# A novel method for the absolute fluorescence yield measurement by AIRFLY

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**Abstract**

One of the goals of the AIRFLY (AIR FLuorescence Yield) experiment is to measure the absolute fluorescence yield induced by electrons in air to better than 10% precision. We introduce a new technique for measurement of the absolute fluorescence yield of the 337 nm line that has the advantage of reducing the systematic uncertainty due to the detector calibration. The principle is to compare the measured fluorescence yield to a well known process – the Čerenkov emission. Preliminary measurements taken in the BFT (Beam Test Facility) in Frascati, Italy with 350 MeV electrons are presented. Beam tests in the Argonne Wakefield Accelerator at the Argonne National Laboratory, USA with 14 MeV electrons have also shown that this technique can be applied at lower energies.

*Key words:* Air fluorescence detection, 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 emission

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induced by extensive air showers (EAS) is a well established technique [1]. Atmospheric nitrogen molecules, excited by EAS charged particles (mainly $e^{\pm}$), emit fluorescence light in the $\approx$ 300–400 nm range. The fluorescence detection of UHECR is based on the assumption that the number of fluorescence photons of wavelength $\lambda$ emitted at a given stage of a cosmic ray shower development, *i.e.* at a given altitude $h$ in the atmosphere, is proportional to the energy $E_{dep}^{shower}(h)$ deposited by the shower particles in the air volume. Since a typical cosmic ray shower extends up to about 15 km altitude, the fluorescence yield must be known over a wide range of air pressure and temperature. Measurements by AIRFLY of the fluorescence yield dependence on atmospheric parameters (pressure, temperature and humidity), together with the spectral distribution between 280 nm and 430 nm are presented in two separate contributions [2,3].

It should be noted that $E_{dep}^{shower}(h)$ is the sum of the energies deposited by EAS particles with a spectrum spanning from keV to GeV. It is thus important to verify the proportionality of the fluorescence emission to the energy deposit over a wide range of electron energies. In [4], the proportionality of the fluorescence light to the energy deposit at a few % level was tested over the energy ranges 0.5 to 15 MeV, 50 to 420 MeV and 6 to 30 keV. However, only relative measurements within each range were performed, and absolute measurements of the fluorescence yield are in principle needed to verify that the proportionality constant is the same in the three measured energy ranges.

The absolute fluorescence yield is currently one of the main systematics on the cosmic ray energy determination by EAS experiments which employ the fluorescence technique. It is only known at the level of 15 % and for a few electron energies [5]. In this work, we will report preliminary results of the measurements of the absolute fluorescence yield of the most prominent line – 2P(0,0) 337 nm by a technique intended to keep the systematics below 10 %. The data were taken in the BTF (Beam Test Facility) of the INFN Laboratori Nazionali di Frascati, which can deliver 50–800 MeV electrons. Additionally, we have performed several tests at the the Argonne Wakefield Accelerator (AWA), located at the Argonne National Laboratory, which can deliver 3–15 MeV electrons. The results presented here are preliminary and the intention of the authors is to show that the methodology is appropriate to achieve accuracies below the 10 % level.

The paper is organized as follows: in Section 2 the technique proposed to measure the absolute fluorescence yield is presented and applied to the measurements in the BTF; in Section 3 recent measurements in the AWA are presented and the additional systematic uncertainties due to the smaller electron energies discussed; in Section 4 we conclude and discuss future work.

## 2. Absolute Fluorescence Yield Measurements at 350 MeV

### 2.1. *Description of the method*

AIRFLY uses a pressure chamber constructed of an aluminum tube with various flanges welded to it for windows, gauges, gas inlet and pump-out. The electron beam passes through the axis of the chamber. A photon detector, with a 337 nm interference filter in front, is placed in one of the flanges perpendicular to the chamber axis. The measurements are taken in two modes sketched in Fig. 1. In the fluorescence mode, the isotropic fluorescence light produced by the electrons in the field of view of the detector is recorded. In this mode, contributions from other sources of light, like Čerenkov or transition radiation, are negligible due to the non-isotropic emission of such mechanisms. In the Čerenkov mode a thin mylar mirror at an angle of 45° is inserted remotely into the beam, redirecting the Čerenkov light into the detector. In this mode, the Čerenkov light fully dominates over fluorescence.

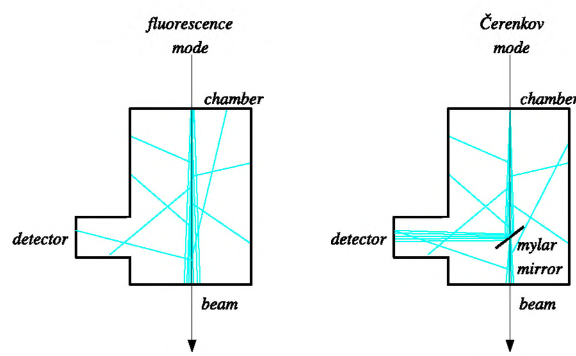


Fig. 1. Setup for the measurement of the absolute fluorescence yield. Remotely controlled mirror allows to switch between Čerenkov and fluorescence modes without beam interruption.

The absolute fluorescence yield is then determined using the ratio of the signal measured in the fluo-

$$
\begin{aligned}
\underbrace{N_{fl}(337)}_{measured} &= \underbrace{Y_{fl}}_{known} \times \underbrace{G_{fl}}_{MC} \times \underbrace{T \times Q(337)}_{\sim cancel} \times \underbrace{N_{e^-}}_{relative} \\
\overbrace{N_c(337)}^{measured} &= \overbrace{Y_c}^{known} \times \overbrace{G_c}^{MC} \times \overbrace{T \times Q(337)}^{\sim cancel} \times \overbrace{N_{e^-}}^{relative} \times \overbrace{R_m}^{measured}
\end{aligned}
\qquad (1)
$$

rescence and in the Čerenkov configurations from Equations 1. The Čerenkov yield $Y_c$ is known from the theory, the apparatus geometrical factors $G_{fl}$ and $G_c$ are derived from the full Geant4 simulation of the detector and take into account the probability of a photon being emitted in each case and also the fact that Čerenkov light is very directional and fluorescence is emitted isotropically . Relative number of incident electrons is measured by monitoring devices. The filter transmittance $T$ and the detector quantum efficiency $Q(337)$ are identical in both configurations and therefore cancel. The mylar mirror reflectivity $R_m$ was measured.

## 2.2. *Experimental setup and data analysis*

The BFT (Beam Test Facility) in Frascati is capable of delivering electrons of energy 50 to 800 MeV and positrons of energy 50 to 550 MeV, with intensities ranging from a single particle to $10^{10}$ particles per bunch at a repetition rate up to 50 Hz. The typical pulse duration is 10 ns. The absolute fluorescence yield was measured at 350 MeV.

A hybrid photodiode (HPD) capable of single photoelectron counting was used as the main photodetector. The photocathode was placed 202 mm from any beam and the optical path was baffled to avoid any reflections off the housing walls.

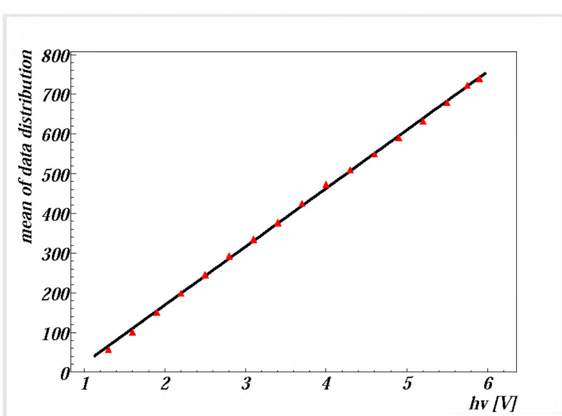


Fig. 2. Dependence of the mean value of the ADC signal on the HPD high voltage.

A 337 nm interference filter was placed in front of the HPD, the aperture was limited to 40 mm at 60 mm perpendicular distance from the beam to allow only up to 20° angle of incidence. A fast scintillator 100 by 100 mm, 5 mm thick, was used to monitor the beam intensity. The beam intensity was also monitored by NaI(Tl) calorimeter with excellent single electron resolution, placed at the end of the beam line.

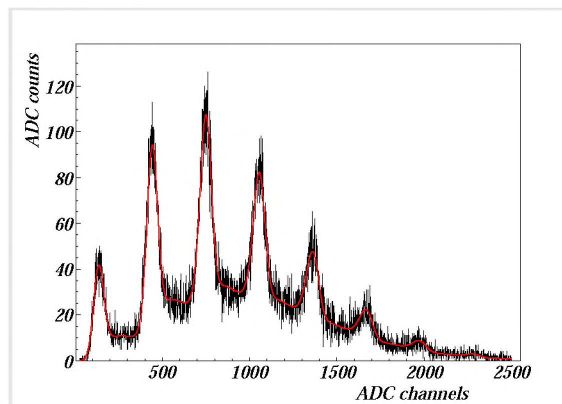


Fig. 3. An example of HPD signal (dots) fitted by the Simulated-annealing routine (continuous line) .

To improve the signal to noise ratio in the fluorescence mode, it was necessary to maximize the dynamic range of the HPD by changing the high voltage. The fluorescence data were taken at the highest possible and the Čerenkov data at the lowest possible high voltage applied to the HPD. Linearity of the HPD response with respect to the high voltage was verified and is shown in Fig.2. In the fluorescence mode, due to the small number of photons, the analysis of the Frascati runs was done using the single photoelectron signals from the HPD. Intensity of the fluorescence signal in number of photoelectrons was obtained using the model described in [6], which takes into account backscattering of the photoelectrons. The simulated-annealing fitting method [7], [8] was used to fit the model to the data. It is a Monte-Carlo minimization routine that has the advantage of being able to escape from local minima. An example of the HPD signal fitted by the Simulated-annealing routine is shown in Fig. 3. The background was determined in the same way and subtracted.

In the Čerenkov mode, due to the large number of photons, the average signal in ADC counts is calculated, the background subtracted and converted into number of photoelectrons. Consequently it was necessary to determine the conversion factor from ADC counts to photoelectrons ($C_c$) as a function of voltage. This was done by two methods: using LED with the intensity adjusted so that individual photoelectrons are visible, and using the Čerenkov signal from the beam with two different intensities monitored by the scintillation palette. Both methods gave a consistent result within 2 %.

The illumination of the photocathode is different in Čerenkov mode (a light cone) and fluorescence mode (uniform illumination). The photocathode uniformity is important to understand the detector systematic uncertainties. To understand it, the Čerenkov signal was measured for different pressures. As the pressure decreases the Čerenkov light-cone becomes narrower and also the multiple scattering of electrons becomes smaller making the Čerenkov light spot to cover a smaller part of the photocathode. The measured dependence of the Čerenkov signal on the pressure is shown in Fig. 4. A nonlinearity for high pressures would indicate that some Čerenkov photons are lost on the way to photocathode. Also a nonuniformity of the photocathode would spoil the linearity of this plot. From the good linearity of the Čerenkov pressure dependence (see Fig. 4) it is possible to deduce that the part of Čerenkov light falling outside of the photocathode is negligible and the nonuniformity, if any, should be limited to the very edges of the photocathode.

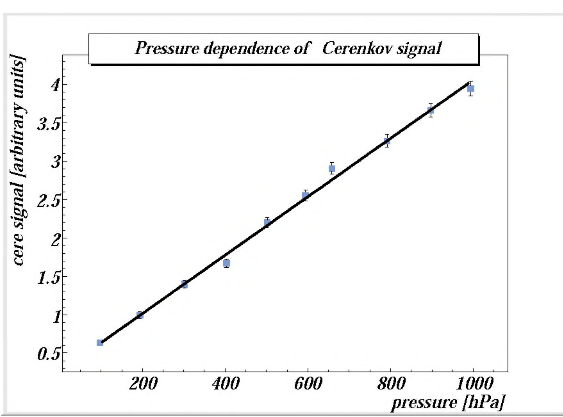


Fig. 4. Dependence of the Čerenkov signal on pressure. A good linearity is observed, see text for more details.

### 2.3. *Monte Carlo Simulations and checks*

A full Monte Carlo simulation of the experimental setup was performed using Geant4 [9]. In the simulation, the fluorescence yield was set to 19 photons/MeV deposited in a step sampled from the spectrum of Bunner (280 – 520 nm) [10]. This number leads to 4.74 photons/m/e$^-$ at 350 MeV in 1 m$^3$ of air or 1.24 photons/m/e$^-$ at 337.1 nm line in the same volume (4.17 photons/m/e$^-$ between 300 - 400 nm) at the pressure 993 hPa and temperature 18 °C. The 337.1 nm line then forms 26.2 % of the total number of photons. As the filter transmittance strongly depends on the incidence angle (see Fig. 5) and the distribution of incident angles in the fluorescence and Čerenkov case differs significantly these effects have to be included in the simulation of the geometrical factor. The default GEANT4 implementation of the Čerenkov process was used [9].

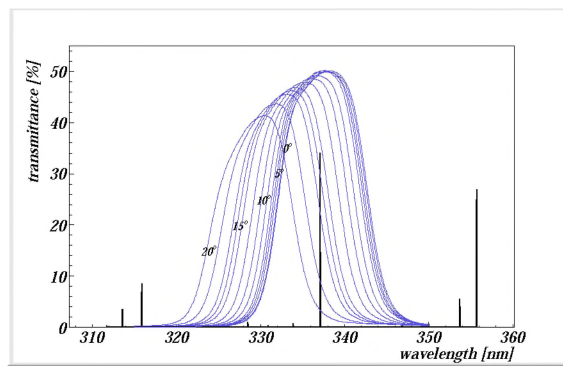


Fig. 5. Measured transmittance of the 337.1 nm interference filter at 13 different angles of incidence between 0° and 20° on top of the schematic nitrogen spectrum.

To check our simulations, the number of Čerenkov photons detected per 350 MeV primary electron was experimentally measured and compared with Monte Carlo results. The measurement was done in pure nitrogen which has a slightly higher index of refraction than air. The beam intensity was reduced to the point where it was possible to see individual electrons in the calorimeter and also single photoelectrons in the HPD. The HPD signal was analyzed by fitting the backpulse model using the Simulated-annealing method to the data. An example of data histogram from the calorimeter and corresponding signal in HPD are shown in Fig. 6. The background was estimated at 0.0021 p.e./bunch. The calorimeter signal was analyzed in the following way: number of hits in each individual peak was multiplied by the corresponding number of electrons, summed up and divided by the number of bunches. Another approach is to fit a Poisson distribution into the number of hits for each peak. Average of three consecutive run yields $0.0158 \pm 0.0003$ photoelectrons/e$^-$.

This result can be then compared with the full Monte Carlo simulation. Assuming the quantum efficiency reported by the manufacturer (24.3 % at 337 nm) and using the measured filter transmittance interpolated between the angles and wavelengths, we obtained an average number of Čerenkov photons detected per 350 MeV primary electron of 0.0152, in agreement with the data.

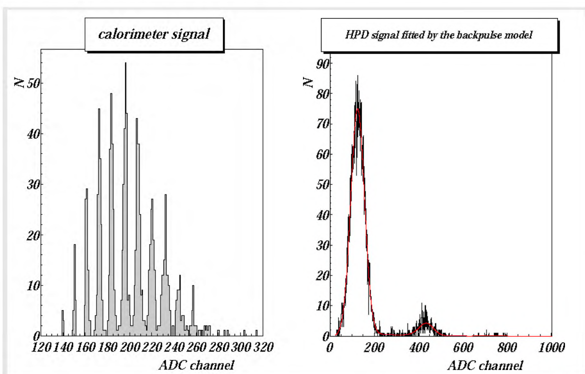


Fig. 6. Calorimeter and the corresponding Čerenkov signal detected by HPD.

### 2.4. *Preliminary results*

The resulting fluorescence yield of the 337 nm line is derived as

$$Y_{\rm fl} = \underbrace{\frac{N_{fl}(337)}{S_c(337)} \times C_c}_{R_{\rm meas}} \times \frac{N_c^{e^-}}{N_{fl}^{e^-}} \times \frac{1}{R_{sim}} \times Y_{\rm i}, \quad (2)$$

where $N_{fl}(337)$ is the measured fluorescence signal in photoelectrons, $S_c(337)$ is the measured Čerenkov signal in ADC counts and $C_c$ is the conversion factor from ADC counts to photoelectrons. The ratio $\frac{N_c^{e^-}}{N_{fl}^{e^-}}$ is measured by a fast scintillator. The ratio of fluorescence to Čerenkov signals obtained from simulations $R_{sim} = 1.330 \times 10^{-3}$ is proportional to the $Y_{\rm i}$ (which enters the simulation). The measured ratio yields $R_{meas} = 1.10 \times 10^{-3}$.

The preliminary absolute fluorescence yield derived at 993 hPa and 18 °C is

$$19\,\mathrm{ph/MeV} \times 0.262 \times 1.10/1.330 = 4.12\,\mathrm{ph/MeV}\,. \quad (3)$$

The quantity 19 ph/MeV and the relative spectrum is contained also in the simulated ratio $R_{sim}$ and the two occurrences cancel, therefore the resulting fluorescence yield does not depend on the choice of initial values. While our result is still preliminary, it compares well with the value of 4.32 ph/MeV deposited at sea level quoted by Bunner [10]. Also, it is within 20% of the fluorescence yield that may be derived from other more recent measurements [5]. This agreement strengthens our confidence in the validity of the method.

### 2.5. *Discussion of systematic errors*

Many tests and simulations were done in order to understand the systematic uncertainties of the absolute measurement. The measured background was very small – about $(0.006 \pm 0.001)$ p.e./bunch and amounted to about 10 % of the fluorescence signal. In the Čerenkov case the background is negligible so the uncertainty introduced by the background subtraction is 2 % (statistical uncertainty). The beam intensity normalization is a relative quantity. The statistical error is negligible. The uncertainty of 1 % assigned to this aspect accounts for the possible nonuniformity in the plastic scintillator response.

The HPD fitting method uncertainty stems from the fact that the merit function has a broad minimum causing that a slight change in the fitted parameters will lead to a slightly different number of photoelectrons but the quality of the fit will stay the same. This effect was estimated to amount to 3 %. HPD calibration and filter transmittance were already discussed previously. The mylar mirror reflectivity at the wavelength range needed was measured to be $(84 \pm 1)$ %. Systematic effect caused by a slight misalignment of the detector components was studied in simulations. The photocathode nonuniformity is currently under study. The photocathode coverage differs significantly between the fluorescence and Čerenkov case so any radial nonuniformity could influence the ratio in a substantial way. Therefore the largest systematic error was assigned to it. Current estimates of the systematic uncertainties taken into account are summarized in table 1.

Contamination by the 333.9 nm line is below 1 %. Also the contribution of transition radiation from the mirror was found to be negligible.

Statistical uncertainty amounts to 1.5 %.

The systematic uncertainties in table 1 are still preliminary. In particular, additional work is needed

| | |
|---|---|
| background subtraction | 2% |
| beam intensity normalization | 1% |
| beam position and spotsize | 1% |
| geometry (misalignment) | 4% |
| HPD fitting method | 3% |
| HPD calibration (ADC/p.e.) | 2.3% |
| simulation (model) | 2% |
| 45° mirror reflectivity | 1.2% |
| 337 nm filter transmittance | 2% |
| photocathode uniformity and angular dependence | 5% |

Table 1
Systematic errors of the absolute fluorescence yield measurement.

to understand the photocathode nonuniformity, and dedicated measurements are foreseen. Also, the AIRFLY apparatus was moved to Argonne after this first measurement, which did not allow for additional tests and crosschecks of the result. New measurements with an improved apparatus are foreseen.

Nevertheless, this estimate shows that a systematic uncertainty $< 10\%$ on the absolute yield can be achieved with the experimental method proposed in this paper.

## 3. Absolute Fluorescence Yield Measurements at 15 MeV

As it was mentioned in Section 1, absolute fluorescence yield measurements at 15 MeV would allow us to verify the proportionality of fluorescence yield and energy deposit in the energy range 1–400 MeV. Additionally, it will confirm the results presented in the previous section with a measurement that suffers from different systematic errors. In this line, measurements were performed at the Argonne Wakefield Accelerator (AWA), located at the Argonne National Laboratory. The measurement principle is the same as outlined before, i.e. the absolute fluorescence yield is obtained from the measured ratios of the signal in the Čerenkov and fluorescence mode (Fig. 1).

The LINAC was able to deliver electrons in the energy range 3–15 MeV. It was operated at 5 Hz, with bunches of maximum charge of 1 nC and length 15 ps (FWHM) and typical energy spread of ± 0.3 MeV at 14 MeV. The beam spot size was typically 5 mm diameter, with negligible beam motion. The beam intensity was monitored with an integrating current transformer (ICT), placed directly before the beam exit flange. The signal from the ICT was integrated, digitized, and recorded for each beam bunch. The Čerenkov/fluorescence light was detected by a photomultiplier tube (PMT Hamamatsu H7195 model) with a narrow band 337 nm filter, located about 80 cm away from the beam axis. A shutter installed in front of the PMT allowed measurements of background. The PMT was surrounded by considerable lead shielding to reduce beam-related backgrounds.

The electrons in this energy range are below the Čerenkov threshold in air, and, for that reason, we used in the Čerenkov mode gases with larger refraction indexes (Freon-12 and $SF_6$). The high voltage settings for the PMT were the same in the Čerenkov and fluorescence mode. Due to the large number of photons in the Čerenkov mode ($\sim$ 1000 times larger than in the fluorescence mode) and to avoid the PMT saturation, an attenuation filter is placed in front of the PMT during the Čerenkov measurements.

The LINAC was operated in a mode allowing the bunch charge to fluctuate over a wide range. The correlation of the PMT and ICT signals, which showed a linear relation, was fitted and the slope $S_{meas}$ was taken as an estimator of the fluorescence signal. The same procedure was applied with the shutter closed to estimate the background, which was subtracted.

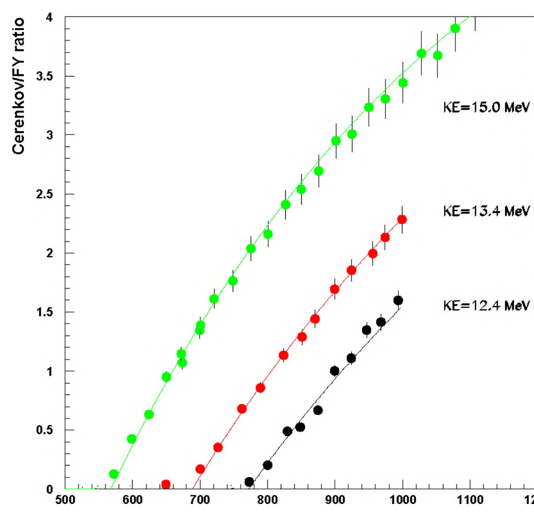


Fig. 7. The measured ratios of the Čerenkov to fluorescence signal as a function of pressure for three electron energies ( 12.4, 13.4 and 15 MeV). The Čerenkov gas used was Freon-12.

Fig. 7 shows the measured ratios of the Čerenkov to fluorescence signal as a function of pressure. Systematic uncertainties on the measured ratios were estimated from run to run fluctuations. The fluorescence signal was measured in air at a fixed value of pressure (800 hPa), temperature (ambient) and for an electron energy of 13.4 MeV. The Čerenkov signal was taken in Freon-12 for a range of pressures and 3 electron energies ( 12.4, 13.4 and 15 MeV). The data were taken during the test beam on February 2006. It should be noted that the threshold for Čerenkov production is given by $n\,\beta$ being $n$ the refraction index of the gas and $\beta$ the speed of the electron. In this work the refraction index of Freon-12 was treated as an unknown and compared with the values quoted in the literature.

Full Monte Carlo simulations of the detector setup were performed using Geant4. The predicted ratios of Čerenkov and fluorescence signal (at the energy and pressure indicated above) were parameterized as a function of electron energy, pressure and refraction index of the Čerenkov gas. It should be noted that this parameterization should be the Čerenkov formula with a normalization given by simulations at a specific energy, pressure and refraction index. However, we have found that the Coulomb scattering of electrons travelling through the beam exit window, chamber entrance window and the gas, distorts the Čerenkov cone acting as a diffuser. Consequently, most of the Čerenkov cone is not contained in the photocathode and only ~25 % (for p=800 mb, E=13.4 MeV and $n$=1.00108) of the light is detected in most of the cases. Therefore, a more complicated parameterization is performed.

A maximum likelihood method was then applied to fit all the data in Fig. 7. The free parameters fitted were: the refraction index of the gas at 1000 mb ($n$), the absolute fluorescence yield for the 337 nm line, and three offsets for the electron energy. In the likelihood function we also include three terms to account for the fact that the nominal electron energies have an uncertainty of 0.3 MeV. Results of the fit are the solid lines in Fig. 7. The energy offsets were all below 0.3 MeV and the refraction index $n$=1.00101 ±0.00001 is reasonably compatible with what we found in the literature ($n$=1.00108). The absolute fluorescence yield was within ≈ 25% of the value obtained at 350 MeV (see Section 2.4).

Two more test beams were performed in December 06 and February 07, using different experimental setups, optical elements and two different gases (Freon-12 and $SF_6$). The data sets are not as complete as the one presented before, but we applied the same analysis and we found the same absolute fluorescence yield within 5 %.

The systematics of this measurement are currently under investigation. Preliminary studies indicate that variations of 1 degree in the beam angle can lead to variations of 10 % in the absolute fluorescence yield. The Čerenkov light distribution in the photocathode is very uniform due to the Coulomb scattering effect, and therefore the systematics due to non-uniformities of the photocathode should be much less important than in the Frascati measurement. Contribution from transition radiation was found to be negligible. The most important systematic is the modelling of the Coulomb scattering in the full Monte-Carlo simulations. Coulomb scattering is a well know microscopic process, but its modelling in the Monte Carlo is not done in a microscopic way, therefore an algorithm has to be adopted. We used the algorithm implemented in Geant4 [11], we checked that the angular distribution of electrons close to the mylar mirror fits rather well the analytical formula for multiple scattering from Moliere Theory in [12]. We have also varied the multiple scattering according to the errors of $\theta_{rms}$ quoted in [12] and observed variations of ~ 5 % in the number of Čerenkov photons. However, and since this measurement heavily relies on the modelling of this effect, an experimental proof of the goodness of this modelling is necessary.

The assessment of the systematic errors is an undergoing process, and we estimate that the current uncertainty is not smaller than 15%. It is clear that at 15 MeV we are more model dependent due to multiple scattering of electrons. The AIRFLY chamber was designed to perform the absolute yield measurement at GeV energies, where multiple scattering is small. We are currently studying experimental setups to reduce the effect of multiple scattering in this measurement, as well as ways to verify the Monte Carlo modelling of this effect.

## 4. Outlook

A novel technique to measure the absolute fluorescence yield of the most prominent line – 2P(0,0) 337 nm has been presented.

Preliminary measurements performed at the BTF facility in Frascati with 350 MeV electrons showed that a systematic uncertainty below the 10 % level is within reach.

We also investigated the feasibility of the absolute yield measurement with the same technique at lower energies. We performed a series of beam tests in the Argonne Wakefield Accelerator with 12 to 15 MeV electrons. The systematic uncertainty of these measurements were found to be at least 15 % due to the increased importance of multiple scattering at these lower energies. We are confident that a new experimental setup and dedicated measurements to verify the Monte Carlo modelling of multiple scattering will eventually reduce the systematic uncertainty to the 10 % level.

AIRFLY has now completed the measurements of the air fluorescence spectrum dependence on atmospheric parameters. The pressure dependence has been published [13]. The analysis of the temperature and humidity dependence is advanced, and results on a selected set of lines has been presented at this Workshop [3]. AIRFLY will now focus on the measurement of the absolute yield, and measurements with an improved apparatus, which takes advantage of the experience gained with the preliminary tests reported in this paper, are foreseen both at GeV and MeV energies.

## 5. Acknowledgments

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