Measurement of air-fluorescence-light yield induced by an electromagnetic shower

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Abstract

For most of the Ultra-High-Energy-Cosmic-Ray (UHECR) experiments and projects (HiRes, AUGER, TA, JEM-EUSO, TUS,...), the detection technique of Extensive Air Showers is based, at least, on the measurement of the air-fluorescence-induced signal. The knowledge of the Fluorescence-Light Yield (FLY) is of paramount importance for the UHECR energy reconstruction. The MACFLY experiment was designed to perform absolute measurements of the air FLY and to study its properties. Here, we report the result of measurement of dry-air FLY induced by 50 GeV electromagnetic showers as a function of the shower age and as a function of the pressure. The experiment was performed at CERN using a SPS-electron-test-beam line. The result shows the air FLY is proportional to the energy deposited in air ($E_d$). The ratio $FLY/E_d$ and its pressure dependence remain constant independently of shower age, and more generally, independently of the excitation source used (single-electron track or air shower).

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1 Introduction

The most challenging research in the field of cosmic-ray physics is certainly the highest-energy region of the cosmic-ray spectrum (around $10^{20}$ eV) where the GZK effect is predicted. The origin of these Ultra-High-Energy Cosmic Rays (UHECR) is still enigmatic. Precise measurements of their spectrum and arrival-direction anisotropy could provide important clues to understand their origin. However, the UHECR are rare, and their detection is an experimental challenge. In the 60’s, a measurement technique based on the air-fluorescence light was proposed. This light, observed in the near-UV region ($\sim$300-400 nm), is induced by the de-excitation of the air molecules (mainly $N_2$) occurring along the Extensive Air Showers (EAS) produced by the interaction of UHECR with the atmosphere. Since, most of the past, current and future experiments: HiRes, Pierre Auger Observatory, Telescope Array, Ashra, OWL, EUSO/JEM-EUSO, TUS, use the air-fluorescence signal to measure the UHECR flux, the knowledge of the Fluorescence-Light Yield (FLY) is of paramount importance for the UHECR energy reconstruction.

In the past, the air fluorescence was a subject of extensive laboratory measurements. In 1967, A. N. Bunner summarized the existing data in his thesis and proposed a FLY model with an uncertainty estimated at $\sim 30 \%$. In spite of electron-beam-based measurements of Kakimoto et al. in 1996 and Nagano et al. in 2003, the uncertainties were still large inducing important systematics to UHECR experiments. A historical review of the air-FLY measurements can be found elsewhere.

The controversy and discrepancy between the AGASA and HiRes experiments lead the community to pursue its effort to improve the knowledge of the air fluorescence (absolute light yield, spectrum) and of its dependencies with pressure, temperature, humidity, electron energy, shower age, etc. Since 2002, a dozen of new independent experiments were proposed and took data. In these experiments, the air is excited with a high-energy-electron beam (like for MACFLY, FLASH and AirFLY), a radioactive source or a low-energy-electron gun. A comparison and discussion of the results of these experiments can be found in the proceedings of the latest air-fluorescence workshop. Two types of experiments were carried out, using thin or thick target. For the first type the fluorescence light is induced directly by interactions of primary electrons with the air, whereas for the second type, the light is induced by interactions of electromagnetic showers similar to EAS. Only two experiments used thick targets: FLASH and MACFLY.

The MACFLY (Measurement of Air Cherenkov and Fluorescence Light Yield) experiment has been designed to measure the light induced by both a single-
electron track and a high-energy electromagnetic shower developing in air. Actually, the experiment is composed of two devices, MF1 for the single-track fluorescence (thin target) and MF2 for the electromagnetic-shower fluorescence (thick target). The MF1 results, obtained for different electron energies (1.5 MeV, 20 GeV and 50 GeV), as well as an air-FLY model were previously published. In this paper, we focus on the air-FLY measurements performed with the MF2 device at the CERN-SPS-X5-electron-test-beam line with 50 GeV electromagnetic showers. We compare these measurements with Monte Carlo simulations of shower development implementing a FLY model based on the MF1 results.

2 Experimental setup

The MF2 device is composed of a pressurized chamber containing the gas under study, a pre-shower system and an optical system. The chamber is a quasi-cylindrical (96 cm in diameter and 146 cm long) large-volume (∼1 m³) tank internally covered with black paper (see Figure 1). The electron beam is aligned with the axial symmetry axis of the tank. It impinges on the pre-shower system which is a variable thickness target used to initiate electromagnetic showers inside the chamber. The pre-shower system is installed upstream the chamber, in a recess of 15 cm deep from the entrance wall of the tank (end-cap). The optical system measures the fluorescence light emitted by the excited air contained in the tank. It uses six UV-sensitive phototubes (PMTs) EMI9820QA. These PMTs are installed on the entrance end-cap on a 350 mm radius circle centered on the beam line. They point to the gas volume making a 20.5° angle with the beam direction. They are separated from the inner gas by quartz windows. The optical system is also composed of Winston cones and of different colored glass filters. The results presented in this paper correspond to the measurements performed using the Schott BG3 filters, which has a large transmittance band (290-440 nm). The same filter was used for the MF1 measurements (The MF1 device is described elsewhere).

The SPS-beam line is a pulsed beam delivering about 10 000 particles by spill (every 16.8 s). The purity of the beam is better than 98% for 50 GeV electrons. Along the beam line, upstream MF2, we have installed also the MF1 device, a beam-position chamber (delay chamber) with a resolution of about 0.6 mm and a trigger system composed of two sets of scintillating counters, one upstream and one downstream the MF1 device, as shown in Figure 2. The beam-spot size measured by the delay chamber is about 4 × 7 mm².

An external gas system allows to fill both chambers, MF1 and MF2, with the desired gas mixture, at a specific pressure. The two chambers are equipped with pressure and temperature gauges to control both parameters during the
In this paper, we report the FLY measurement of the following gas mixture: 80\%(N_2) and 20\%(O_2). This composition is close to the atmospheric dry air which is an admixture: 78.08\%(N_2)-0.93\%(Ar)-20.99\%(O_2). The gas system enables to fill both chambers at the same time with the same gas, leading to simultaneous identical measurements with MF1 and MF2.

3 Pre-shower system

When interacting in materials, high-energy electrons develop electromagnetic showers. The longitudinal development and the lateral spread of the shower are characterized respectively by the radiation length, $X_0$, and by the Molière radius, $R_{Mo}$, of the material $^{[24]}$. In the air, an electromagnetic shower takes several kilometers for developing (at atmospheric pressure $X_0 \approx 300\text{ m}$). Then, in order to sample air-shower development in laboratory, we have to use a fast and compact shower initiator. Here we use a pre-shower system made of a variable thickness copper target.
Fig. 3. The MF2 pre-shower system is a copper-disk-stack target surrounded by a lead-shielding tube.

We choose copper because of its properties: high density ($\rho = 8.96 \text{ g/cm}^3$) and low atomic number ($Z = 29$) which initiate compact showers with a small lateral spread ($X_0 = 14.3 \text{ mm}$, $R_{Mo} = 14.9 \text{ mm}$). The characteristics of the electromagnetic shower induced in the copper target are close to the EAS characteristics. The critical energy is of the same order of magnitude ($\sim 24 \text{ MeV in copper}$ and $\sim 80 \text{ MeV in air}$) and the energy of the secondary particles is similar. Moreover, the particle density of the shower in the MF2-chamber gas after the pre-shower (from $10^3$ to $10^5 \text{ e}^+/-/\text{m}^2$) is in the range of the particle density encountered in UHECR EAS at the shower maximum (from $10^3$ to $10^7 \text{ e}^+/-/\text{m}^2$) (25).

Figure 3 shows a sketch of the pre-shower system. The target is made of a stack of copper disks, 10 mm thick each. The age of the shower changes as a function of the number $N$ of disks in the stack. The equation 1 gives the pre-shower thickness (expressed in $X_0$ units) as a function of $N$. One copper disk corresponds to $(0.7 \pm 0.002)X_0$. All the matter on the beam line upstream the copper target (Trigger scintillator, MF1 chamber, etc.) corresponds to $(0.27 \pm 0.05)X_0$.

$$X_N = (0.27 + N \times 0.7)X_0 .$$

In copper, at 50 GeV, the maximum of the shower development is at $7X_0$ ($\sim 10 \text{ cm}$). The pre-shower system allows to reproduce the air shower development in real atmosphere, on several kilometers, until the shower maximum. The sampling values used here are: 0, 1, 3, 5, 7 and 10 copper disks.

In order to minimize the background induced in the PMTs by the showers, the copper-disk-stack target is surrounded by a lead shielding (20 mm thick)
which protects the PMTs from the backscattered particles.

4 Data taking and FLY reconstruction

The data recording is performed on an event by event basis. It uses a VME based DAQ system running a Labview program. The signal from all PMTs (MF1, MF2 and triggers) is recorded by QADC (CAEN-V792) which integrate the charge during 100 ns. We define two kinds of event: Beam Events (BE) and Random Event (RE). A BE is triggered when an electron passes through the two sets of scintillator counters (FLY measurement). The RE are randomly triggered (background measurement). For every run about one million events are recorded: 500 000 BE and 500 000 RE.

The air FLY is rather weak and the majority of photons emitted are lost in the chamber. The typical mean number of photon detected by a PMT is about 0.01 pe/evt (photoelectron per event). The method to extract the mean Detected Light (DL) of a run from the data is described in the MF1 paper [23]. This method can reconstruct the DL at the level as low as 0.01 pe/evt with an uncertainty smaller than 4%.

The detected light (DL) could come from several sources: Fluorescence (FDL), Cherenkov (CDL) and Background (Bgd). The overall signal is then:

\[ DL = FDL + CDL + Bgd. \]  

(2)

Figure 4 shows the DL reconstructed from data and the estimation of CDL and Bgd contributions to the total measured light. The FDL is determined by subtracting CDL and Bgd to DL. The main part of the DL comes from the fluorescence whatever the conditions (50 GeV showers in dry air at 500 hPa for the left panel or at 100 hPa for the right one).

The background level is determined from both, RE of the run and BE in vacuum where no light from neither fluorescence nor Cherenkov is expected. The background comes mainly from backscattered particles of the showers. The MF2 device has been designed to minimize it. As one can see in figure 4, the background is quite low compared to the fluorescence signal but it grows with the shower age (pre-shower thickness). That is why we limit our FLY measurements to the shower maximum. The uncertainty of the background measurement is about 20%.

We estimate the Cherenkov radiation contribution with a Geant4 [26] based Monte-Carlo simulation program. The Cherenkov light yield is important at atmospheric pressure ($\sim 20$ ph/m/electron). However it is not contributing so
Fig. 4. Measured light in dry air at 500 hPa (left) and 100 hPa (right) in milli-pho-
toelectron per event (mpe/evt) as a function of the pre-shower thickness (in $X_0$). Triangles represent the total signal (DL); dotted line is for the Bgd estimation from vacuum measurements; dot-dashed curve is the CDL simulation; stars are the FDL data (after substraction of Bgd and CDL); dashed line is the FLY model for showers. The solid line is the sum of the all contributions.

much to the detected signal because it is mainly emitted in the forward direc-
tion, downstream, where it is absorbed on the black surface of the chamber. The uncertainty of the CDL after diffusion on the black surface is estimated
at 50%.

Finally we extract the FLY in MF2 from the FDL, after dividing it by the
MF2 efficiency $\varepsilon_{MF2}$ (see next section):

$$FLY = \frac{DL - CDL - Bgd}{\varepsilon_{MF2}}.$$

(3)

5 Calibration and systematic errors

The Monte Carlo simulation plays a crucial role in the calibration and data
analysis of the MACFLY experiment. The exact geometry and matter of all
parts of MF2 (pre-shower, gas) and of other objects (MF1, scintillator) which
are in the beam line have been reproduced carefully in a Geant4 based simu-
lation program. For the external parts, only the details bigger than few cen-
timeters are described. The optical properties of the optical system and of
the inner chamber surfaces are also implemented. The fluorescence emission
is assumed isotropic and its geometrical distribution is assumed to match the
deposited energy distribution. The simulation program tracks all the optical
photons until the PMT-photo-detection surface or until their absorption.

All the phototubes used for the MACFLY experiment are tested and cross cali-
| Errors sources            | Absolute | relative |
|--------------------------|----------|----------|
| MF1 calibration          | 13.7%    | -        |
| MF1/MF2                  | 18%      | -        |
| Geometrical distribution | ∼3%      | ∼3%      |
| DL reconstruction        | ∼3%      | ∼3%      |
| CDL Simulation           | ∼1.5%    | ∼1.5%    |
| Bgd Measurement          | ∼1.5%    | ∼1.5%    |
| TOTAL                    | 23.1%    | ∼4.7%    |

Table 1
Systematic uncertainties of MF2 measurements in dry air at 100 hPa and for 5 $X_0$-thick-pre-shower target.

brated in laboratory with a test bench using stabilized UV LED (370 nm) (22). Then, to calibrate the MF2 device we use the MF1 chamber which is well calibrated (23). In order to do that, we performed measurement in both chambers filled with the same gas at same pressure and temperature, and without pre-shower target in front of MF2 (0 disk). In this configuration, both chambers measure FLY induced by the same 50 GeV-electron tracks. As the two measurements are in the same condition, the $FLY/E_d$ should be the same in the two chambers.

$$FLY/E_d = \frac{FDL_{MF1}}{\varepsilon_{MF1} \times E_{dMF1}} = \frac{FDL_{MF2}}{\varepsilon_{MF2} \times E_{dMF2}}.$$  \hspace{1cm} (4)

where $FDL_{MF1}$ and $FDL_{MF2}$ are the fluorescence light measured (in pe/evt) with MF1 and MF2, $\varepsilon_{MF1}$ and $\varepsilon_{MF2}$ are the light collection efficiencies of MF1 and MF2, $E_{dMF1}$ and $E_{dMF2}$ are the energy deposited in the air inside the measurement chambers of MF1 and MF2. The collection efficiency of MF1 is much better than the MF2 one. For the same light yield, the $FDL_{MF1}$ is about 12 times higher than $FDL_{MF2}$. The ratio between the $E_{dMF1}$ and $E_{dMF2}$ is estimated by Monte Carlo simulation at 0.15. Then, we determine the MF2 efficiency from the $\varepsilon_{MF1}$:

$$\varepsilon_{MF2} = \frac{FDL_{MF2}}{FDL_{MF1}} \cdot \frac{E_{dMF1}}{E_{dMF2}} \cdot \varepsilon_{MF1} = (7.0 \pm 1.5) 10^{-5} \text{pe/photon.}$$  \hspace{1cm} (5)

The single-electron-track (no pre-shower) air fluorescence produces a very weak signal in the MF2 PMTs (<0.001 pe/evt). The uncertainty on this measurement is large and induces an absolute calibration uncertainty of MF2 larger than for MF1 (see detail in table 1).

The systematic error of $E_{dMF1}$ and $E_{dMF2}$, obtained by Monte Carlo simulation,
Fig. 5. Dry-air-Fluorescence-Light Yield per unit of length (photon/meter) in dry air (100 hPa & 500 hPa) emitted by 50 GeV electromagnetic showers as a function of the shower age. Dotted lines correspond to a model of shower development in copper.

is dominated by the air-density uncertainty (about 1% at 500 hPa and 2% at 100 hPa). For the inter-calibration measurement, both chambers are filled with the same gas, then this systematic is negligible. However, the spacial geometry distribution of the energy deposited in the MF2 chamber changes as a function of the shower age. As the fluorescence emission should match the deposited energy distribution, the geometrical acceptance of MF2 could change as a function of the shower age. The systematic error induced by this effect has been estimated by simulation to be less than 3%.

The background and the Cherenkov radiation represent a small fraction of the raw measured light (see figure 4) and induce small systematic errors. The Cherenkov contribution grows with pressure (density) and induces more uncertainty at higher pressure. Table 1 shows the contribution of the different systematic effects to the global uncertainty at 100 hPa and for $5X_0$-thick preshower. The systematic errors of relative measurements are rather good ($<5\%$) and grow only up to $\sim7.5\%$ at 500 hPa.

6 Result and discussion

We measured FLY of dry air excited by electromagnetic showers for several pressures and for several shower-age values. Figure 5 shows the mean number of fluorescence photons emitted when a 50 GeV shower traverses a one-meter-thick layer of air as a function of the shower age. We have performed
Fig. 6. Dry-air-Fluorescence-Light Yield per unit of deposited energy (photon per MeV) as a function of: (left) gas pressure, for two thicknesses of the pre-shower; (right) shower age, for two values of the pressure. A comparison with our FLY model [23] is also shown (dotted lines).

such measurements for two different pressures: 100 hPa and 500 hPa. The dotted lines are proportional to a model of energy lost ($dE/dX$) by a 50 GeV-electron-induced shower developing in copper, based on Geant4 simulations. The measured air FLY follows well the expected shower development.

To check the properties of air-fluorescence light induced by air shower, we compare our results to the air-fluorescence model developed by Colin [22] found to reproduce well the MF1 results [23]. This model assumes the air FLY to be proportional to the energy deposited ($E_d$) in the air volume. Thus, the ratio $FLY/E_d$ (expressed in photons per MeV) should be independent of the excitation source. For each FLY measurements with MF2, $E_d$ inside the chamber was obtained by Monte Carlo simulation. Figure 6 shows the variations of $FLY/E_d$ as a function of the pressure (left panel) and as a function of the shower age (right panel).

The pressure dependence was measured for two pre-shower thickness: $2.36X_0$ and $5.16X_0$. We compare these results with the FLY model based on MF1 measurements [23] realized with the same gas mixture and the same optical filter (dotted line in Figure 6). For the two shower ages, the air $FLY/E_d$ has the same variation with pressure as for air fluorescence induced by a single-electron track. Comparison with other experiments is difficult because it requires a knowledge of the deposited energy in these experiments and corrections from the experimental differences (air composition, filter, etc.). However, the MACFLY model has been already compared with past [22] and recent [21] experiments and shows similar pressure dependence.

The shower-age dependence was measured at two pressures: 100 hPa and 500 hPa. In both case, we do not find any significant variation of $FLY/E_d$ with
the shower age, in agreement with the FLY model (doted lines). This result is also in good agreement with the FLASH thick-target experiments which measured shower-age dependence in ambient air \(15\). This shows clearly that the \(FLY/E_d\) properties are independent of the excitation source of the air. There is no clue of special behavior from saturation effect at the EAS density, or from low-energy-electron excitation of air molecules as it could be expected \(27\). Thus, air-FLY results obtained from electron-track experiments (thin target) can be directly used to determine the properties of the fluorescence induced by air showers. According to our result, the systematic error induced by the extrapolation from electron track to electromagnetic shower must be less than 5%.

7 Conclusion

Using the MF2 device of the MACFLY experiment, we measured the Fluorescence-Light Yield induced by 50 GeV electromagnetic showers in a laboratory-controlled air \((80\%(N_2)-20\%(O_2))\). We studied both pressure and shower-age dependencies. The FLY variations with pressure, measured at two shower ages, are the same as the one measured with the single-electron-track device MF1 \(23\). The FLY variations with shower age, measured at two pressures, are well reproduced by the shower-development simulations implementing our air-fluorescence model which assumes the air FLY to be proportional to the energy deposited in the air volume. No evidence for FLY variation with the air-excitation source was found.

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