Astroparticle Physics 34 (2010) 164–172

Contents lists available at ScienceDirect

Astroparticle Physics

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

Comparison of available measurements of the absolute air-fluorescence yield

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ARTICLE INFO

Article history:
Received 17 May 2010
Accepted 29 June 2010
Available online 3 July 2010

Keywords:
Air-fluorescence yield
Fluorescence telescopes
Ultra-high energy cosmic rays
Extensive air showers

ABSTRACT

The uncertainty in the absolute value of the fluorescence yield is still one of the main contributions to the total error in the reconstruction of the primary energy of ultra-energetic air showers using the fluorescence technique. A significant number of experimental values of the fluorescence yield have been published in the last years, however reported results are given very often in different units (photons/MeV or photons/m) and for different wavelength intervals. In this work we present a comparison of available results normalized to its value in photons/MeV for the 337 nm band at 800 hPa and 293 K. The conversion of photons/m to photons/MeV requires an accurate determination of the energy deposited by the electrons in the field of view of the experimental setup. We have calculated the energy deposition for each experiment by means of a detailed Monte Carlo simulation including the geometrical details of the particular setup whenever possible. Our predictions on deposited energy, as well as on some geometrical factors, have been compared with those reported by the authors of the corresponding experiments and possible corrections to the fluorescence yields are proposed.

1. Introduction

Charged particles of a cosmic ray shower, mostly electrons, passing through the atmosphere lose energy by inelastic collisions with air molecules. A small fraction of the total deposited energy is emitted by molecular nitrogen as UV fluorescence radiation in the ~300–400 nm spectral range. The detection of this radiation provides a precise determination of the longitudinal profile allowing the reconstruction of the cosmic ray properties, in particular its energy. This technique [1] was first successfully used by the Fly's Eye experiment [2] and later by HiRes [3]. Fluorescence telescopes are presently being employed by the Pierre Auger Observatory [4] and the Telescope Array experiment [5]. On the other hand, the JEM-EUSO project [6] and the S-EUSO free-flying satellite mission [7] are being designed for the detection of fluorescence traces of air showers viewing downward from the top of the atmosphere.

The ratio between number of fluorescence photons and deposited energy, i.e., the fluorescence yield Y, is a key calibration parameter determining the energy scale of the fluorescence telescopes. A number of absolute measurements of the fluorescence yield have been carried out in laboratory experiments in the last years.

At atmospheric pressure, fluorescence emission in the spectral range of interest basically comes from the Second Positive (2P) system of N_2 and, to a much less extent, the First Negative (1N) system of N_2^+. Each one results from the transition between two electronic states and consists of a set of molecular bands corresponding to different combinations of vibrational levels v–v' of the respective upper and lower states. Excitation cross section of the 1N system decreases with energy in the 10^2–10^6 eV range showing a very smooth growing behavior at larger energies. That of the 2P system peaks at about 15 eV decreasing strongly with an E^{-2} dependence. As a consequence, high-energy electrons themselves are very inefficient for the generation of air fluorescence. In fact, as is well known, fluorescence emission along the track of an energetic primary electron is mainly induced by low-energy secondary electrons ejected in successive ionization processes. The efficiency for fluorescence emission varies with the energy spectrum of these secondaries,[1] which in principle depends on the primary energy. However, a theoretical calculation using a detailed Monte Carlo simulation [8–10] has demonstrated that the fluorescence yield is nearly constant for energies above a few kiloelectronvolts. This E-independent behavior of the fluorescence yield has been checked experimentally [11–13].

A number of experimental values of the absolute fluorescence yield are available in the literature. Essentially, in these experiments a beam of electrons crosses a collision chamber filled with air at known conditions. However, different techniques can be used. Many authors [13–18] have used electrons from a source of ^{90}Sr with energy around 1 MeV. Other absolute measurements have been performed with higher energy electrons from accelerators. The MACFLY Collaboration [13] used the CERN/SPS-X5 test

[1] For instance, electrons with energies below the threshold for fluorescence excitation promptly lose all their energy, but induce no fluorescence.

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doi:10.1016/j.astropartphys.2010.06.007

beam facility which delivers a pulsed electron beam of about 10^4 electrons per spill (4.8 s duration) every 16.8 s. Measurements at 20 and 50 GeV were carried out using this facility. The FLASH Collaboration [19,20] used the Final Focus Test Beam facility at the Stanford Linear Accelerator Center which provided 28.5 GeV electrons in 3 ps pulses of about 10^8 electrons at a rate of 10 Hz. The AIRFLY Collaboration is carrying out absolute measurements of the air-fluorescence yield using different accelerators. Preliminary results obtained with 350 MeV electrons at the Beam Test Facility of the Instituto Nazionale di Fisica Nucleare have been presented in [21]. New measurements using a 120 GeV proton beam from the Meson Beam Test Facility at Fermilab were presented at the 6th AFW [22] and very likely final results will be published soon.

In this work we will compare the absolute values reported by the above authors. In many occasions comparison cannot be done directly. For instance, some authors measure single intense fluorescence bands while others detect the integrated fluorescence in a wide spectral range. Comparison between these experimental results can be carried out if the relative intensities of the bands along the fluorescence spectrum are known. We will normalize all the results to the most intense fluorescence band at 337 nm using accurate experimental data in full agreement with theoretical intensity ratios proposed in [8–10].

On the other hand, some authors report their measurements in units of photons per electron and meter while others give directly the Y parameter in photons per unit deposited energy (e.g., photons/MeV). The conversion factor between both magnitudes is the energy deposited per electron and unit path length. As it has been pointed out [8–10], an accurate determination of the deposited energy requires discounting that corresponding to secondary electrons outside the field of view of the optical system used to detect the emitted fluorescence. To evaluate this effect we have carried out a MC simulation of the various experimental setups. When possible a dedicated simulation including geometrical details has been performed. Also the effect of the spatial distribution of deposited energy on the optical efficiency of the experimental setup has been evaluated in some cases. As a result of this study absolute values of the fluorescence yield normalized to that of the 337 nm band at 293 K and 800 hPa in dry air will be shown with a discussion on possible corrections to be applied. A previous comparison at 1013 hPa for some of the above measurements has been published recently [10]. In this work we will update those results and extend the comparison to other experimental results.

2. Fluorescence yield

2.1. Units

In the literature, several parameters have been used to measure the amount of fluorescence light induced by an electron moving in the atmosphere. A detailed description of the various magnitudes can be found in [23]. The number of photons emitted per electron and unit path length have been used extensively. We will name this parameter as ε and, for a band v–v', it is proportional to the number of nitrogen molecules per unit volume N and the reciprocal of the $1 + P/P'_v$ Stern–Volmer factor, accounting for the collisional deexcitation of the upper level v, where P'_v is a characteristic pressure depending on the gas composition and temperature. If ignoring the contribution of secondary electrons, the proportionality constant would be the so-called optical cross section.

While most secondary electrons have low energy, and thus, short range at atmospheric pressure, a small number of high-energy secondaries can escape the observation region. As a consequence, in a laboratory experiment a fraction of the fluorescence light cannot be detected. Following the parametrization in [8–10], an effective optical cross section $\sigma^{\text{eff}}_{vv'}$ can be defined in such a way that the total number of photons of the v–v' band detected under given experimental conditions (including contributions from both primary and secondary electrons) can be expressed as

$$\varepsilon_{vv'} = N\frac{\sigma^{\text{eff}}_{vv'}}{1 + P/P'_v}. \tag{1}$$

The parameter $\sigma^{\text{eff}}_{vv'}$ depends on E, P and the geometrical features of the experimental setup. Therefore, even for the same primary energy, the measured $\varepsilon_{vv'}$ value depends on the particular experiment. In addition, the pressure dependence of $\varepsilon_{vv'}$ as would be predicted by the Stern–Volmer law is distorted in a geometry-dependent way.

A further pressure dependence arises from the vibrational relaxation of excited nitrogen induced by collisions with surrounding nitrogen molecules in the ground state [24]. The effect of vibrational relaxation is twofold. Firstly, it contributes to the total quenching of a given level v and thus is included in the Stern–Volmer factor (1). Secondly, vibrational relaxation of upper levels ($>v$) provides an additional excitation channel. Although, in principle, this effect may lead to a departure from the Stern–Volmer law, significant deviations have not been appreciated experimentally for any N_2 band in air [25]. In fact, for the 2P(0,0) band, for which detailed data on vibrational quenching are available [24], a simple calculation shows that the only relevant effect of vibrational quenching is a variation of the resulting characteristic pressure respect to the one from pure electronic quenching [26].

The number of photons per unit energy deposited in the medium is a more appropriate parameter for use in fluorescence detectors of cosmic ray showers. Following an already common usage, we will keep the term fluorescence yield to refer to this magnitude Y. For a given band, $\varepsilon_{vv'}$ and $Y_{vv'}$ are related by

$$Y_{vv'} = \frac{\varepsilon_{vv'}}{(\mathrm{d}E/\mathrm{d}x)_{\text{dep}}}, \tag{2}$$

where $(\mathrm{d}E/\mathrm{d}x)_{\text{dep}}$ is the energy deposited per primary electron and unit path length. In the above equation, both the emitted photons and the deposited energy should correspond to the same volume, which is defined by the field of view of the experimental detection system. Note that a significant fraction of energy is deposited by secondary electrons which move away from the path of the primary electron. It has been shown [9,10] that $N\sigma^{\text{eff}}_{vv'}$ and $(\mathrm{d}E/\mathrm{d}x)_{\text{dep}}$ are proportional, resulting $Y_{vv'}$ to be given by

$$Y_{vv'} = \frac{Y^0_{vv'}}{1 + P/P'_{vv'}}, \tag{3}$$

where the $Y^0_{vv'}$ parameter is independent of the experimental conditions and represents the fluorescence yield at null pressure, i.e., in the absence of quenching.

While measurements of the fluorescence yield at atmospheric pressure by different authors show a reasonable agreement, the available data on the P'_v parameters show large discrepancies.[2] Therefore the extrapolation of the fluorescence yield to null pressure is unsafe, making the $Y^0_{vv'}$ parameter unsuitable for our proposes. In this work, comparison will be thus performed using the fluorescence yields measured at given atmospheric conditions.

2.2. Deposited energy

The energy deposited by an electron per unit path length within a given volume can be expressed [10] as

[2] Notice that many authors ignore the additional pressure dependence of $\varepsilon_{vv'}$ due to secondary electrons [10].