The effect of uncertainties in air-fluorescence quenching on the reconstructed shower parameters of ultra-high energy cosmic rays

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DOI: 10.7529/ICRC2011/V02/0926

Abstract: The measurement of parameters associated to the air-fluorescence quenching of water and the temperature dependence of the collisional cross sections are subjected to large experimental errors. Using a simple analytical method, the effect of the uncertainties of these quenching parameters on the reconstructed profile of energy deposition in the atmosphere by ultra-high energy cosmic rays is studied.

Keywords: Air-fluorescence yield. Fluorescence Telescopes. Ultra-high energy cosmic rays

1 Introduction

The fluorescence technique has proved to be very useful for the determination of the features of ultra-high energy cosmic rays. Fluorescence telescopes measure the longitudinal development of the energy deposited in the atmosphere by the cosmic ray shower, via the air-fluorescence light emitted by the secondary charged particles. The fluorescence yield Y, defined as the number of air-fluorescence photons emitted per unit deposited energy, is a key parameter for a precise reconstruction of the shower development. The Y variable depends on atmospheric conditions (i.e. pressure P, temperature T and humidity) because the fluorescence emission is partly suppressed by the quenching of excited molecular nitrogen with all atmospheric species (i.e., N_2, O_2, H_2O). For a given molecular transition this dependence is given by the well-known expression

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

where Y_0 is the fluorescence yield in the absence of quenching and P' is the characteristic pressure including the effect of every quencher contributing with a fraction of molecules in air f_i.

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

The parameter k is the Boltzman constant, τ is the radiative lifetime of the corresponding excited molecular level, and v_{Ni} and μ_{Ni} are the relative velocity and reduced mass of the two body system N-i respectively. The T dependence of the fluorescence yield is given by equations 1 and 2 taking into account that the collisional cross section σ_{Ni} depends on the kinetic energy of the encounters following a power law ($\sim T^{\alpha}$). The dependence of the fluorescence yield on humidity and temperature is given by the characteristic pressure of water P'_w and the α parameter respectively. Both have to be determined for each molecular transition in dedicated laboratory experiments. Unfortunately these measurements are very difficult and therefore very scarce data are available and with large experimental uncertaintes.

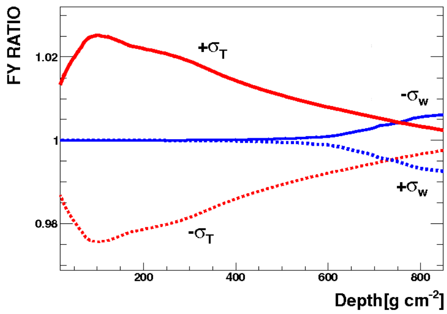
The goal of this work is to determine the impact of the uncertainties in P'_w and α on the reconstruction of the shower parameters. To this end, a simple procedure presented in [1] has been used. The shower development is described by a Gaisser-Hillas profile assuming a given set of fluorescence yield data. A shift in the α and P'_w parameters gives rise to a change in the fluorescence yield profile and therefore in a variation of the longitudinal development of the deposited energy leading to a deviation in the reconstructed values of both, the shower maximum depth $X_{\max}$ and the primary energy.

2 Method

Assuming a certain longitudinal profile of deposited energy $\mathrm{d}E/\mathrm{d}X$, the number of fluorescence photons generated per unit atmospheric depth X is determined by the fluorescence yield

$$\frac{\mathrm{d}n_\gamma^{\mathrm{gen}}}{dX} = \frac{\mathrm{d}E}{\mathrm{d}X}Y(X)\,. \qquad (3)$$

The total calorimetric energy E can be obtained from the integral of the longitudinal profile and therefore



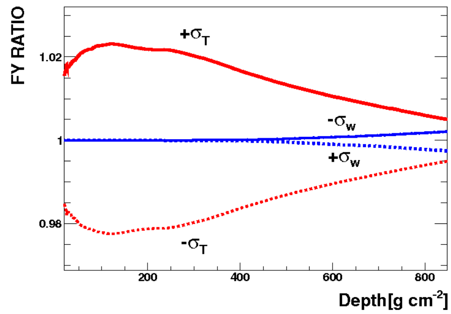


Figure 1: Ratio Y'/Y of the modified fluorescence yield divided by the reference one as a function of atmospheric depth for February (left) and August (right). Modified yields have been obtained by shifting P'_w in $\pm\sigma_w$ and α in $\pm\sigma_T$ separately.

$$E = \int_0^\infty \frac{1}{Y(X)} \frac{\mathrm{d}n_\gamma^{\mathrm{gen}}}{\mathrm{d}X} \mathrm{d}X \,. \quad (4)$$

For a different fluorescence yield assumption $Y'(X)$, the profile of deposited energy consistent with the measured profile of fluorescence light is

$$\frac{\mathrm{d}E'}{\mathrm{d}X} = \frac{\mathrm{d}E}{\mathrm{d}X} \frac{Y(X)}{Y'(X)} \,, \quad (5)$$

and thus, the new calorimetric energy is

$$E' = \int_0^\infty \frac{\mathrm{d}E}{\mathrm{d}X} \frac{Y(X)}{Y'(X)} \mathrm{d}X \,. \quad (6)$$

The effect of changing the fluorescence yield selection on the calorimetric energy can be evaluated by comparing (4) and (6) while the effect on the X_{max} value can be obtained by comparing the shape of the $\mathrm{d}E/\mathrm{d}X$ and $\mathrm{d}E'/\mathrm{d}X$ profiles. The $Y(X)$ value depends on wavelength and therefore the above expressions have to be integrated in the wavelength interval of the telescope.

In practice, the atmosphere scatters a non-negligible fraction of photons in their way to the telescope. Also the optical elements of the detector absorb a certain fraction of those photons reaching the telescope window. Both atmospheric transmission and optical efficiency are wavelength dependent and therefore, in general, a correction has to be applied to expression (5) to account for these effects (see [1] for details). For the present application these corrections have found to be negligible.

The longitudinal development of deposited energy will be described by a Gaisser-Hillas (GH) profile,

$$\frac{\mathrm{d}E}{\mathrm{d}X} = \left(\frac{\mathrm{d}E}{\mathrm{d}X}\right)_{X_{\mathrm{max}}} \left(\frac{X - X_0}{X_{\mathrm{max}} - X_0}\right)^{(X_{\mathrm{max}}-X_0)/\lambda} e^{\frac{X-X_0}{\lambda}} \quad (7)$$

where X_0 and λ are shape parameters and X_{max} is the shower maximum depth. In this work, proton and iron showers of 30$^{\mathrm{o}}$ and 60$^{\mathrm{o}}$ with energies of 10^{19} and 10^{20} eV have been used. The choice of the corresponding G-H parameters has been described in [1].

3 Air-fluorescence yield data

The air-fluorescence data used in this work consists of the absolute value for the 337 nm band of Nagano *et al.* Y_{337} = 6.38 ph/MeV at 800 hPa and 293 K [2], relative intensities and the corresponding $P'(\lambda)$ values in dry air at the same pressure and temperature for 34 wavelengths [3]. The effect of humidity and the temperaure dependence of the collisional cross section has been included using the P'_w and α values reported by AIRFLY for 14 wavelengths [4]. As already mentioned, the measurement of these parameters is very difficult and apart from those of AIRFLY, just a few results with larger uncertainties are available in the literature (see [5] for a review). In order to study the effect of the uncertainties in P'_w and α in the shower reconstruction we have calculated the shower profile of deposited energy after shifting P'_w and α in $\pm n\sigma_w$ and/or $\pm n\sigma_T$ respectively for n = 1, 2. Values of $\sigma_w = 0.10 \times P'_w$ and $\sigma_T = 0.25 \times \alpha$ have been used for all wavelengths. These shifts represent an estimate of the average experimental errors reported in [4] weighted with the relative intensity of the corresponding transitions.

The effect of these shifts in P'_w and α on the fluorescence yield profile, integrated in the wavelength interval 296 - 428 nm, has been evaluated using the monthly average description of the atmosphere measured at the Auger site [6]. In figure 1 the ratio of the fluorescence yield Y' modified by shifting the P'_w and α values in $\pm\sigma_w$ and $\pm\sigma_T$ respectively, divided by the reference fluorescence yield Y has been represented as a function of the atmospheric depth for a humid (February) and a dry (August) month. As displayed in this figure, the shift in the α parameter gives rise to a deviation in the fluorescence yield of about 2% at high altitudes while the variation in the water quenching has a small efect of about 1% near the ground. This behaviour was expected since humidity is only relevant near the ground while temperature corrections are only expected at high altitudes.

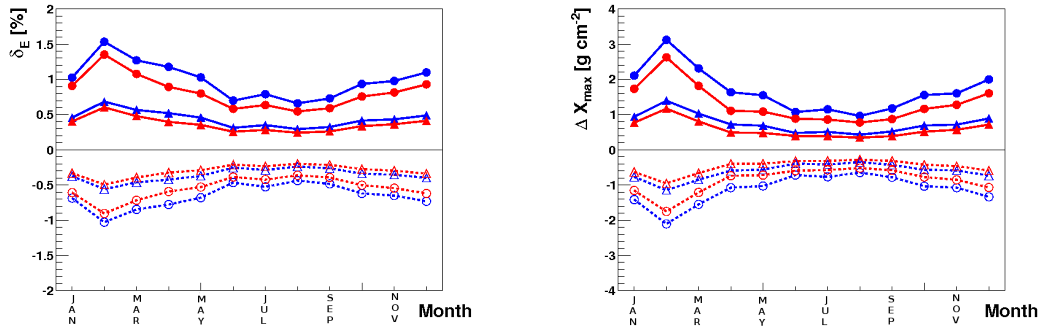


Figure 2: Effect on energy and shower maximum depth of a shift of $\pm\sigma_w$ (triangles on continuous lines) and $\pm\, 2\sigma_w$ (circles on dashed lines) in the P'_w parameter for proton (blue) and Fe (red) showers of $30°$ and 10^{19} eV. Filled (open) symbols correspond to positive (negative) P'_w shifts

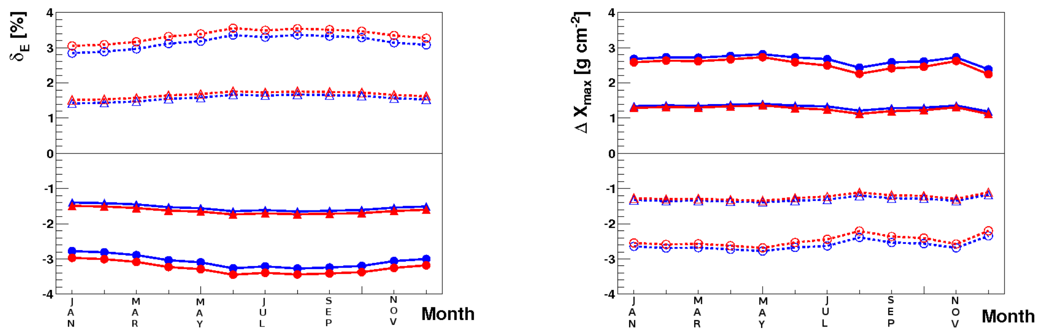


Figure 3: Same as figure 2 for $\pm\sigma_T$ and $\pm\, 2\sigma_T$ shifts in the α parameter for $60°$ showers of 10^{19} eV.

4 Results

Following the procedure described above, the average GH profile of the energy deposited in the atmosphere has been generated for each primary type, incident angle and energy. Then, shifts in the P'_w and/or α quenching parameters have been applied and the modified shower profiles have been analysed. As a result, we have calculated the corresponding deviations in shower maximum depth, i.e., $\Delta X_{\max} = X^{\mathrm{m}}_{\max} - X_{\max}$ and the relative variations in the calorimetric energy, i.e., $\delta E = (E^{\mathrm{m}} - E)/E$, where the superscript m refers to the modified profiles. In order to better evaluate the different contributions of the uncertainties in temperature and humidity parameters, their effects have been first evaluated separately (Figs. 2 and 3) and later the combined effect will be also discussed (Figs. 4 and 5).

For vertical ($30°$) 10^{19} eV showers, a 20% uncertainty in P'_w (i.e., $2\sigma_w$) would give rise to an uncertainty in between 0.7% and 1.5% in energy and in between 1 and 2.5 gcm^{-2} in $X_{\max}$ depending on humidity (see Fig. 2). On the other hand, the impact on inclined showers ($60°$) has found to be negligible, as expected, since a significant fraction of the energy is deposited well above ground and therefore weakly subjected to humidity effects. Inclined showers are more sensitive to temperature effects. At $60°$ a 50% uncertainty in α (i.e., $2\sigma_T$) translates into uncertainties of about 3% in E and 3 gcm^{-2} in $X_{\max}$ nearly independent on season (see Fig. 3).

The combined effect of uncertainties in both parameters has been studied. The results for energy reconstruction and shower maximum depth are shown in Figs. 4 and 5 respectively. The effect of a positive (negative) shift in P'_w is an increase (decrease) in the fluorescence yield while a positive (negative) shift in α decreases (increases) the yield. Therefore, when both parameters are shifted in the same (opposite) direction the total effect on the fluorescence yield partly cancels (maximizes). This feature is clearly seen in Fig. 4, in particular for vertical showers, which are more sensitive to humidity effects. For inclined showers the temperature effects dominate and therefore both combinations give a similar result nearly independent on season. The total effect of σ_w and σ_T uncertainties in P_w and α respectively translates into an uncertainty in the calorimetric energy in between 1% and 0.5% for vertical showers and $\approx$ 1.5% for inclined showers. In regard with the shower maximum depth (Fig. 5), shifts in the same direction ($\pm\sigma_w \pm \sigma_T$) add up their contributions while those in opposite direction ($\pm\sigma_w \mp \sigma_T$) partially cancel for vertical showers, leading to a combined effect ranging from 1 to 2 gcm^{-2}. Again, for inclined showers temperature effects are dominant and the combined result is of about 1 gcm^{-2} independent of season.

For a given energy, lighter primaries develop deeper in the atmosphere and thus proton showers are more sensitive to

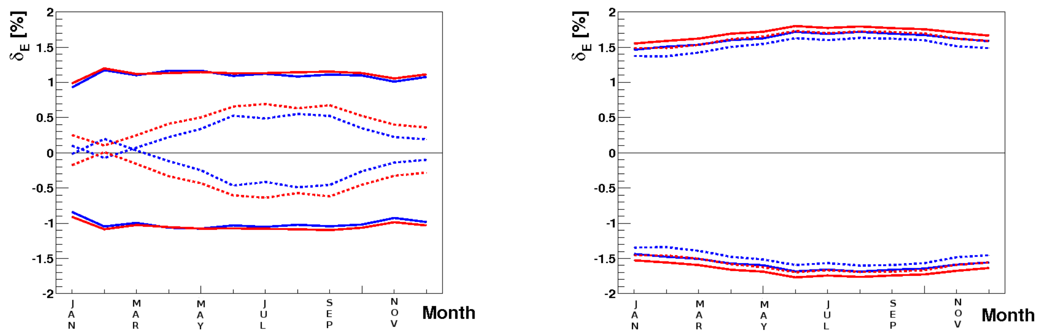


Figure 4: Combined effect of uncertainties in P'_w and α parameters on energy reconstruction for proton (blue) and Fe (red) showers of 10^{19} eV with zenith angle of 30° (left) and and 60° (right). Dashed lines connect results for combined effects when shifts are applied in the same direction ($\pm\sigma_w \pm \sigma_T$) while continuous lines represent opposite shifts ($\pm\sigma_w \mp \sigma_T$).

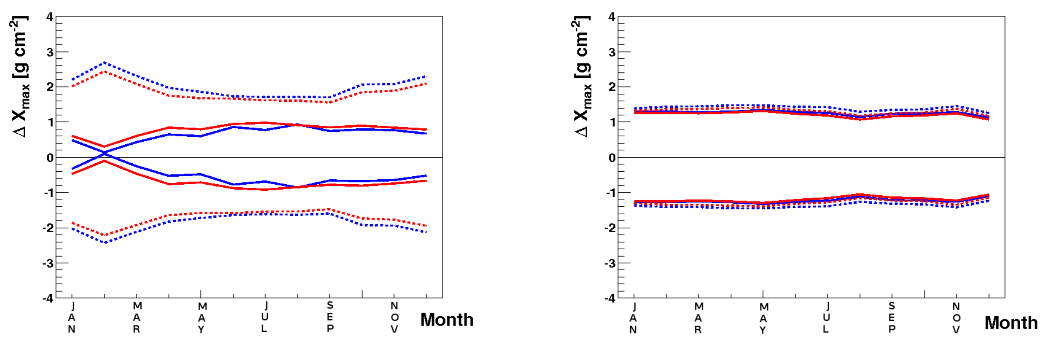


Figure 5: Same as figure 4 for the shower maximum depth

humidity effects than iron showers while the latter are more sensitive to temperature. These features can be observed in Figs. 2-5, in particular for vertical showers, although the mass dependence of δE and $\Delta X_{\max}$ is not relevant. Also, we have found that the above results can be applied to 10^{20} eV showers.

5 Conclusions

Present measurements of the quenching parameters related to humidity and the temperature dependence of the total collisional cross section are subjected to large experimental errors. In this work, the impact of these errors on the uncertainty in the reconstructed values of the shower energy and maximum depth has been studied. Uncertainties in $X_{\max}$ at the level of 1.5 gcm^{-2} have been found. The effect on calorimetric energy ranges from about 1% (30°) to 1.5% (60°). The effect on primary energy is expected to be even smaller since the invisible energy, which contributes to about 10% of the total energy is not affected by fluorescence yield variations. In addition, the information of Cherenkov light, which is a very important ingredient in the reconstruction algorithms [7], is not used in this simple procedure. As a consequence, our predictions on the effect of a variation of the fluorescence yield on shower energy are expected to be somewhat overestimated. Therefore, assuming the experimental errors reported in [4], a total uncertainty in primary energy of below 1% is expected. This contribution is smaller than the one from other atmospheric effects [8]. Other measurements of P'_w and α deviates significantly to those used here (see [1] for a review). However, even a large deviation has not a significant impact on shower reconstruction. For instance, a variation by a factor 2 in the P'_w values would lead to a deviation of about 2% in the primary energy.

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