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 photons produced at the EAS axis calculated for some forms of dE/dx and FLY. The showers were simulated with the CORSIKA[7] program version 6617 using the hadronic model Sibyll 2.1 [8]. 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 0° and 60°.

The calculation of the number of photons at the shower axis along the longitudinal development, can be expressed as the dependence of energy loss in the atmosphere and the fluorescence yield. Thus:

\[ N_\gamma(h) = FLY(\lambda, p, T)\Delta X \]  

(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 430 nm. 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 others emissions. Thus this equation for the total emission of fluorescence can be expressed by:

\[ FLY = \frac{(dE/dx)_{E_0}}{(dE/dx)_{E_0}} \rho \left\{ \frac{A_1}{1 + \rho B_1\sqrt{T}} + \frac{A_2}{1 + \rho B_2\sqrt{T}} \right\} \]  

(2)

where \((dE/dx)_{E_0}\) is the energy loss normalized to \(E_0\) — in ref.[1], \(E_0 = 1.4 MeV\), while in ref. [2], \(E_0 = 0.85 MeV\) — \(\rho\) is the medium density in \(kg/m^3\), \(T\) is the medium temperature in Kelvin and the constants \(A_1\) and \(A_2\) in \([m^2 kg^{-1}]\), and \(B_1\) and \(B_2\) in \([m^3 kg^{-1} K^{1/2}]\) are derived from the experiments. See the values in table I.

<table>
<thead>
<tr>
<th>Reference</th>
<th>(A_1)</th>
<th>(A_2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ref. [1]</td>
<td>89.0 ± 1.7</td>
<td>55.0 ± 2.2</td>
</tr>
<tr>
<td>ref. [2]</td>
<td>144.4 ± 4.3</td>
<td>69.5 ± 12.2</td>
</tr>
<tr>
<td>ref. [1]</td>
<td>1.85 ± 0.04</td>
<td>6.40 ± 0.03</td>
</tr>
<tr>
<td>ref. [2]</td>
<td>2.40 ± 0.18</td>
<td>20.10 ± 0.90</td>
</tr>
</tbody>
</table>

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]. In 1994, W.R.Leo [6], described it:

\[ \frac{dE}{dx} = \frac{A\rho Z}{2}\tau^2 A \left[ \ln \left( \frac{\tau^2 (\tau + 2)}{2I_{mc}^2} + F(\gamma) - \delta - 2C \right) \right] \]  

(3)

where \(B = 0.1535 MeV/(g/cm^2)\), \(\rho\) is the density, \(Z\) the atomic number, \(A\) the number of mass of the absorber medium, \(\tau\) the kinetic energy of incident particle in units of \(mc^2\) \((F(\gamma)\) is a function whose form depends whether particle is a electron or positron, \(\beta = v/c\) of incident particle, \(I\) is the mean excitation potential, \(\delta\) 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 deducted) and $C/Z$ is a fixed for high speeds.

In 2004, M. S. Longair [5] proposed a modification of the Bethe-Bloch writing it as:

$$\frac{dE}{dx} = e^2 \rho \mu \left[ \ln \frac{\mu^2 m_e^2 E_{\text{max}}}{2 I^2} - \left( \frac{2}{\gamma} - \frac{1}{\gamma^2} \right) \ln 2 + \frac{1}{\gamma^2} + \frac{1}{8} \left( 1 - \frac{1}{\gamma} \right)^2 \right]$$

where $E_{\text{max}} = \left( \frac{\mu^2 m_e^2}{\kappa^2} \right)$ is the maximum kinetic energy, $\gamma$ is the Lorentz factor, $e$ is the charge of electron and $\varepsilon_0$ is the permittivity of the medium in which the particle spreads. It is interesting to note that this form is the permittivity of the medium in which the particle spreads.

The program CORSIKA, according to the CORSIKA-SCHOOL (2009) [9], has the following form for the Bethe-Bloch:

$$\frac{dE}{dx} = 2 \cdot 1.535 \text{ MeV/(g/cm}^2) \frac{Z}{A} \frac{1}{\beta^2} \times \left[ \frac{1}{2} \left( \ln 2m_e^2 \beta^2 \gamma^2 E_{\text{max}}^2 \right) - \beta^2 - \frac{\delta}{2} \right]$$

II. RESULTS - DE/DX

On figure 1 there is a comparation between the different DE/DX described above, including a comparison between DE/DX obtained by CORSIKA with and without the factor $\delta$.

The results for DE/DX was obtained at sea level (760 mmHg), 288° Kelvin and $\rho = 1.2 \text{kg/m}^3$.

III. RESULTS - FLUORESCENCE YIELD

The influence of this correction in FIY was higher than expected producing the continuous lines on the figure 2.

IV. RESULTS - NO. PHOTONS

Here we show the number of photons for the mean of 1000 primaries of proton with angles between 25 and 35 degrees, where we calculated it using DE/DX by Leo, Longair and Corsika and FIY by Kakimoto et al. and Nagano et al.

![Fig. 2. The continuous lines was obtained using the equation 2 with the two terms and the dashed line was obtained using just the first term.](image)

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![Fig. 3. Photons number calculated by different FIY.](image)

Fig. 3. Photons number calculated by different FIY.

On the figure 3, the mean was calculated for the number of photons produced by 1000 showers on each step of $5g/cm^2$ in atmospheric depth. The width of the line is related with the sigma of the mean in each step of the atmospheric depth. The values of the sigma are between 5% and 7%.

V. CONCLUSIONS

i) The inclusion of the correction in density ($\delta$) in the forms of DE/DX is significantly important for energies above $10^8$ eV.

ii) The number of photons has been therefore changed.

iii) The dependency of the FIY with the wave-length, $\lambda$, need to be calculated.

VI. ACKNOWLEDGMENTS

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REFERENCES