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MEASUREMENTS OF FLUORESCENCE YIELD OF ELECTRONS IN AIR UNDER ATMOSPHERIC CONDITIONS: A KEY PARAMETER FOR ENERGY OF COSMIC RAYS

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Abstract. The measurement of the fluorescence yield and its dependence on atmospheric properties such as pressure, temperature or pollutants, are essential to obtain a reliable measurement of the primary energy of cosmic rays. A new type of absolute measurement of the nitrogen fluorescence yield in the air will be performed at LAL using 3 items which will yield an unprecedented precision in all conditions of pressure, temperature, and pollutants. A 5 MeV electron beam will be provided by the new electron accelerator PHIL at LAL(Laboratoire de l'Accélérateur Linéaire, Univ Paris-Sud, CNRS/IN2P3, Orsay). This source will induce florescence yield inside an integrating sphere. The sphere will be surrounded by a spherical envelope to create a temperature controlled chamber (a Dewar). With this setup it will be possible to vary the temperature from -60 C to +40 C and the pressure from 1 to 0.01 atm. An output device on this sphere will be equipped with a set of optical fibers driving the fluorescence light to a Jobin-Yvon spectrometer equipped with an LN_2 cooled CCD. The fluorescence spectrum in the 300-430 nm range will be accurately measured in steps of 0.1 nm resolution. A PMT equipped with a BG3 filter (the same as on JEM-EUSO) will be set on the sphere to measure the integrated yield. The expected precision of the yield should be better than 5%.

Keywords: Ultra high-energy cosmic rays, air fluorescence technique

1 Introduction

A precise measurement of the energy is essential for the study of ultra-high energy cosmic rays. Basically, two types of detectors are used for this purpose:

- Surface arrays which sample the shower tail: this method records the lateral development of the shower of secondary particles using an array of particle detectors.
- Fluorescence detectors which record the longitudinal development of the shower and observe the atmospheric fluorescence induced by charged particles in the shower.

The second method is currently the most precise one to estimate the energy of cosmic rays, and is used by the Fly's Eye experiment (Bird et al. 1994), HiRes (Song et al. 2000), Telescope Array (Tokuno et al. 2008), and the Pierre Auger Observatory (Auger 2010). The future JEM-EUSO telescope (Takahashi et al. 2009) will also detect extensive air showers from the International Space Station with this method.

Fluorescence detectors record the longitudinal profile of air showers induced by cosmic rays through the detection of the fluorescence light generated by secondary charged particles. Since the fluorescence intensity is proportional to the deposited energy, the integration in depth of the fluorescence profile allows a calorimetric determination of the primary energy. This measurement of primary cosmic ray energy is relatively model independent, as the fluorescence intensity is proportional to the electromagnetic energy released by the shower into the atmosphere. For the Pierre Auger Observatory, the uncertainty in the energy using the fluorescence

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method is around 22%, and the main source of systematic uncertainties comes from the limited accuracy in the measurement of the air-fluorescence yield. In the Pierre Auger Observatory (Auger 2010) the uncertainty in the fluorescence yield contributes 14% to the total systematic error of the energy calibration. This parameter is thus a key for determining the energy of ultra-high energy cosmic rays detected by a fluorescence telescope. We will measure the fluorescence yield using a 5 MeV electron beam and calibrated detectors in order to improve the accuracy of this value to a precision of 5%.

2 Fluorescence yield

Air-fluorescence photons are produced by the de-excitation of atmospheric nitrogen molecules excited by the shower electrons. Excited molecules can also decay by colliding with other molecules, using the process of collisional quenching. This effect increases with pressure, reducing fluorescence intensity.

Atmospheric effects, including pressure, temperature, and composition, must also be reproduced and studied in order to understand the real conditions present during the production of fluorescence photons within an extensive air shower. As the excitation cross sections show a fast decrease with energy, secondary electrons from ionization processes are the main source of fluorescence light. For this reason, it is necessary to simulate the production of fluorescence photons in order to evaluate the fiducial volume needed for interaction. The fluorescence spectrum consists of a set of molecular bands represented by a set of discrete wavelengths λ. The range of this spectrum is the near UV between 300 to 430 nm.

The fluorescence yield for a line, Y_λ, is defined as the number of photons emitted by the primary charged particle per meter of path. The deposited energy of an electron per unit of length is defined as:

$$\rho \frac{dE}{dX} \tag{2.1}$$

The number of photons produced with this energy depends on the fluorescence efficiency of the line, ϕ_λ:

$$Y_\lambda(\text{photons/e/cm}) = \phi_\lambda \frac{\rho}{h\nu} \frac{dE}{dX}. \tag{2.2}$$

This efficiency, ϕ_λ, depends on the lifetime of the level (de-excitation) and also on the effect of pressure, temperature, and composition (Takahashi et al. 2009). For example, the dependence of Y_λ on atmospheric conditions can be described by the so-called characteristic pressure $P^{'}$. $P^{'}$ contains a contribution af all possible quenchers (I.E., N_2,O_2,H_2O).

$$Y_\lambda(P,T) = \frac{Y_\lambda}{1 + \frac{P}{P^{'}(\lambda,T)}}. \tag{2.3}$$

$$\frac{1}{P'} = \sum_i \frac{f_i}{P'_i} \tag{2.4}$$

$$P^{'} = \frac{kT}{\tau} \frac{1}{\sigma_{N_i} v_{N_i}} \tag{2.5}$$

With f_i is the fraction of molecules of type i in the mixture, σ_{N_i} is the collisional cross section which depends on the particular band, and v_{N_i} is the relative velocity of the molecules; k is the Boltzman constant and τ the radiative lifetime of the corresponding level.

The total fluorescence yield Y_{tot} is thus the sum of all Y_λ:

$$Y_{tot} = \sum_\lambda Y_\lambda. \tag{2.6}$$

Knowing both the fluorescence yield and its dependence on atmospheric properties accurately is essential in order to obtain a reliable measurement of the energy of cosmic rays in experiments using the fluorescence method (Rosado et al. 2011; Arqueros et al. 2009; Rosado et al. 2010). Even if the previous studies reproduce these effects by simulation and using the absolute value in dry air at a given pressure and temperature, the direct measurement of these effects is also essential in order to understand the different values used by the experiments (Monasor et al. 2009). Studying the total spectrum of fluorescence emission is also fundamental for JEM-EUSO in order to optimize data analysis.

3 Principle of the experiment

3.1 Experimental set up

The aim of this experiment is to measure the fluorescence yield of each line with a 5% accuracy using an electron beam as a source of electrons (reproducing the electrons of an extensive air shower), an integrating sphere with control of pressure, temperature, and composition in order to measure atmospheric effects, and calibrated detectors.

The electron beam will interact with gas inside an integrating sphere. A fraction of the emitted fluorescence light will be detected and measured with both a Jobin-Yvon spectrometer equipped with an LN_2 cooled CCD, in order to study each spectral line separately, and also a photo-multiplier tube equipped with a BG3 filter (the same filter as the JEM-EUSO project).

The integrating sphere must be vacuum-tight and part of a dewar to allow studying the yield at low temperatures (down to −60 C).The basic property of the integrating sphere being that the probability to detect light is independent from where the light is produced inside the sphere The size of the sphere depends on pressure (due to the pressure dependence of the distance of ionization of secondary electrons and multiple scattering) from a few centimeters at 1 atm to a few decimeters at very low pressure (0.01 atm). The exact size of the sphere is determined using Geant4 simulations to reproduce multiple scattering and the mean free path of secondary electrons.

The source of electrons is an electron accelerator (PHIL) developed at the Laboratoire de l'Accélérateur Linéaire (LAL) and presented in the next section.

The calibration of the detectors is fundamental in order to obtain an accurate measurement of the fluorescence yield.

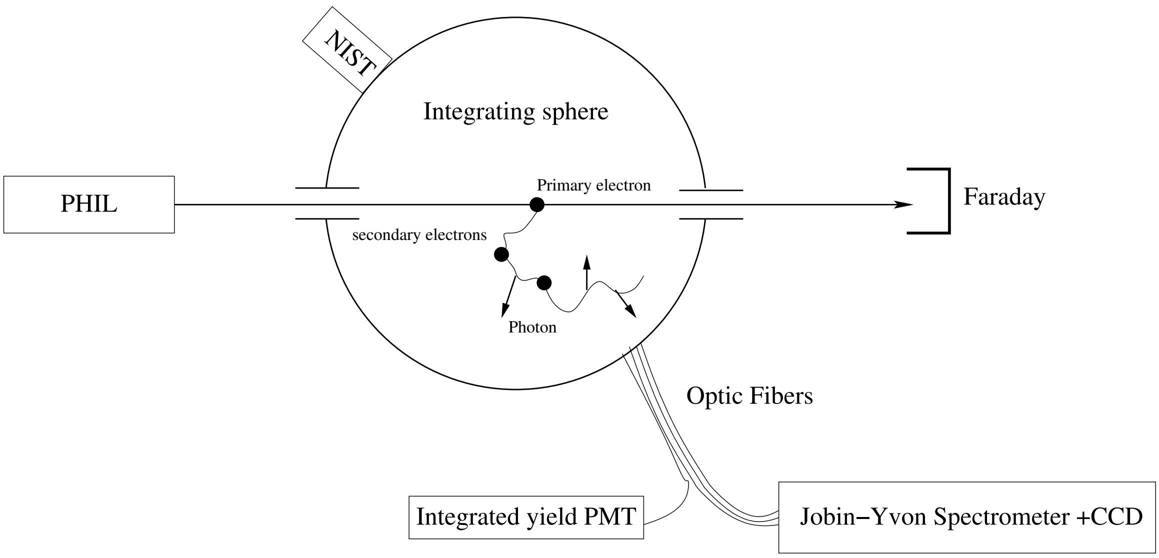

Fig. 1. Design of experiment

3.2 PHIL: the electron Beam

The "PHoto-Injector at LAL" (see Brossard et al. 2010, and `http://phil.lal.in2p3.fr/`) is an electron beam accelerator at LAL. This accelerator, which is primarily dedicated to the testing and characterization of electron photo-guns and high-frequency structures for future accelerator projects, can also be used to simulate the electrons emitted by an extensive air shower.

PHIL is currently a 6-meter-long accelerator with 2 diagnostic beam lines. The direct beam line will be used to inject electrons into an integrating sphere. An Integrating Current Transformer (ICT) and a faraday cage will provide the estimated beam charge, beam size, and beam position measurement with high accuracy. The main characteristics of PHIL, for our configuration, have been summed up in Table 1. For the measurement of the fluorescence yield, precise knowledge of the source (energy, position, charge...) is an important part of the

Table 1. Characteristics of PHIL

Characteristics	Values
Charge per bunch	between 50 pC to 300 pC
Energy	3-5 MeV
Energy spread	less than 10%
Bunch length	a few ps
Beam transverse dimension	0.5 mm

total accuracy. Using the PHIL accelerator, these parameters will be available with an accuracy of $\sim 2\%$. A separative window will connect the PHIL accelerator with the sphere.

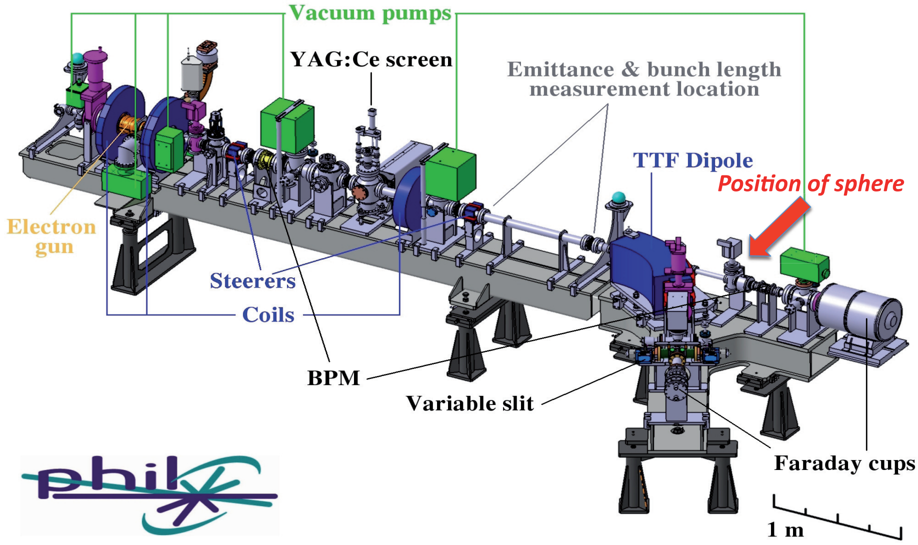

Fig. 2. The PHIL accelerator: Futur position of the sphere is indicated with the red arrow

3.3 Detectors

For the integrated measurement, fluorescence photons will be detected and counted by a photo-multiplier tube (PMT) with the same filter as in the JEM-EUSO project. The calibration of the detector is a key parameter in this kind of experiment. The overall PMT efficiency will be measured using a NIST photo-diode, accurate to 1.5%.

Spectral measurements are interesting because the effect of temperature, pressure, and composition are not the same for each spectral line. These effects are also interesting for the future JEM-EUSO project in order to study the signal to noise ratio, which changes with the wavelength.

The fluorescence lines will be measured using a Jobin-Yvon spectrometer equipped with a LN_2 cooled CCD. The CCD will be calibrated using the calibrated photo-multiplier tube at the second output of the spectrometer.

The patented method of calibration has been developed and used with success by G. Lefeuvre, P. Gorodetzky, and their collaborators, and is explained in the thesis of G. Lefeuvre (see Lefeuvre 2006; Lefeuvre et al. 2007).

The expected accuracy of the detectors (PMT and CCD camera) should be around 2 %.

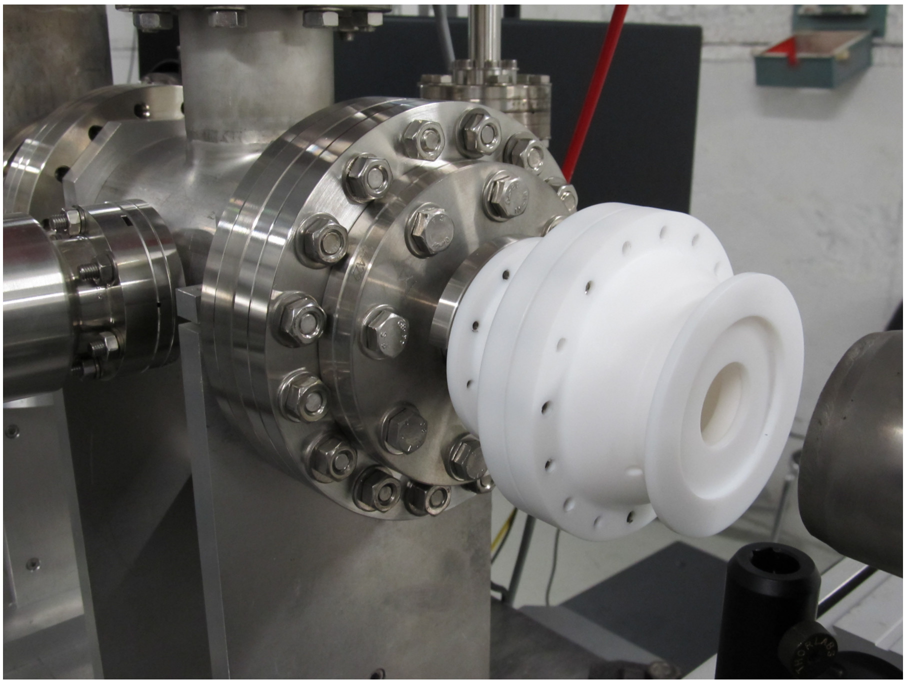

Fig. 3. First sphere in Teflon on the PHIL accelerator

4 Conclusions

The experiment will provide both the "integrated" measurement and "spectral" measurement of the fluorescence yield with high accuracy under a wide range of atmospheric conditions. The first step of the experiment will debug the measurement at 1 atm with a sphere of 6 cm in diameter. It will be performed during the next months (started in september 2012) and the study of atmospheric effects (temperature/pressure/composition) will be made during the year 2013.

A combined 2% accuracy for the detector and $\sim 2-3\%$ accuracy for the charge of the electron beam will allow measurement of the fluorescence yield with an accuracy of up to 5%.

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