The ionization energy deposit in the atmosphere and the fluorescence light generation at shower axis

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Abstract. **Since the first measurements of the fluorescence emission in gases, induced by fast ionizing particles, a new branch for investigation opened up and detections of cosmic radiation through fluorescence light are today frequent for primaries exceeding 0.1 EeV. The particles deposit part or all their energy by ionization of air molecules and produce fluorescence radiation leaving a track of fluorescent light as the shower develops. This light can be observed by telescopes designed specifically to capture near-ultraviolet low-intensity photons during clean and moonless night skies.**

A detailed study on the energy deposit of electromagnetic particles in several atmospheric layers is addressed. We take into account parameterizations for density, temperature and composition of each layer and test different formulations for the energy deposit. We use then different measurements for fluorescence yield to evaluate their influence on the total number of photons in the shower axis as a function of the slant depth.

Keywords**: Extensive Air Showers, Fluorescence and Simulation**

I. INTRODUCTION

Studies on the production of photons in the atmosphere by ionization processes caused by charged particles from EAS are strongly dependent on parameterized forms of the Fluorescence Yield (FlY), Kakimoto *et al* and Nagano *et al* [1], [2] are some of the most used. The energy deposit (dE/dx) is calculated using Bethe-Bloch formula [3], [4] and further corrections due to the polarization effects of the medium density (parameter δ).

This work presents an analysis on the dependence of the number of the photons produced at the EAS axis calculated for some forms of dE/dx and FlY. The showers were simulated with the CORSIKA[5] program version 6617 using the hadronic model Sibyll 2.1 [6]. The chemical composition of the primaries were chosen to be proton and the energies fixed in 10^{17}, $10^{17.5}$, 10^{18}, $10^{18.5}$, 10^{19}, $10^{19.5}$, 10^{20} and $10^{20.5}$ eV, where 1000 events were simulated for each energy. The thinning factor used was of 10^{-5} and the zenith angles were sorted between 25^o and 35^o.

The calculation of the number of photons emitted per charged particled at the shower axis along the longitudinal development can be expressed as the dependence of the fluorescence yield, thus:

$$N_\gamma(h) = FlY(\lambda, p, T)\Delta x \quad (1)$$

Kakimoto *et al.* do a parameterization of the fluorescence emission as a function of the energy and altitude to the total emission of photons in the range of $300\,nm$ and $430nm$. Nagano *et al.* use the equation of Kakimoto *et al.* with another energy normalization. The first term accounts for the main emission peak and the second term for the other emissions. Thus this equation for the total emission of fluorescence can be expressed by:

$$FlY = \frac{\left(\frac{dE}{dx}\right)}{\left(\frac{dE}{dx}\right)_{E_o}} \rho \left\{ \frac{A_1}{1+\rho B_1\sqrt{T}} + \frac{A_2}{1+\rho B_2\sqrt{T}} \right\} \quad (2)$$

where $(dE/dx)_{E_o}$ is the energy loss normalized to E_o — in Ref.[1], $E_0 = 1.4\,MeV$, while in Ref. [2], $E_0 = 0.85\,MeV$ — ρ is the medium density in kg/m^3, T is the medium temperature in Kelvins and the constants A_1, A_2, B_1 and B_2 are derived from the experiments and are given in Table I.

	$A_1\ [m^2kg^{-1}]$	$A_2\ [m^2kg^{-1}]$
Ref.[1]	89.0 ± 1.7	55.0 ± 2.2
Ref.[2]	147.4 ± 4.3	69.8 ± 12.2
	$B_1\ [m^3kg^{-1}K^{1/2}]$	$B_2\ [m^3kg^{-1}K^{1/2}]$
Ref.[1]	1.85 ± 0.04	6.50 ± 0.33
Ref.[2]	2.40 ± 0.18	20.10 ± 6.90

TABLE I
CONSTANTS USED IN EQUATION 2.

In the ionization, the energy loss per unit path is described, in general, by the Bethe-Bloch formula [3], [4], which is discribed in the book by W.R.Leo [7] as:

$$-\frac{dE}{dx} = \frac{k\rho Z}{\beta^2 A}\left[\ln\frac{\tau^2(\tau+2)}{2(I/(m_ec^2))^2} + F(\tau) - \delta - \frac{2C}{Z}\right] \quad (3)$$

where $k = 0.1535 MeV/(g/cm^2)$, ρ is the density, Z the atomic number, A the number of mass of the absorber medium, τ the kinetic energy of incident particle in units of m_ec^2 ($F(\tau)$ is a function whose form depends whether the particle is a electron or positron), $\beta = v/c$ of incident particle, I is the mean excitation potential, δ is the density correction — This is derived from the fact that the electric field of the particles tend to polarize the atoms on his way. Because of this polarization, electrons away from the path of the particle will be shielded and contribute less to the energy loss, and its contribution will be reduced — and C/Z is the shell correction important only for low speeds.

In the book by M.S. Longair [8] the Bethe-Bloch formula is written as:

$$-\frac{dE}{dx} = \frac{e^4 \rho Z}{8\pi\epsilon_o^2 v^2}\left[\ln\frac{\gamma^2 m_e v^2 E_c^{max}}{2I^2} + G(\gamma)\right] \quad (4)$$

where $G(\gamma) = \frac{1}{\gamma^2} + \frac{1}{8}\left(1 - \frac{1}{\gamma}\right)^2 - \left(\frac{2}{\gamma} + \frac{1}{\gamma^2}\right)\ln 2$,

$E_c^{max} = \left(\frac{\gamma^2 m_e v^2}{1+\gamma}\right)$ is the maximum kinetic energy acquired in a given collision, γ is the Lorentz factor, v is the incident particle speed, e is the electron charge, and ϵ_o is the permittivity of the medium. Notice that in this form there is no correction factor δ.

The program CORSIKA, according to the CORSIKA School [9], has the following form for the Bethe-Bloch:

$$-\frac{dE}{dx} = \frac{kZ}{\beta^2 A}\left[\left(\ln\frac{2\beta^2\gamma^2 E_c^{max}}{(I^2/(m_e c^2))}\right) - 2\beta^2 - \delta\right] \quad (5)$$

II. Results

A. Energy loss

In Fig.1 we compare the different dE/dx formulas, as described above. We included a comparison of CORSIKA formula with and without the factor δ, such that we can clearly see its influence at high energies. The results for dE/dx were obtained at sea level ($P = 760\,mmHg$, $T = 288\,K$ and $\rho = 1.2\,kg/m^3$).

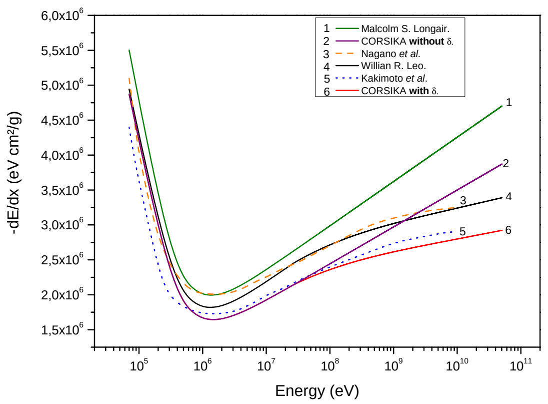

Fig. 1. dE/dx for different formulations.

B. Fluorescence yield

The influence of these corrections in FlY was higher than expected, as we can see in Fig.2. The results are discrepant within a factor of 2.9 near the altitude of $15\,km$.

C. Number of photons at shower axis

In the figure 3, we show the average number of photons for 1000 showers using every combination for dE/dx and FlY. The showers were simulted with zenith angles between 25° and 35° and the longitudinal profile was divided in steps of $5\,g/cm^2$ in atmospheric depth.

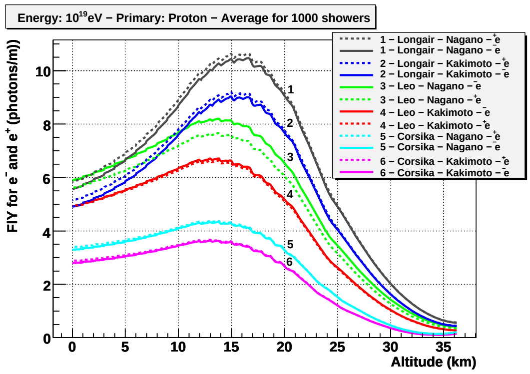

Fig. 2. The continuous lines were obtained using the labeled formulations for electrons, while the dashed lines were obtained for positrons.

The lines widths are related to the standard deviation of the average in each step of atmospheric depth. Their values are between 5% and 7%. The factor of discrepancy is about 2.2 among the different combinations at the shower maximum depth.

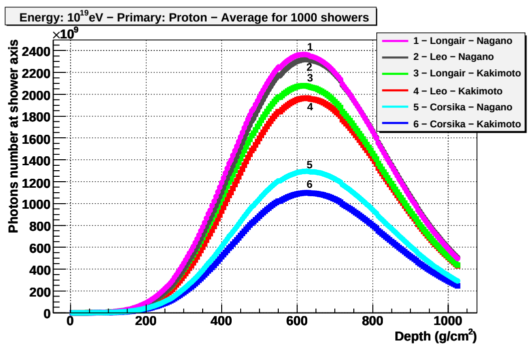

Fig. 3. Number of photons at shower axis calculated by different combinations of dE/dx and FlY.

III. Conclusions

i) The inclusion of the density correction (δ) in the formulas for dE/dx is significantly important for energies above $100\,MeV$;

ii) The influence of this term in the FlY is striking. The combination given by equation with parameterization by Kakimoto *et al.* [1] is the closest to the expected results in the literature [10];

iii) Therefore, the number of photons at the shower axis has changed, what has a very important influence in the reconstruction chain for extensive air showers experiments.

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