The effect of the fluorescence yield selection on the relative energy scales of the Auger and TA experiments

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Abstract:
The Auger and TA experiments use different fluorescence yields for shower reconstruction. The corresponding effect on their relative energy scales is studied. Simple analytical calculations show that the energy reconstructed by the TA telescopes should be larger than that of Auger. A detailed simulation has provided a more realistic evaluation of this effect showing similar results. Our analysis indicates that, if we neglect other contributions, the discrepancy in the energy scales due to the fluorescence yield would be of about 17%.

Keywords: Fluorescence Yield, Auger, Telescope Array, Energy scale of fluorescence telescopes

1 Introduction

The air-fluorescence yield FY is a key parameter for the accurate measurement of the calorimetric energy of UHE cosmic-ray showers by means of fluorescence telescopes. In practice, the FY is determined by a set of parameters: the absolute number of fluorescence photons per unit deposited energy at a given wavelength interval, the relative wavelength spectrum in the range of interest and the characteristic pressures accounting for the collisional quenching of the excited molecules of nitrogen. An accurate description of the fluorescence yield should also include the dependence of these quenching parameters with the humidity and temperature of the atmosphere (see [1] for details).

The fluorescence intensity is proportional to the energy deposited by the shower in the atmosphere, and therefore, the uncertainty in the absolute value of the FY is expected to translate linearly to the reconstructed energy. On the other hand, the impact of a change in the assumed wavelength spectrum depends on the optical efficiency of the telescope. The quenching parameters and the treatment of humidity and temperature, although less relevant, also have a non-negligible impact in the energy scale.

The Auger and TA experiments are presently taking fluorescence data of air showers to measure the energy spectrum of cosmic rays at the highest energies. In these experiments, different FY data are used for the analysis, and therefore, their energy scales should be different. The absolute spectral yields at 1013 hPa and 293 K assumed in both experiments and the corresponding optical efficiencies are displayed in Fig. 1.

The Auger experiment uses the FY parameters measured by the AIRFLY collaboration, that is, the absolute value[1] at 337 nm recently published in [4], the wavelength spectrum and quenching parameters from [5] and the humidity and temperature parameters from [6]. The relative optical efficiency of the Auger telescopes [7] is dominated by the filter (MUG6 glass manufactured by Schott-Desag), although other elements (e.g., mirror and PMT) also contribute.

The TA collaboration[2] uses the absolute value of the integrated fluorescence yield (300 - 400 nm) from Kakimoto et al. [8] and the wavelength spectrum measured by FLASH [9]. This spectrum has two additional bands not reported by Kakimoto that are added by TA to get their total absolute yield. The quenching parameters are also those from Kakimoto et al. [8]. Neither the humidity effects nor the temperature dependence of the quenching cross section is included in the FY model used by TA. The UV filter is a BG3 glass (manufactured by Schott) with a higher transmittance over a wider wavelength interval than the MUG-6 glass employed by Auger. Note that some weak molecular bands, usually not taken into account (e.g., by Airfly) because they are absorbed by other narrower UV filters, can contribute to the total fluorescence signal recorded by TA.

In this work, the impact of the assumed FY on the relative energy scales of these experiments is studied. For this purpose, we will use in the first place an analytical method that allows us to evaluate the combined effect of the FY and optical efficiency, although it neglects some ingredients of the shower analysis (e.g., the effect of the Cherenkov light on the energy reconstruction). In a second step, we will show a procedure to obtain a more realistic evaluation of the impact of the FY using the simulation and reconstruction tools of the Auger collaboration. Also, we propose a similar analysis that could be used with real data. A preliminary work was already published in [2], but this procedure is validated here using a detailed MC simulation.

2 Method

For a given shower, the number of fluorescence photons per unit depth at any point of the track that are detected by a telescope can be expressed as

$$\frac{\mathrm{d}N}{\mathrm{d}X}(X) = E\,f(X)G(X)\int \mathrm{d}\lambda\,\varepsilon(\lambda)T(X,\lambda)Y(X,\lambda)\,. \quad (1)$$

The parameters in the above equation are defined as follows: X is the slant depth at the given shower point; $E\,f(X)$

1. Note that the Auger collaboration has recently changed the value of the absolute yield that they use [3]. The present work updates the preliminary results shown in [2] where a different value had been used.
2. Black Rock Mesa and Long Ridge telescopes.

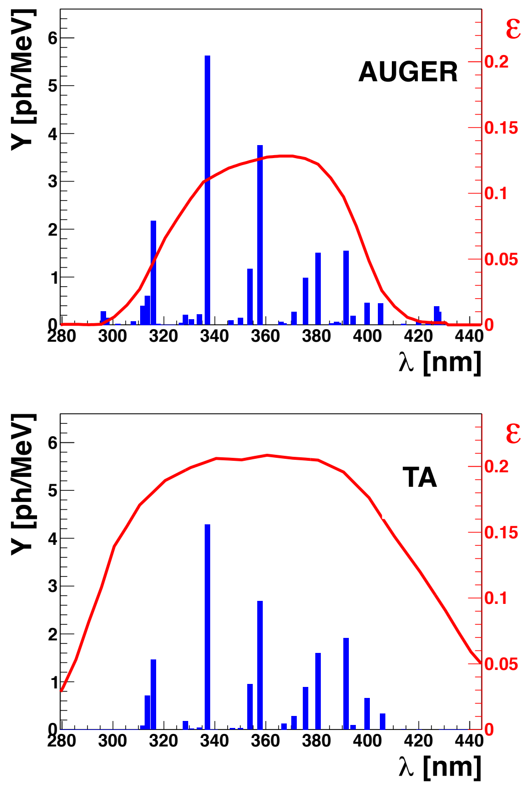

Fig. 1: Absolute fluorescence yield spectra at 1013 hPa and 293 K (dry air) employed by the Auger and TA experiments (blue bars). The red line represents the optical efficiency of the corresponding telescopes including all optical elements.

is the energy deposited per unit depth, where E is the calorimetric energy given by the integral over all slant depths and $f(X)$ is the normalized energy deposit profile; $G(X)$ is the geometrical factor for collecting fluorescence light isotropically emitted at the shower point; $\varepsilon(\lambda)$ is the wavelength-dependent efficiency of the telescope; $T(X,\lambda)$ is the atmospheric transmission of the light traveling from the shower to the telescope; and $Y(X,\lambda)$ is the wavelength differential fluorescence yield including its atmospheric dependence at the given height.

The total number of fluorescence photons detected by the telescope is proportional to the calorimetric energy of the shower, that is, $N = CE$. According to (1), the proportionality factor C is given by

$$C = \int_{\text{fov}} \mathrm{d}X\, f(X) G(X) \int \mathrm{d}\lambda\, \varepsilon(\lambda) T(X,\lambda) Y(X,\lambda)\,, \quad (2)$$

where the integration extends over all slant depths within the field of view of the telescope. Note that all the dependencies on geometry, atmospheric parameters, etc. of the integrated signal N are included in this parameter C. Therefore, in this analytical approach, the reconstruction of the shower energy is equivalent to solve the integral (2).

Now, let us assume two telescopes placed at the same location and with same field of view, but with different efficiencies ε_1 and ε_2. For a given shower, the integrated signals N_1 and N_2 recorded by these telescopes will be different, although the right calorimetric energy E will be reconstructed from both signals, provided that the FY and all the parameters needed for the reconstruction are properly characterized. However, if different yields Y_1 and Y_2 are assumed for each telescope, the reconstructed energies E_1 and E_2 will be different as well. This can be expressed with the following relations:

$$N_1 = C[\varepsilon_1, Y]\,E = C[\varepsilon_1, Y_1]\,E_1$$
$$N_2 = C[\varepsilon_2, Y]\,E = C[\varepsilon_2, Y_2]\,E_2\,, \quad (3)$$

where the $C[\varepsilon, Y]$ factors are given by introducing the corresponding ε and Y values in equation (2). Therefore, the ratio of the reconstructed energies is

$$\frac{E_2}{E_1} = \frac{C[\varepsilon_1, Y_1]}{C[\varepsilon_2, Y_2]}\frac{N_2}{N_1} = \frac{C[\varepsilon_1, Y_1]}{C[\varepsilon_2, Y_2]}\frac{C[\varepsilon_2, Y]}{C[\varepsilon_1, Y]}\,. \quad (4)$$

In principle, this E_2/E_1 ratio can only be evaluated if either the signals N_1 and N_2 of both telescopes for the same shower are available or the *true* yield Y is known. Nevertheless, if one of the two telescopes is assumed to use the *true* yield, e.g., $Y_1 = Y$, equation (4) is reduced to

$$\frac{E_2}{E_1} = \frac{C[\varepsilon_2, Y_1]}{C[\varepsilon_2, Y_2]}\,. \quad (5)$$

Note that Y_1 only needs to describe the *true* relative fluorescence spectrum and the atmospheric dependencies so that equation (5) holds, because a constant factor in the yield cancels out in the ratio of equation (4). In section 3, the relative difference in the energy scales of TA and Auger due to the combined effect of the FY and efficiency is obtained from (5).

A different approach that can provide more realistic results is to use the reconstruction algorithms of these experiments. Note that, in expression (1), the recorded signal is assumed to be caused only by fluorescence light, although a non-negligible amount of Cherenkov light is also emitted by the shower and detected by the telescope. The reconstruction algorithms take into account this Cherenkov light contribution (e.g., see [10]), and therefore, our analytical method based on equations (1-5) is expected to overestimate the impact of a change of the FY on their energy scales.

Let us assume again that the experiment 1 uses the *true* yield and that both experiments can reconstruct the *true* energy if using this *true* yield. The difference in their energy scales is the difference in the reconstructed energy that would be observed by the experiment 2 when replacing its original *wrong* yield Y_2 by the *true* one Y_1. That is, the E_2/E_1 ratio could only be evaluated, in principle, by using the analysis software and data (either real or simulated) of the experiment that is supposed to use the *wrong* yield.

Nevertheless, as far as the influence of the optical efficiency of the telescopes is concerned, both the signal and the reconstructed energy of the experiment 2 can be emulated by means of the analysis tools of the experiment 1 for a simulated shower. This can be achieved by implementing the optical efficiency of the experiment 2 in the simulation and reconstruction algorithms of the experiment 1.[3] This procedure is employed in section 4 to obtain the E_2/E_1 ratio.

In a further step, we show that there is no need to simulate the signal of the experiment 2 to evaluate the E_2/E_1 ratio using the analysis software of the experiment 1. Assuming

3. Other differences in the design of the telescopes or in the reconstruction algorithms are disregarded.

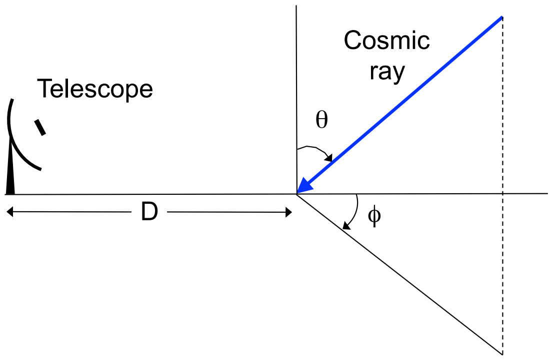

Fig. 2: Diagram showing the definitions of the geometrical parameters used in this work.

that signals recorded by the telescopes, including Cherenkov light contributions, are proportional to the calorimetric energy of showers, relations (3) are still valid, but now the parameters N_1, N_2, E_1 and E_2 represent the actual signals and reconstructed energies of the experiments.[4] In addition, the following relation:

$$N_1 = C[\varepsilon_2, Y_1]\, E_1^* = C[\varepsilon_2, Y_2]\, E_2^* \qquad (6)$$

can be written, where E_1^* and E_2^* are respectively the energies that would be reconstructed by the software of the experiment 1 from a signal N_1 when the yields Y_1 and Y_2 are used, but artificially replacing its efficiency ε_1 by that of the experiment 2 in the reconstruction algorithm. Obviously, these reconstructed energies are fake, nevertheless their ratio should give the wanted relative difference in the energy scales. That is, from (3) and (6), we obtain

$$\frac{E_2}{E_1} = \frac{E_2^*}{E_1^*}\,. \qquad (7)$$

Note that this would allow us to calculate the E_2/E_1 ratio using either simulated or real data of the experiment 1 only. The above relationship is validated in section 4 using simulated data.

3 Results of the analytical approximation

For the calculations presented here, showers are generated assuming a Gaisser-Hillas function for the profile of energy deposit $E\,f(X)$. The shower geometry is defined by the zenith angle θ, the azimuthal angle ϕ and the distance D from the telescope to the impact point at surface (see figure 2). The field of view of the telescope is assumed to cover 30° in elevation and 180° in azimuth, with the shower impact point being just in front of the telescope. The atmospheric transmission $T(X,\lambda)$ is calculated using data from [11]. For the purpose of comparison, we assume the same atmospheric profile that is used in the simulated showers of section 4.

In this analysis, the relative fluorescence spectrum and the quenching parameters measured by the Airfly collaboration [5, 6], which are the most precise and complete ones available in the literature, are taken as the *true* ones. In doing so, Auger and TA correspond respectively to the experiments 1 and 2 in equation (5). The percentage difference in the reconstructed energies is defined in this work as

$$\Delta E = 200\frac{E_{\mathrm{TA}} - E_{\mathrm{Auger}}}{E_{\mathrm{TA}} + E_{\mathrm{Auger}}}\,. \qquad (8)$$

This energy deviation is expected to depend on the average mass thickness of air $\langle r \rangle$ that separates the shower and the telescope, because the atmospheric attenuation modifies the spectrum of the fluorescence light reaching the telescope. Differences in the quenching parameters assumed by these experiments can make ΔE to be also dependent on the average height $\langle h \rangle$ where the fluorescence light is produced. So, we define

$$\langle r \rangle = \int_{\mathrm{fov}} \mathrm{d}X\, f(X) r(X)\,; \quad \langle h \rangle = \int_{\mathrm{fov}} \mathrm{d}X\, f(X) h(X)\,, \quad (9)$$

where the weighted averages are restricted to the fraction of shower within the telescope field of view.

In figure 3 and 4, the percentage difference ΔE is plotted versus $\langle r \rangle$ and $\langle h \rangle$ respectively, for two typical showers initiated by Fe nuclei of 10^{19} and 10^{20} eV with three different orientations. The θ and D parameters are adjusted so that $\langle r \rangle$ varies while $\langle h \rangle$ is kept constat (figure 3), and vice versa (figure 4).

Results show that ΔE is between 16% and 23%, basically depending on $\langle r \rangle$ and $\langle h \rangle$ only, as expected.Note that this deviations are significantly larger than those from our previous result of [2] because the absolute yield of Auger has increased by 11%.

4 Results with simulated showers

As discussed in section 2, a procedure based on the reconstruction of simulated showers can be used to achieve a more realistic evaluation of the effect of the assumed FY on the energy scale. Some tests have been carried out using air showers simulated with the CORSIKA code [12]. Fluorescence signals of the telescope have been generated for these showers using the software of the Auger experiment and assuming that the yield of Auger is the *true* one. Two kind of telescope signals have been simulated: using the optical efficiency of Auger (i.e., default Auger signals) or replacing the optical efficiency of Auger by that of TA, emulating in this case the signal that TA would have recorded. These fluorescence signals of Auger and TA have been reconstructed with the Auger software for both assumptions of FY and optical efficiency. In this way we can obtain, for instance, the energies E_{Auger} and E_{TA} that respectively Auger and TA would reconstruct for the same shower.

Next we discuss the results for a particular example. The case is a CORSIKA shower initiated by a Fe nuclei of 10 EeV and a zenith angle $\theta = 26°$. This shower reaches its maximum development at an atmospheric depth of 679 g cm^{-2} and its axis crosses the ground at 25 km from the telescope with an azimuthal angle $\phi = 169°$. Using this air shower, Auger and TA signals have been simulated 30 times each to calculate the average and RMS of the corresponding reconstructed energies.

First, we checked that the primary energy is properly reconstructed irrespective of the implemented optical efficiency. For this test, the same efficiency (either that of Auger or that of TA) and the same yield (i.e., that of Auger) were employed in both the simulation of the signal and its reconstruction. Fully compatible average energies of 9.44 ± 0.14 and 9.48 ± 0.18 EeV were found for the Auger and TA signals respectively. This energy corresponds to E_{Auger} in e-

4. The factors $C[\varepsilon, Y]$ are no longer described by (2).

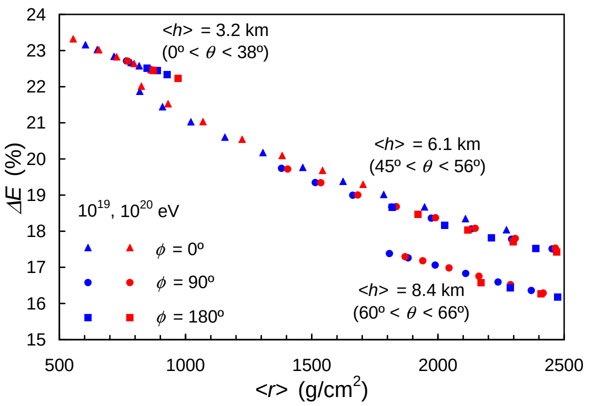

Fig. 3: Percentage difference in the reconstructed energies of TA and Auger as a function of $\langle r \rangle$ for several values of $\langle h \rangle$ and many combinations of the θ, ϕ, D parameters and two shower profiles.

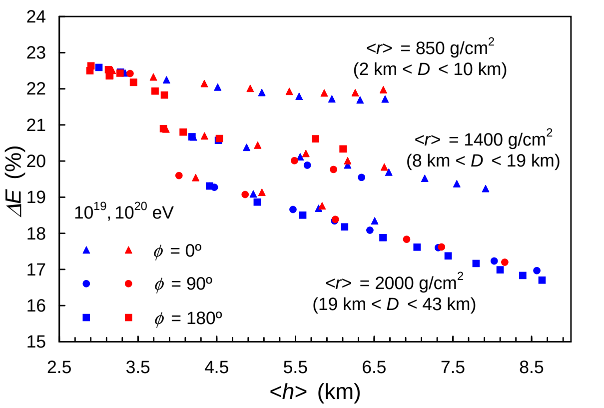

Fig. 4: Same as figure 3 but as a function of the parameter $\langle h \rangle$.

quation (8) and is in agreement with the MC input within the expected uncertainties of the reconstruction algorithm.

The E_{TA} energy has been obtained from the emulated TA signal when both the yield and efficiency of TA are used in the reconstruction. The result was $E_{\mathrm{TA}} = 11.02 \pm 0.21$ EeV, that is, 17% larger than E_{Auger}. The corresponding deviation obtained by the analytical model ($\langle h \rangle = 4.81$ km, $\langle r \rangle = 2080$ g cm^{-2}) is 19%, that is, the realistic ΔE is smaller that the analytical one, as expected.

An interesting conclusion of the arguments presented in section 2 is that the relative deviations in the energy scale of two experiments can be evaluated from (7) by only reconstructing real data of the one that uses the *true* yield, i.e., Auger in our assumption. This procedure has been validated with the simulated events by calculating the fake energies E^*_{TA} and E^*_{Auger}, that is, those obtained from the simulated Auger signal when the TA efficiency is used in the reconstruction in combination with the yields of TA and Auger, respectively. The results were $E^*_{\mathrm{TA}} = 8.70 \pm 0.12$ EeV and $E^*_{\mathrm{Auger}} = 7.48 \pm 0.11$ EeV, and therefore, the relation $E_{\mathrm{TA}}/E_{\mathrm{Auger}} = E^*_{\mathrm{TA}}/E^*_{\mathrm{Auger}}$ is fulfilled, as expected.

Further tests generating telescopes signals assuming the TA yield as the *true* one are being carried out. In addition, we are studying different combinations of the θ, ϕ and D parameters and also other primaries, e.g., protons. In all cases, the relationship (7) has been confirmed.

5 Conclusions

The fluorescence telescopes of the Auger and TA experiments assume different fluorescence yields, and thus, their corresponding energy scales are expected to be different. According to a simple analytical procedure, the TA energy should be larger than that of Auger by an amount that decreases with the shower-telescope distance from 23% down to about 16% (figure 3).

A more realistic evaluation of the relative energy scales can be performed by using simulated showers and reconstructing with the analysis software of a single experiment, which includes the contribution of the Cherenkov light detected by the telescopes. As a preliminary result, we have found that the TA energy should be larger than that of Auger by an amount of about 18% for close showers decreasing with the telescope-shower distance. This result has been obtained assuming that the fluorescence yield is perfectly described by the AIRFLY data. Similar analyses using the reconstruction algorithm of the TA experiment would be very useful as a further confirmation of our predictions.

We have also shown that this procedure could be applied to real data of a single experiment according to equation (7), which has been validated using simulated showers.

Finally, we note that this result only accounts for the effect of using different yield data. Obviously, other ingredients of the shower reconstruction have an important role, e.g., the optical calibration of the telescope, the treatment of the atmospheric parameters, the reconstruction technique, etc., and therefore, we cannot state that the actual energy deviations of these experiments are those mentioned above. Crosschecks of the reconstruction methods of both experiments using the same fluorescence yield data would be highly desirable.

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