Stigmatic and High-Resolution Spectrograph Optimized for Studying the Air-Fluorescence Yield in Electron Beam Accelerators

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***Abstract*. A brief review of the research for studying the yield of the air fluorescence and the progress in our activities in this field are presented in this work. The experimental world-wide progress is directed to emulate the processes using electron beam incident to thin or thick target. In this work, we present further improvements for an asymmetric Czerny-Turner type UV spectrograph for giving stigmatic nitrogen spectrum images produced from extended light sources, like those at electron beam accelerators. A set of molecular spectra of nitrogen, in the range of the main band heads in UV-region 5 nm wide, have been recorded using a spectral discharge lamp. We have also concentrated on the FNS 0-0 transition line at 391.44 nm selected for further spectral analysis. By fitting these spectra with the theoretical model based on the vibrational and rotational quantum energy levels, we determined the rotational temperature and other model and instrumental parameters. This method could be applied on the spectra obtained at electron beam accelerators to determine the gas temperature. In addition, we present the performance tests of a CCD detector for significantly improving the signal-to-noise ratio due to the operation near the liquid nitrogen temperature in comparison with the thermoelectrically cooled CCD.**

***Keywords*: Fluorescence yield, Spectrograph, Electron beam**

I. INTRODUCTION

The motivation for this work comes from the interesting results of many experimental and theoretical studies for the estimation of air fluorescence yield (AFY) in extensive air showers [EAS] produced by Ultra High Energy Cosmic Rays [1], [2], [3]. The measurements of FY were originally based on using interference filters to select the main air fluorescence lines in the ultraviolet region. Later, spectrographs were introduced to record the resolved spectra during air AFY measurements in accelerators [4], [5]. In [4] we have presented spectra from a spectral lamp, made by Meltz Electrolamps Moscow (MEM), containing air at pressure of the order of 50 Torr. We used this lamp as an emulator of light produced by high energy electron beams passing through chamber containing air at low pressure. In [5], the effort of recording spectrally resolved air fluorescence is enhanced by introducing spectrographs next to the low pressure air chamber. Among the most systematic efforts for determining the air fluorescence yield is the FLuorescence Yield experiment (AIRFLY) [2]. The goal of the AIRFLY is to measure the fluorescence yield (FLY) induced by electrons in air to better than 10 % accuracy. A detailed knowledge of the fluorescence emission characteristics is crucial for Ultra High Energy Cosmic Ray air shower energy reconstruction using the fluorescence technique. Presently, the main source of systematic uncertainties comes from our limited accuracy in the fluorescence yield. In this paper the current status of our knowledge, both experimental and theoretical, will be discussed. According to relevant reference and in spite of this advantage, fluorescence telescopes are presently limited by the uncertainty in the fluorescence yield, that is, the calibration parameter which converts number of fluorescence photons into absolute energy units. For instance, in the Pierre Auger Observatory the uncertainty in the fluorescence yield contributes a 14 % to the total systematic error in the energy calibration which is presently 22 % [6]. On the other hand, progress on the theoretical understanding of the various processes leading to the air-fluorescence emission is being carried out. One of the required works is to study the energy dependence of AFY while in these efforts the improving of the modeling of air fluorescence yield description is also included. Nevertheless low or medium resolution spectrographs could be used for recording the nitrogen spectrum, high-resolution analysis of the spectral structure allow the determination of the rotational temperature investigating a relationship with the kinetic gas temperature. We have presented [7] the design and details of the high-resolution UV spectrograph which now has achieves a resolution of 0.04 nm with sufficient sensitivity. This instrument could be proposed for measuring the FY at high energies, i.e. at tens of GeV range. In Section I the improvements of a Czerny-Turner type spectrograph are presented, in section II we describe the obtained spectra, in section III the data analysis method is given, while in section

IV the prospects and conclusions are discussed.

II. Further improvements of the UV spectrograph

One appealing spectrometer characteristic would be its capability to record quickly the complete spectral set of lines covering the range between 337 and 391 nm and operating with extended light sources like that in electron beam accelerators [9]. By recording the resulting spectrum in as great spectral resolution as possible, we can compare the dynamics of "artificial shower" occurring in a thin or thick target in accelerator experiments with the real showers in atmosphere. The recent improvements concern the reducing of the spherical abberations and some other techniques as are described bellow:

- Modification of the optical configuration to be asymmetric which allowed us to cancel the meridian coma. This has been achieved satisfying the *Rosendahl* (or cubic cosine) condition which can be written as follows:

$$\left(\frac{cos\alpha}{cos\beta}\right)^3 = \left(\frac{cos\alpha_1}{cos\alpha_2}\right)^2 \frac{tan\alpha_2}{tan\alpha_1} \qquad (1)$$

  where α and β are the incidence and diffraction angles respectively, α_1 and α_2 are the incidence angles of the collimated and focusing mirrors respectively. This ratio depends on the incidence and diffraction angles selected, and thus, concerns a given wavelength. In practice, this condition should be approximately valid for a relatively narrow spectral region as in our case ($\Delta\lambda = 44$ nm).
- The geometrical dimensions are appropriate to satisfy the *Rayleigh* criterion for reducing the spherical abberations, $D \leq 256\lambda f_n^3$, where D is the mirror diameter, λ is the wavelength and f_n is the f-number. For f-number equal to 9.1 in our case and assuming a wavelength of 350 nm, the obtained value is much smaller than the critical one.

By obtaining such spectra, we can reduce the uncertainties in the relative yield at the different spectral lines working with a CCD sensor with the lowest possible dark count and read noise. Thus we are planning to use an available CCD sensor (type CCD30-11) which uses the technique AIMO of E2V company which leads to better sensitivity while the detector has the capability to operate at near LN_2 temperature. In room temperature 24 ^{o}C (297 K) and assuming a leakage current equal to 0.5 nA/cm^2 the total dark signal has been calculated to be 194 e^-/pixel/s using an empirical formula. The read noise is around 5 e^-/pixel/s and according to the formula of the total noise, $N_t = \sqrt{Dt + N_r^2}$, where D is the dark noise, N_r is the read noise and t is the exposure time. The read noise is negligible in this temperature. In practice, the improvement of the dark signal during cooling is limited by the read noise and this is reached around 190 K. In this operating temperature it is expected to achieve a signal-to-noise ratio around 20 for 1h time exposure per vertical strip 222 μm wide and 6656 μm height, covering the whole structure of the recording line in a typical accelerator beam such of the AIRFLY experiment. We obtained some performance test data with this CCD in temperature range down to -138 ^{o}C. The agrement between our data and the calculated one is of the order of 25 $\%$. This discrepancy can be explained due to leakage current uncertainty. The quantum efficiency of this CCD is given by the manufacturer noted as *broadband coated* and has the following values at wavelengths of nitrogen fluorescence emission lines: at around $\lambda = 358$ nm $QE = 0.35$ reaching $QE = 0.65$, at around $\lambda = 391$.

III. Recorded nitrogen molecular spectra

We obtained the nitrogen spectrum in various spectral windows of 5 nm along the range from 337 nm to 428 nm with an entrance slit of 30 μm and exposure time 5 min. As detector we used a CCD with an array of 1600x1200 pixels from SBIG, model ST-2000XM, equipped with a thermoelectric cooling system achieving a temperature down to -15 ^{o}C. In front of the grating we placed a diaphragm of 25x50 mm in order to reduce the effective area and thus maximizing the spectral resolution. An appropriate band head for doing the analysis and determining the rotational temperature is the transition $N_2^+(B^2\Sigma_v^+ \rightarrow X^2\Sigma_g^+)$ of the FNS 0-0 at 391.44 nm. A set of molecular spectra of nitrogen, in the range of the main band heads in UV-region 5 nm wide, have been also recorded using a spectral discharge lamp. As detector we used was a 1.92 Mpixels CCD cooled at a temperature down to -15 ^{o}C, movable along a pre-determined focal curve. The calibration of the spectrograph has been verified using a Pt-Ne hollow cathode lamp. The image recorded is seen in Fig. 1 while the plot of the integrated counts along the vertical strips is shown in the same Figure. Another indicative spectrum is that obtained in a spectral window where both lines 357.69 nm and 353.67 nm are visible (see Fig. 2). These pair of lines and also the pair 375.54 and 380.49 nm were used to achieve more accurate calibration.

IV. Data analysis and results

The method we used for the spectrum analysis is based on non-linear multi-parametric chi square fit on the R and P branch of the rotational transition sequence [8]. Each recorded band head system of the nitrogen can be analyzed according to the theory of diatomic molecules. Our aim is to perform a non-linear fit in order to determine the rotational temperature among a large set of other secondary parameters. Apart of the complexity of this procedure, it is necessary to identify the individual peaks, by means of their nature in the rotational transition sequence, i.e. R or P branch. A theoretical expression describing a such rotational-vibrational (rovibronic) spectrum has to contain the

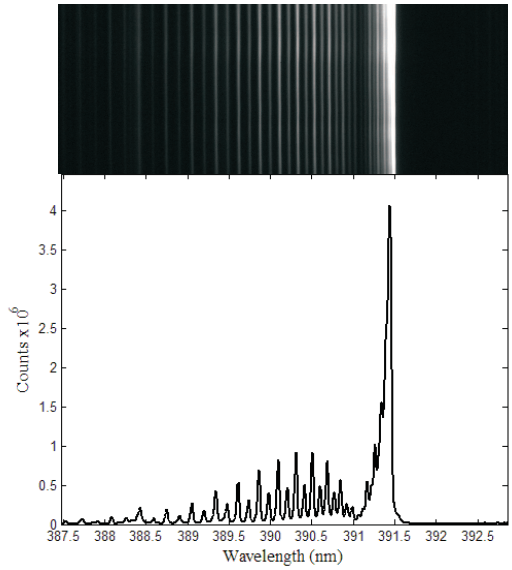

Fig. 1: Image of line 391.44 nm and the integrated plot along x-axis of the CCD

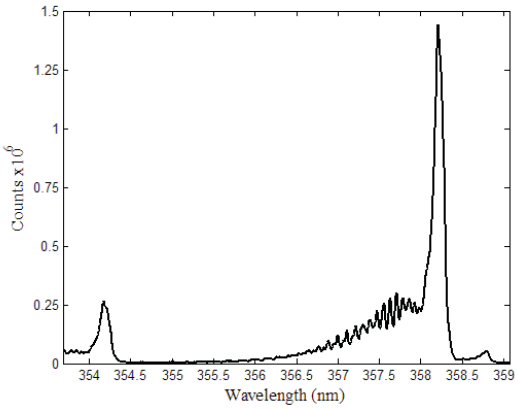

Fig. 2: Spectrum of 357.69 nm and 353.67 nm band heads

popularity coefficients of each particular transition multiplied with the Boltzmann distribution. The recorded peak is affected by the instrumental broadening described with a gaussian function. The general formula of the intensity as a function of the rotational quantum levels can be written as follows:

$$I_R, P = C \sum_{J'=0}^{N} g(J')(2J'+1) \\ exp\left[-\frac{hcB_{v,i}J'(J'+1)}{k_B T_r}\right] \\ exp\left[-\frac{4ln2\left[\lambda - \lambda(J') + \Delta\lambda(J')\right]^2}{(\delta\lambda)^2}\right] \quad (2)$$

where $B_{v,i} = BJ'(J'+1) - DJ'^2(J'+1)^2$ is the rotational constant expression at the vibrational level v including inharmonic behavior with D to be the centrifugal distortion constant (equal to $5.92x10^{-6}$ cm^{-1} in the case of nitrogen molecules), J' is the rotational quantum number, $g(J')$ is the statistical weight (equal to 1 for odd J' and 1/2 for even J'), $\lambda(J')$ is the peak wavelength at the individual quantum number, $\Delta\lambda(J')$ is the uncertainty, os the peak wavelength, $\delta\lambda$ is the instrumental spectral resolution, T_r the rotational temperature, k_B is the Boltzmann constant, C is an arbitrary constant and N is the number of the recorded peaks. The above equation is valid for R-branch and P-branch as well. The total intensity should be the summation of the two terms: $I_{R+P} = I_R + I_P$. Therefore, we have to specify the sequence of the R and P quantum numbers, J'_R and J'_P respectively. This can be deduced from the so-called *fortrat* diagram, where the lower level rotational constant B_v and upper rotational constant B_{v+1} in the case of nitrogen molecules have the values 2.083 cm^{-1} and 1.932 cm^{-1} respectively according to literature. The band head is located at $J'_P = 13$ which is obtained from the condition of maximizing the function:

$$\Delta v = f(m) = (B_v + B_{v+1})m + (B_v - B_{v+1})m^2 \quad (3)$$

where $m = J'_R + 1$ for R branch and $m = -J'_P$ for P branch, represented a pseudo quantum variable for the necessity to obtain a smooth curve in the *fortrat* diagram. The maximizing value (m_H) is obtained by the formula:

$$m_H = -\frac{B_v - B_{v+1}}{2(B_v + B_{v+1})} \quad (4)$$

which in our case has been calculated $m_H = -13$, leading to band head location corresponding to $J'_P = 13$. However, the structure around the band head is developed in the range from $J'_P = 1$ to $J'_P = 13$ and further from $J'_P = 14$ up to practically $J'_P = 17$ along the symmetrical branch. The next lines (for $J' > 17$) are visible in the obtained spectrum and essentially constitute the folded-back portion of the rotational P branch. This portion of P branch overlaps with the blue-degraded R branches (because $B_v > B_{v+1}$) which start to appear only for wavelength less than 391 nm (were $m = 0$), as it is obvious from the missing peak. This overlapping is a characteristic property of the transition N_2^+ FNS and allows easier determination of the rotational temperature. The relation between R branches and P branches can be expressed as $J_P = J_R + 27$. For $J_R = 0$ we have $J_P = 27$ and thus the R and P branch spectrum are now more clear. The fitting curve has to have a similar form like the above Eq. 2 in which we have specified the set of the free parameters used. For each peak we need 2 free parameters (intensity factor and the wavelength location uncertainty) while the instrumental spectral resolution is an additional free parameter, common for all the lines. We applied the above fitted procedure on 31 rotational lines included the band head and using 64 parameters in total. The first step of the fitting is to identify the peak locations by an appropriate algorithm with an accuracy of 1/10 of the resolution of the nominal spectrograph.

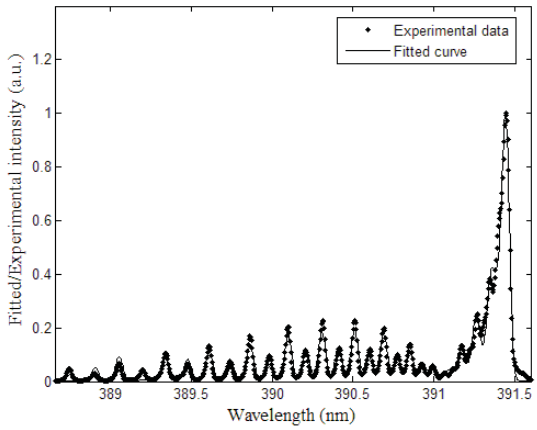

Fig. 3: Fitting of the full rotational spectrum included the band head of 391.44 nm line. We fitted 31 rotational lines.

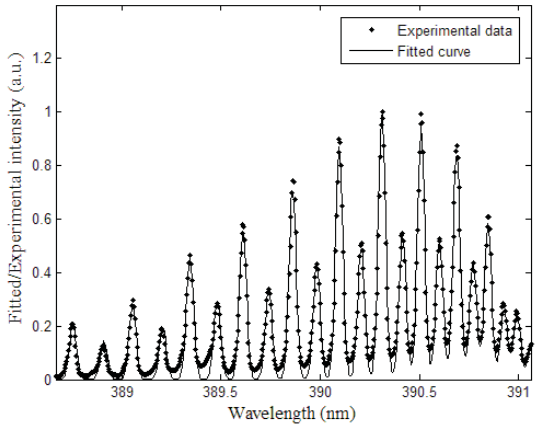

Fig. 4: Fitting of the rotational R branch of 391.44 nm line. We fitted only 21 of 31 rotational lines.

In our case this accuracy is of the order of 0.004 nm. The fit result for the full spectrum of the 391.44 nm line is shown in Fig. 3 while the fit for the R branch line is given in Fig. 4.

The results obtained from the fitting mainly concern the free parameter of the rotational temperature. From the fit including the band head of 391.44 nm we found T_r =330K and from the fit using only the rotational lines we found T_r =346K. In the first case, the accuracy in determine the temperature is higher due to the higher number of constrains in the fit procedure. The uncertainty of T_r is estimated of the order of 5 %. We have to investigate the relationship between the rotational temperature and the kinetic temperature of the gas. The knowledge of the gas temperature should be useful for the determination of the AFY in the accelerator beam. In the process of fluorescence emission the gas (nitrogen) molecules are out of equilibrium and thus the temperature changes only locally. The deposited energy is transferred to the molecules because of the high number of rotational quantum energy levels. Therefore, the electron beam interacts with the gas molecules under this modified temperature condition.

V. Conclusions and prospects

Some substantial actions for improving the high-resolution 1m-spectrograph have been done in order to achieve stigmatic imaging. During evaluation of the new configuration we obtained a series of nitrogen fluorescence spectra within preselected spectral windows studying the rovibronic emission spectrum of the nitrogen molecule. The analysis was is based on the theoretical formalism containing the rotational temperature which is the main parameter to be determined. The method we use is a non-liner fitting on the integrated data recorded. The obtained values of the rotational temperature are consistent with that are referred in the literature. In this work we also studied experimentally the signal-to-noise ratio of a CCD from E2V cooled near LN_2 to evaluate the possibility of using this spectrograph, equipped with this CCD, in electron beam accelerators. This was done recording the dark image and calculated the total noise during cooling down. Based on these results, we are able to predict the sensitivity of our spectrograph operating in accelerator beam.

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