Nuclear Instruments and Methods in Physics Research A 597 (2008) 55–60

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research A

journal homepage: www.elsevier.com/locate/nima

A novel method for the absolute fluorescence yield measurement by AIRFLY

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ARTICLE INFO

Available online 22 August 2008

Keywords:
Air fluorescence detection
Ultra high energy cosmic rays

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 Cherenkov 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.

1. Introduction

The detection of ultra high energy ($\gtrsim 10^{18}$ eV) cosmic rays using nitrogen fluorescence emission 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 λ 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 $E_{\text{dep}}^{\text{shower}}(h)$ 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 and 430 nm are presented in two separate contributions [2,3].

It should be noted that $E_{\text{dep}}^{\text{shower}}(h)$ 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 Ref. [4], the proportionality of the

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doi:10.1016/j.nima.2008.08.049

fluorescence light to the energy deposit at a few % level was tested over the energy ranges 0.5–15, 50–420 and 6–30 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 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.

$$\frac{\underbrace{N_{337}(fluo)}_{measured}}{\overbrace{N_{337}(cer)}} = \frac{Y_{\mathrm{fl}} \times \underbrace{Geom_{fluo}}_{MC} \times \underbrace{T_{filter} \times QE_{337}}_{\sim cancel} \times \underbrace{N_{e^-}}_{relative}}{\overbrace{Y_{\mathrm{cer}}}^{known} \times \overbrace{Geom_{cer}} \times \overbrace{T_{filter} \times QE_{337}} \times \overbrace{R_{mirror}}^{measured} \times \overbrace{N_{e^-}}} \qquad (1)$$

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 Cherenkov or transition radiation, are negligible due to the non-isotropic emission of such mechanisms. In the Cherenkov mode a thin mylar mirror at an angle of 45° is inserted remotely into the beam, redirecting the Cherenkov light into the detector. In this mode, the Cherenkov light fully dominates over fluorescence.

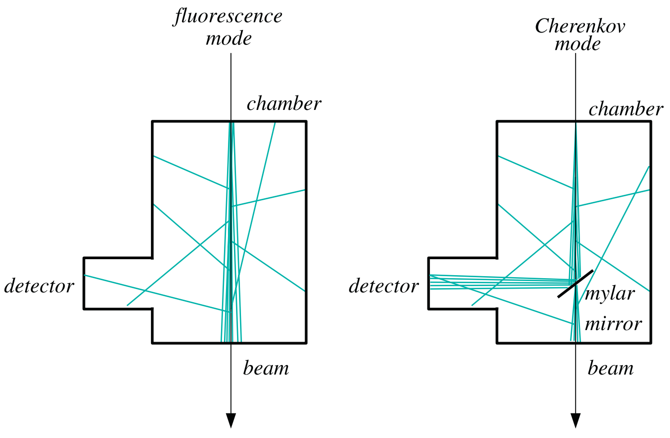

Fig. 1. Setup for the measurement of the absolute fluorescence yield. Remotely controlled mirror allows to switch between Cherenkov and fluorescence modes without beam interruption.

The absolute fluorescence yield is then determined using the ratio of the signal measured in the fluorescence and in the Cherenkov configurations from Eqs. (1). The Cherenkov 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 Cherenkov 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 in Frascati is capable of delivering electrons of energy 50–800 MeV and positrons of energy 50–550 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.

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.

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 Cherenkov 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 Ref. [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 Cherenkov 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. Conse-