of 23 μ m width.

Conclusions and prospects

In this work we presented a study of high-resolution UV spectra, similar to these produced from EAS fluorescence, by emulating them experimentally. Recently we have started developing spectral lamps containing air at variable pressures, and we are planning to record air-fluorescence yield under selected pressures at high spectral resolution. The work is useful as it allows examining the efficiency of other relevant components such as candidate optical filters for EAS fluorescence detectors. The one meter focal length spectrograph assembled has already been tested successfully for alignment and for its imaging optics. We are ready to start recording spectra in high resolution in UV region.

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