Average value of available measurements of the air-fluorescence yield

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DOI: 10.7529/ICRC2011/V02/0442

Abstract: The air-fluorescence yield is a key parameter for determining the energy scale of ultra-high-energy cosmic rays detected by fluorescence telescopes. For comparison purposes, available measurements of the absolute air-fluorescence yield have been normalized to common units and same experimental conditions. Corrections in the evaluation of energy deposition are proposed for some experiments. A simple statistical analysis shows that these corrections favor the compatibility among the various experiments. As a result, an average value of 5.45 ph/MeV for the fluorescence yield of the 337 nm band (20.1 ph/MeV for the spectral interval 300 - 420 nm) at 1013 hPa and 293 K with an uncertainty of around 5% is found. This result is fully compatible with that recently presented by the AIRFLY collaboration (still preliminary) in such a way that including this latest result could even lowered the final uncertainty below the 5% level with high reliability.

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

1 Introduction

The air-fluorescence yield Y, defined as the number of photons per unit of energy deposited by the shower in the atmosphere, is a fundamental calibration parameter which determines the energy scale of fluorescence telescopes. The absolute value of the fluorescence yield is measured in dedicated experiments where a beam of charged particles (usually electrons) hit an air volume inside a collision chamber generating fluorescence radiation that is measured with an appropriate optical system.

A number of absolute measurements of the fluorescence yield have been published in the last years [1, 2, 3, 4, 5, 6, 7]. Unfortunately, direct comparison of these absolute values is not possible because some authors measure single intense fluorescence bands while others detect the integrated fluorescence in a wide spectral range. In addition, some measurements [1, 2, 3] (type A) are given in units of ph/m, and converted by the authors into ph/MeV neglecting the energy deposited by secondary electron outside the field of view of the optical system. Recent experiments [4, 5, 6, 7] (type B) have performed detailed simulations to calculate the energy deposition as well as the geometrical factors using well-known MC codes, e.g., GEANT4 and EGS4. In [8, 9], these absolute measurements were normalized to their corresponding Y_{337} values (i.e., the air-fluorescence yield for the 337 nm band measured in units of ph/MeV) at given pressure and temperature in such a way that a simple statistical analysis allowed us to obtain an average value. In these works, a dedicated simulation algorithm [10] was used to determine the energy deposition and geometrical factors of the experiments. These simulations showed that, in experiments of type A significant corrections in the determination of the energy deposited in the experimental observation volume are needed, whereas a good agreement (at the level of 2%) is found between our calculations and those carried out by type B experiments.

In next section we will discuss some features of the simulation algorithm which has leaded us to propose corrections to some fluorescence-yield values. Finally, a comparison between these normalized Y_{337} results following a procedure similar to that presented in [8, 9] will be carried out, although here no correction will be applied to type B experiments.

2 The simulation algorithm

Unlike other MC codes like GEANT or EGS, our simulation algorithm [10] has been developed to treat individual interactions of both primary and secondary electrons with the molecules of the medium. All processes giving rise to energy deposition are included. Molecular excitation for the emission of 2P and 1N photons are treated separately in such a way that fluorescence emission can be also calculated and therefore a theoretical fluorescence yield can be obtained too.

By means of this algorithm we have performed two kind of simulations, i.e., generic simulations where primary electrons are forced to interact in the center of a sphere of radius R filled with air at given pressure, and detailed simulations

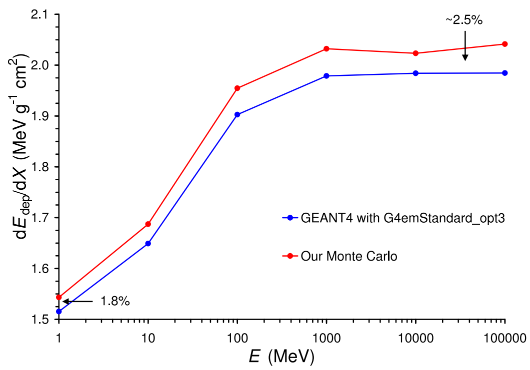

Figure 1: Comparison of simulation results between our algorithm and GEANT4 on electron energy deposition for a cube 10 cm side.

including the geometry as well as other experimental features (see [8]).

We have started some tests to compare in detail the predictions on energy deposition of our algorithm with those of GEANT4. Next, some preliminary results will be shown. For this comparison, the G4emStandard_opt3 library of GEANT4 including multiple scattering, ionization, bremsstrahlung and emission of both X rays and Auger electrons was used. The energy threshold for production of secondary electrons was 1 keV. The medium was a cube of 10 cm side filled with air at 1013 hPa and 273 K (1.29 mg/cm^3). Electrons with energies ranging from 1 MeV to 100 GeV impinged the cube along an axis going through the center of opposite faces. The energy deposited per unit mass thickness $(\mathrm{d}E/\mathrm{d}X)_{\mathrm{dep}}$ was calculated as the ratio of the integral deposited energy divided by the average track length of electrons, which is somewhat larger than the cube side (by 1% - 5% at 1 MeV). As shown in figure 1, a good agreement is found in this parameter with discrepancies of about 2%. However, the deviation in the integral deposited energy is larger (about 5% at 1 MeV). We have found that this disagreement is due to the fact that our simulation predicts somewhat larger deflections in the beam particles compared to GEANT4, leading to slightly longer electron tracks within the cube. The same comparison has been carried out for a sphere of 10 cm diameter. While a similar agreement ($\sim$ 2%) is found for $(\mathrm{d}E/\mathrm{d}X)_{\mathrm{dep}}$, deviations in the integral energy deposition at 1 MeV turn out to be below 1%. For this geometry the effect of larger deflections is a shorter average track length. We are presently studying the effect of the different treatment of electron scattering in these simulations. Note that in our algorithm, both inelastic and elastic collisions are treated individually instead of using the multiple scattering approximation.

Other tests carried out using G4emStandard (without X-rays and Auger electrons generation), G4emPenelope and G4emLivermore have given similar results for these pressure and geometries. Further comparisons for different pressures and volume sizes are in progress.

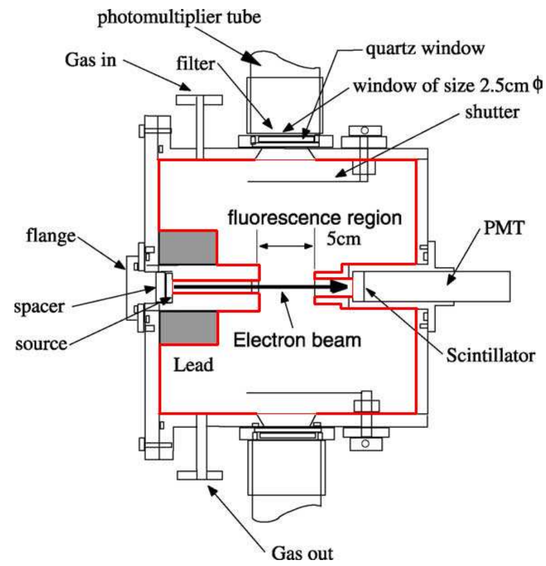

Figure 2: Schematic drawing of the experiment of Nagano *et al.* [2]. The red contour represents the geometry implemented in our simulation.

3 Simulation of fluorescence yield experiments

We have performed a simulation of those type A experiments compared in this work. As an example, we will give a brief description of the detailed simulation we carried out [8] for the experiment of Nagano *et al.* [2]. For this experiment we have included the geometry of the collision chamber (see figure 2) as well as other experimental features and corrections which have been applied to account for several approximations assumed by the authors.

The approximations made by Nagano *et al.* are the following. Firstly, they assumed that all the fluorescence is emitted from the beam itself, while a fraction of the light is produced by high-energy secondaries well outside the beam region. Secondly, they calculated the number of photons per meter assuming they are emitted in a length equal to the gap distance $\Delta x_{\mathrm{gap}} = 5$ cm, and thus, neglecting the dispersion of beam electrons. Finally, for the calculation of the fluorescence yield, they assumed that the energy deposited in the observation volume equals the collisional energy loss $(\mathrm{d}E/\mathrm{d}x)_{\mathrm{loss}}$ at 0.85 MeV as given by the Bethe-Bloch formula. Therefore, the fluorescence yield value Y_{Nag} reported by Nagano *et al.*, should be corrected by three factors accounting for the above mentioned approximations:

$$Y = Y_{\mathrm{Nag}} \frac{\Omega_{\mathrm{beam}}}{\Omega} \frac{\Delta x_{\mathrm{gap}}}{\Delta x} \frac{(\mathrm{d}E/\mathrm{d}x)_{\mathrm{loss}}}{\langle \mathrm{d}E/\mathrm{d}x \rangle_{\mathrm{dep}}} . \quad (1)$$

From our simulation we have found that the acceptance correction, i.e., the $\Omega/\Omega_{\mathrm{beam}}$ factor, increases the fluorescence yield in about 1%. However, this effect is nearly compensated by that of the gap length (same size but op-

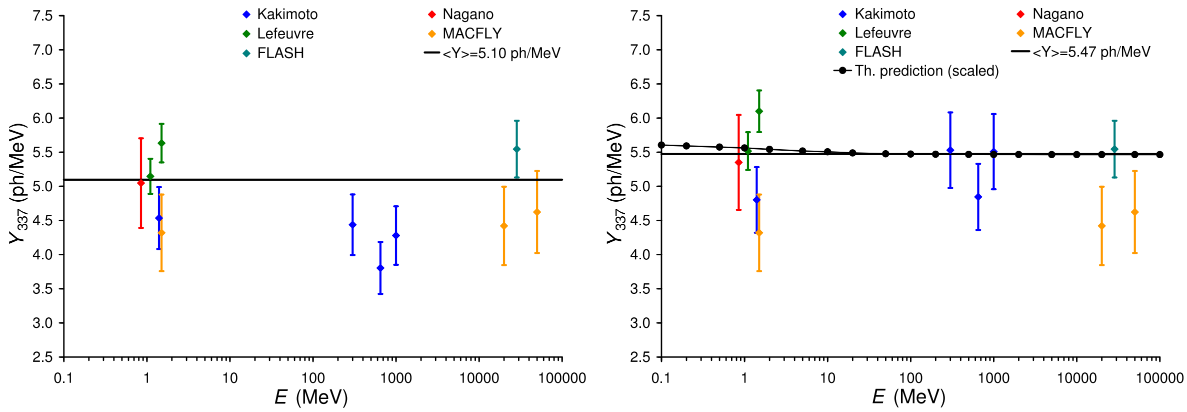

Figure 3: Comparison of normalized Y_{337} values as a function of energy for both uncorrected (left) and corrected (right) values. The horizontal lines represent the corresponding weighted average values. The black circles connected by lines represent the weak energy dependence predicted by our simulation [10].

posite direction). From our simulation, we have obtained that the average energy deposited per electron and unit path length $\langle \mathrm{d}E/\mathrm{d}x \rangle_{\mathrm{dep}}$ is somewhat smaller than $(\mathrm{d}E/\mathrm{d}x)_{\mathrm{loss}}$. As a result, according to our calculations, the fluorescence yield of Nagano *et al.* should be increased by 6%.

The result of the deposited energy from our detailed simulation of the experiment of Nagano *et al.* is fully compatible with the predictions from the generic simulation for a simple geometry, assuming that the observation region can be described by a sphere of radius $R = 5$ cm (see [8]). Thus, for the experiments of Kakimoto *et al.* [1] and Lefeuvre *et al.* [3] we have compared the predictions from our generic simulation with the assumptions of these authors. As a result, the fluorescence yield of the experiment of Kakimoto *et al.* (R = 10 cm) should be increased by 6%, 25%, 27% and 29% for electron energies of 1.4, 300, 650 and 1000 MeV, respectively, while the fluorescence yield of Lefeuvre *et al.* should be increased by 7% and 8% for 1.1 and 1.5 MeV. See [8, 9] for more details.

4 Comparison of fluorescence yield values

Normalized fluorescence yields have been represented as a function of the electron energy in figure 3 for both uncorrected (left panel) and corrected (right panel) values.

The result of the AirLight experiment [5] has not been included in the present analysis, because we have found large discrepancies between our simulation results and those of AirLight that are still unclear. However, note that the error bars of AirLight are larger than those of other experiments discussed here and therefore the conclusions of our analysis is not affected [8, 9].

As can be appreciated in figure 3, measurements are in better agreement when our corrections are included. In addition, the corrected results give more support to the expected energy independence of the fluorescence yield.

In order to know quantitatively to what extent our corrections favor the agreement between the absolute results included in this comparison, a statistical analysis has been performed. In the first place, for a given experiment, results obtained at different energies have been averaged assuming a common systematic error. Then, the average value of this sample $\langle Y \rangle$ has been calculated weighting the data with the reciprocal of the quoted square uncertainties (i.e., $w_i = 1/\sigma_i^2$). The variance $\left(\sum_i 1/\sigma_i^2\right)^{-1}$ and the χ^2 statistic divided by the number of degrees of freedom has been computed correspondingly. The uncertainty in the average fluorescence yield $\sigma_{\langle Y \rangle}$ has been calculated as the product of the variance and χ^2/ndf, following the usual procedure.

The results shown in figure 4 for both uncorrected (upper panel) and corrected (lower panel) values indicate that our corrections lead to a more consistent data sample suggesting that they do improve the determination of the deposited energy for the different experiments. As described in [9], we have checked that the weighting procedure has no significant effect on the final result. Also the $\langle Y \rangle$ value of the corrected sample does not change significantly if some measurement is excluded.

We have also studied the energy (in)dependence of the fluorescence yield in this data sample. Several experiments have supported the assumed independence of the fluorescence yield at the level of 5%. On the other hand, the theoretical analysis described in [10] predicts a slight increase ($\sim 2\%$) with decreasing energies in the $0.1 - 10$ MeV range, which is also compatible with experimental data (see right panel of figure 3). In principle, this effect should be included in order to quantify the consistency of the available results. Fluorescence-yield values have been recalculated by previously scaling all the measurements to a common electron energy of 100 MeV according to the energy dependence predicted by our simulation. This energy scaling slightly lowers the χ^2/ndf value (from 1.21 down to 1.11) while both the average value and its uncertainty remain nearly unchanged. Although this result would support

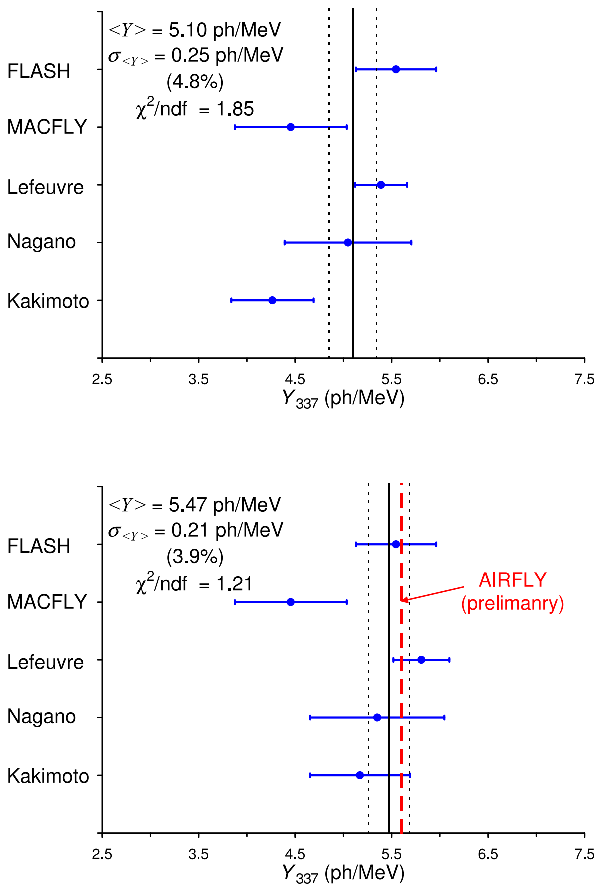

Figure 4: Graphical representation of the Y_{337} values at 1013 hPa and 293 K for both uncorrected (up) and corrected (down) values.

the weak energy dependence predicted by our simulation, we note that the evidence is still very weak.

A detailed analysis of all these features [9] led us to an average value of 5.45 ph/MeV with a conservative estimated error of 5%. According to the comparison of our simulation result on energy deposition with GEANT4, a systematic uncertainty of about 2% should be added, although it does not affect the χ^2 value of the corrected sample.

The recent absolute measurement of the AIRFLY collaboration [7] yields $Y_{337} = 5.60$ ph/MeV with an uncertainty of $\lesssim 5\%$ (still preliminary), which is fully compatible with the above value. If this new result is included in the sample, then a weighted mean value of 5.51 ph/MeV with χ^2/ndf = 0.99 (assuming a 5% error for AIRFLY) is obtained with an uncertainty of $\lesssim 5\%$. Note that if the deviation in energy deposition between our algorithm and GEANT4 (used by AIRFLY) is taken into account, then the difference between the AIRFLY result and the average Y_{337} value of the remaining experiments would be even smaller, and so, the error in the full sample could be further reduced.

As already mentioned, for the comparison presented here we have normalized the fluorescence-yield measurements to its value for the 337 nm band at 1013 hPa and 293 K. However, in some occasions it might be more convenient to use the integral of the fluorescence yield in a wider spectral range and/or other pressure and temperature conditions. The conversion can be easily done following the procedure described in detail in [10]. For instance, the above average value would be of 20.1 ph/MeV ($\pm 5\%$) for the $300-420$ nm spectral range at the same reference pressure and temperature, which would become 20.3 ph/MeV if the measurement of AIRFLY is included.

Our simulation can also provide a theoretical value of the air-fluorescence yield. Unfortunately, the evaluation of the fluorescence emission cannot be very precise due to the large uncertainties in some molecular parameters, leading to a global uncertainty in the fluorescence yield which was estimated to be about 25% [10]. Nevertheless, a result of Y_{337} = 6.3 ph/MeV (using the quenching parameter of [11]) has been found, which is consistent with the experimental ones, providing a valuable theoretical support to these measurements.

5 Conclusions

Available measurements of the absolute air-fluorescence yield normalized to common conditions (1013 hPa, 293 K, 337 nm) and units (ph/MeV) have been compared. Experimental results obtained neglecting the energy deposited by secondary electrons outside the field of view of the optical system have to be corrected by non-negligible factors ranging from 6 to 29%. These corrections increase significantly the compatibility of experimental results. An average value of $Y_{337} = 5.45$ ph/MeV with a 5% uncertainty has been obtained. If the absolute fluorescence yield and error of AIRFLY are confirmed, a consensus on this important parameter with an uncertainty below the 5% level could be reached with high reliability.

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