The impact of the fluorescence yield on the reconstructed shower parameters of ultra-high energy cosmic rays

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***Abstract*. The determination of the fluorescence yield and its dependence on atmospheric properties such as pressure, temperature or humidity, is essential to obtain a reliable measurement of the primary energy in experiments based on the fluorescence technique. A simple procedure to study the effect of the assumed fluorescence yield on the reconstructed shower parameters (energy and shower maximum depth) as a function of primary energy and arrival direction has been developed. The results for several existing sets of fluorescence yield measurements are presented in this contribution.**

***Keywords*: air fluorescence, shower reconstruction**

I. INTRODUCTION

Fluorescence telescopes record the longitudinal profile of air showers induced by very energetic cosmic rays through the detection of the fluorescence light generated by secondary charged particles. This technique allows an accurate determination of the shower maximum depth $X_{\max}$. In addition, 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[1] E. For this purpose, a key parameter is the fluorescence yield Y, that is, the number of fluorescence photons emitted per unit deposited energy. The fluorescence yield which depends on the atmospheric parameters (e.g. pressure P, temperature T, humidity) is measured in dedicated laboratory experiments. The main contribution of the systematic error in the primary energy comes from the absolute value of Y. Also the uncertainties in the dependence of Y on atmospheric parameters have a non-negligible effect on both E and $X_{\max}$ measurements.

In this paper a simple procedure to study the effect of the assumed fluorescence yield on the reconstructed shower parameters will be shown. The shower development will be described by a Gaisser-Hillas profile and a given set of fluorescence yield data will be assumed. The effect of a variation in this parameter (including its atmospheric dependence) is a change in the reconstructed longitudinal development of the deposited energy and thus a deviation in the reconstructed values of both $X_{\max}$ and E. Several sets of available fluorescence yield data will be used to study the impact on the accuracy in the reconstructed shower parameters.

[1]the total primary energy is obtained after a correction accounting for the so-called missing energy.

II. AIR-FLUORESCENCE YIELD

Air fluorescence in the near UV range is basically produced by the de-excitation of atmospheric nitrogen molecules excited by the shower electrons. The spectrum of fluorescence consists of a set of molecular bands represented by their wavelengths λ. Excited molecules can also decay by collisions with an environmental molecule. Because of this effect, the fluorescence yield in the absence of quenching Y_λ^0 is reduced by a factor which grows with pressure.

$$Y_\lambda(P,T) = \frac{Y_\lambda^0}{1 + P/P'(\lambda,T)}\,. \qquad (1)$$

The total fluorescence yield Y in a given wavelength interval can be obtained by adding up the contributions of all the molecular bands Y_λ. The dependence of Y_λ on atmospheric conditions can be described by a single parameter, the so-called characteristic pressure P'. In general P' contains a contribution of all possible quenchers i (i.e., N_2, O_2, H_2O).

$$\frac{1}{P'} = \sum_i \frac{f_i}{P'_i}\,, \quad P'_i = \frac{kT}{\tau}\frac{1}{\sigma_{Ni}\bar{v}_{Ni}}\,, \quad \bar{v}_{Ni} = \sqrt{\frac{8kT}{\pi\mu_{Ni}}}\,. \qquad (2)$$

In the above expressions f_i is the fraction of molecules of type i in the mixture, σ_{Ni} is the collisional cross section which depends on the particular band, and v_{Ni} and μ_{Ni} are the relative velocity and reduced mass of the two body system N-i respectively; k is the Boltzman constant and τ the radiative lifetime of the corresponding level. The T dependence of the fluorescence yield is given by equations (1) and (2) taking into account that the collisional cross section depends on the kinetic energy of the encounters following a power law ($\sim T^\alpha$).

The reconstruction of the shower parameters requires the following data on the fluorescence yield.

1) The absolute value in dry air at a given pressure and temperature for all bands within the spectral range of the telescope[2].
2) The values of P' in dry air at a reference temperature for all bands[3].
3) The value of the characteristic pressure for water P'_w at the reference temperature.

[2]or the absolute value for a reference transition (e.g. 337 nm) and the relative intensities of the bands.
[3]or P'_i for both nitrogen and oxygen.

4) The T dependence of σ_{Ni} for all wavelengths, i.e. the α_λ values for each quencher.[4]

Neglecting the T dependence of σ_{Ni}, 1) and 2) provide enough information for dry air at any pressure and temperature conditions. Adding 3), the air-fluorescence yield can be evaluated for any atmospheric condition. Finally, 4) provides a more accurate extrapolation at temperatures far from the reference one (i.e. at high altitude).

III. FLUORESCENCE-YIELD DATA SETS

In the last years several measurements of the fluorescence yield have been carried out in laboratory experiments injecting accelerated electrons into air targets [1]. Nowadays three data sets combining some of these measurements are mainly being used in cosmic ray experiments using fluorescence telescopes. They are those of Nagano, Kakimoto-Bunner and Auger. In these data sets the humidity effect is neglected. On the other hand the T dependence is calculated assuming a constant collisional cross section. These effects can be implemented by using recent available data.

A. Nagano

Nagano et al. [2] provided fluorescence yields[5] of 15 nitrogen bands at 1013 hPa and 293 K as well as the corresponding P' values at the same temperature.

B. Kakimoto-Bunner

This set which has been used by the HiRes collaboration in 2001 [4], is obtained by a combination of the absolute fluorescence yield measurements[5] at 1000 hPa and 288 K of Kakimoto *et al.* [5] and the relative intensities reported by Bunner [6]. The total number of photons/m crossing the HiRes filter is compared with the absolute yields (also expressed in photons/m) of the three primary bands (337, 357 and 391 nm) to obtain the contribution of the remaining bands. Using the relative intensities and the wavelength-dependence absorption of the HiRes filter, the absolute yields for all the Bunner bands is obtained. The P' values of Kakimoto *et al.* at 288 K are used in this set. The result for the 337 nm band is applied to all the 2P bands and that of the 391 nm is used for the 1N system (only the 391 nm band in this set).

C. Auger

The data set presently used by the Auger collaboration consists of the absolute fluorescence yield reported by Nagano *et al.* for the 337 nm band at 800 hPa and 293 K, the relative intensities measured by AIRFLY at the same conditions and the set of P' values reported by this collaboration at 293 K [7].

[4]or an average value including all components.

[5]experimental results are expressed in photons/meter and the authors calculate the fluorescence efficiency assuming that the energy loss of electrons in their set-up is fully deposited inside the field of view of the optical system. This assumption has been questioned recently [3].

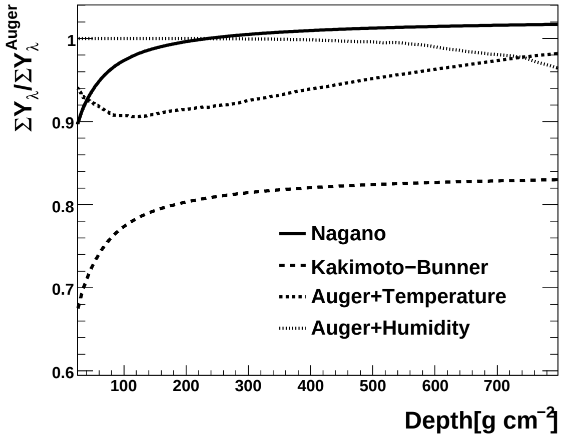

Fig. 1. Ratio of several fluorescence yield assumptions to the one presently used by the Auger collaboration versus atmospheric depth. The comparison is shown for the Nagano and KB data sets. Also the effect of humidity and that of a temperature dependence of the collisional cross section is presented.

D. Effect of water vapor and T dependence

Values of P'_w have been recently measured by AIRFLY as well as the T dependence of the collisional cross section for several bands (i.e. the α_λ values) [8]. The effect of both contributions on any data set can be easily computed using equations (1) and (2).

E. Comparison of data sets

The various data sets have been compared with the Auger one. In figure 1 the ratio of the total fluorescence yield for both Nagano and Kakimoto-Bunner (KB) divided by the one of Auger has been represented against vertical atmospheric depth. For these comparisons a typical atmospheric profile measured at the Auger site in April has been used [9]. The large discrepancy between Auger and KB is significantly reduced when the efficiency of the telescope filter is included (see next section for more details). The effect of humidity on the Auger data set has been also represented as well as the effect of a temperature dependence including the contribution of the collisional cross section. Notice the non-negligible effect of humidity at low altitude ($\approx$ 5%) and that of the T dependence at high altitude ($\approx$ 10%).

IV. METHOD

In this work we propose a simple procedure to evaluate the effect of the assumed fluorescence yield in the reconstruction of shower parameters. The longitudinal profile of the energy deposited per unit atmospheric depth $\mathrm{d}E/\mathrm{d}X$ is described by a Gaisser-Hillas GH function defined by a set of parameters, i.e. the depth of the first interaction, the hadronic interaction length, the depth at the shower maximum and the energy deposited at the shower maximum. Obviously, the total deposited energy E is given by the integral of $\mathrm{d}E/\mathrm{d}X$. Assuming a certain fluorescence yield $Y(X)$ which is a function of the atmospheric depth, the profile of fluorescence intensity is given by $Y(X)\,\mathrm{d}E/\mathrm{d}X$ in units of photons·g^{-1}cm^2. If the fluorescence yield assumption is changed to $Y'(X)$ the observed fluorescence profile would give rise to a reconstructed profile of deposited energy $\mathrm{d}E'/\mathrm{d}X = (Y(X)/Y'(X))\,\mathrm{d}E/\mathrm{d}X$. In practice the total fluorescence yield is modified by the effect of the optical elements of the telescope (mainly the filter) and the atmospheric transmission between the emission point and the telescope location which is also wavelength dependent. As a result, the real number of photons observed per unit deposited energy is $\sum_\lambda Y_\lambda(X)\varepsilon_\lambda T_\lambda(X)$ where ε_λ and $T_\lambda(X)$ are the efficiency of the optical system and the atmospheric transmission respectively. Taking into account all these ingredients, the energy reconstructed for a fluorescence yield assumption Y' is given by

$$E' = \int_0^\infty \frac{\mathrm{d}E}{\mathrm{d}X} \frac{\sum_\lambda Y_\lambda(X)\varepsilon_\lambda T_\lambda(X)}{\sum_\lambda Y'_\lambda(X)\varepsilon_\lambda T_\lambda(X)} \mathrm{d}X \qquad (3)$$

The effect on the shower maximum depth can be also easily studied by comparing the input $X_{\max}$ value and the resulting one from a fit of the $\mathrm{d}E'/\mathrm{d}desX$ profile to a GH function.

As an example in Figure 2 we apply this method to compare the results on the shower parameters when using either the Auger or the KB data. A typical GH profile for a proton shower of 10^{19} eV incoming with 30$^{\mathrm{o}}$ has been assumed. The ratio of fluorescence yields $\sum_\lambda Y_\lambda^{\mathrm{KB}}(X)/\sum_\lambda Y_\lambda^{\mathrm{Auger}}(X)$ is shown as a function of depth. The corresponding modified longitudinal profile, also shown in the figure, gives a total deposited energy higher by about a 20% (from equation (3) neglecting the effect of ε_λ and T_λ). However if the detector efficiency of the Auger telescopes is taken into account the effect is much smaller since the ratio $\sum_\lambda \varepsilon_\lambda{}^{\mathrm{Auger}} Y_\lambda^{\mathrm{KB}}(X)/\sum_\lambda \varepsilon_\lambda{}^{\mathrm{Auger}} Y_\lambda^{\mathrm{Auger}}(X)$ is close to unity[6] in the X interval where the energy deposition takes place. In this case $\delta = (E' - E)/E \approx$ +0.02 (2% difference). Also it can be easily checked that the comparison with the Nagano data set does not show a significant impact on the shower parameters.

V. RESULTS

The method described above has been used to predict the impact of various fluorescence yield assumptions on the reconstructed shower energy and the shower maximum depth. For the comparisons the Auger data set has been used as reference. Typical values of the GH parameters for proton and Fe showers of 10^{19} and 10^{20} eV have been used [11]. Obviously the result varies with the shower geometry since the fluorescence yield depends on the altitude (through pressure, temperature and humidity) while, for a given energy, the shower reaches its maximum at an altitude which grows with the zenith angle θ. Three arrival directions 0$^{\mathrm{o}}$, 30$^{\mathrm{o}}$ and 60$^{\mathrm{o}}$ have been studied. To model the atmosphere, different monthly average profiles measured at

[6]the effect of the atmospheric transmission does not introduce significant differences between fluorescence yield data sets in this case.

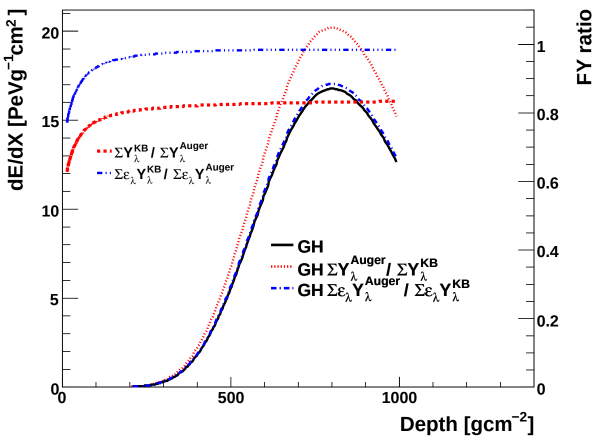

Fig. 2. Comparison of Auger and Kakimoto-Bunner fluorescence yield descriptions and their impact in the shower reconstruction. See text for details.

the Auger site have been used [9]. We have checked that the effect of the selected data set (Nagano, KB or Auger) discussed in the previous section is basically independent on the geometry and the primary energy. However the effect of humidity and temperature depends on the arrival direction since the atmospheric layers for which these effects are relevant correspond to different stages of the shower development, depending on θ. As an example, Figure 3 illustrates the case of an iron-induced shower of 10^{20} eV for two incoming zenith angles (0$^{\mathrm{o}}$ and 60$^{\mathrm{o}}$). The Auger data set has been modified by adding the effect of humidity. The ratio $\sum_\lambda \varepsilon_\lambda^{\mathrm{Auger}} Y_\lambda^{\mathrm{Auger+h}}(X)/\sum_\lambda \varepsilon_\lambda^{\mathrm{Auger}} Y_\lambda^{\mathrm{Auger}}(X)$ is represented against X in the figure[7]. The effect of water vapor is more significant at low altitudes. A vertical shower (upper panel) deposit most of its energy close to the ground and therefore the effect is much larger than for an inclined one (lower panel).

Next, a summary of the main results obtained applying this method is detailed.

A. *Primary energy*

Apart from the above discussed dependence on the specific data set, systematic uncertainties in the energy reconstruction due to the presence of water vapor or a T-dependent collisional cross-section have been also quantified. As already mentioned, these effects are geometry and seasonal dependent due to the different atmospheric conditions undergone by the shower track. Additionally, they are also sensitive to the nature of the primary (mass and energy) due to the different longitudinal developments induced in the atmosphere.

When the water vapor quenching is taken into account deviations, at the level of 3% ($\delta \approx +0.03$), are obtained when all primaries, geometries and seasonal periods are averaged. Nevertheless, maximum differences of around 8% can be found for periods with a high water

[7]the ε_λ parameter has been included to get a more accurate result although its effect in this ratio is not significant.

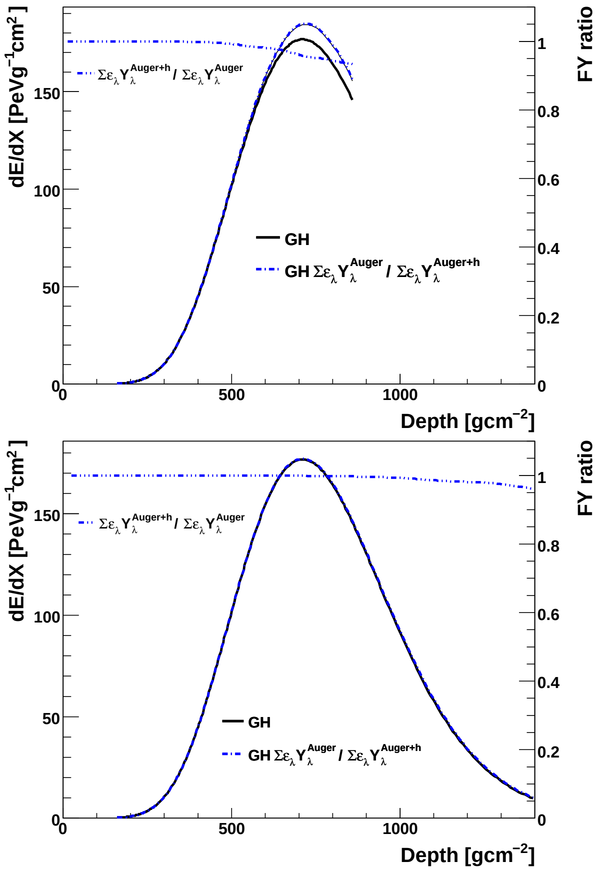

Fig. 3. Humidity effect in an iron shower of 10^{20} eV. The effect is much larger for a vertical shower (upper panel) than for a 60^{o} inclined one (lower panel). See text for more details.

vapor concentration (i.e. April month) and the maximum shower development is reached close to ground[8] On the other hand, a negligible effect due to water vapor is confirmed for inclined showers developing high in the atmosphere.

Average deviations $\delta \approx +0.04$ in the reconstructed energy are also found when the effect of a collisional cross-section dependent on temperature is considered. The difference is found to be also geometry, seasonal and primary dependent. In this case maximum variations of -6% appear for very inclined showers (60^{o}) developing upper in the atmosphere. A negligible effect is observed for showers reaching the maximum energy deposition close to ground.

Another interesting application is the evaluation of the impact of the uncertainty in the fluorescence yield parameters (e.g. P'_w or α values) on the uncertainty in the energy reconstruction. For instance, a 20% uncertainty in P'_w adds a contribution to the total uncertainty in the reconstructed energy smaller than 1%. On the other hand a 50% uncertainty in the α parameters induces an uncertainty in the primary energy rather small (less than 2%).

[8]either high energy, light primary, vertical incidence or a combination of them.

B. *Shower maximum depth*

Regarding the fluorescence yield data sets, the $X_{\max}$ parameter has been proved to be rather insensitive to the selected one with maximum deviations of around 2 g·cm^{-2}. Quenching effects due to water vapor or the additional temperature dependence introduce mean systematic deviations of -5 and +5 g·cm^{-2} respectively. Notice that these effects induce changes in opposite directions and thus the combination of both gives rise to small variations in the reconstructed $X_{\max}$. Again the effect is dependent on the shower development with maximum deviations of -10 g·cm^{-2} for humid seasons and showers with maximum development close to the ground level.

VI. CONCLUSIONS

A simple analytical method has been proposed to quantify the influence of the fluorescence yield on shower reconstruction and some preliminary results have been evidenced. Several data sets of fluorescence yield including absolute values, wavelength spectra, as well as pressure, temperature and humidity dependencies have been used for this study. We have confirmed that the Auger, Nagano and KB data sets lead to close E values (within around a 3%) as far as the optical efficiency of the telescope (wavelength dependent) is taken into account.

The dependence of the fluorescence yield with atmospheric properties (P, T and humidity) and its effect on shower reconstructed parameters have been also analyzed. These effects, when combined, introduce uncertainties at the level of 5% in the reconstructed shower energy. The deviations induced in the $X_{\max}$ parameter are nearly canceled when both T and humidity contributions are considered. On the other hand, even relatively large uncertainties in P'_w or α values have not a significant impact in the total uncertainty of the reconstructed energy.

Notice that the uncertainty in the absolute value of the fluorescence yield (around 13%) translates directly to E. This is the by far the largest uncertainty contribution of the fluorescence yield in the reconstructed energy.

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