On the energy determination of extensive air showers through the fluorescence technique

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The determination of the shower development in air using fluorescence yield is subject to corrections due to the angular spread of the particles in the shower. This could introduce systematic errors in the energy determination of an extensive air shower through the fluorescence technique.

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The fluorescence technique consists on observing the atmospheric nitrogen fluorescence light induced by the passage of the charged particles in a shower through the atmosphere. It is an alternative for ultra high energy cosmic ray (UHECR) detection to the more common experiments that detect the shower front as it reaches ground level. The technique was first explored in a pioneering experiment by the Fly’s Eye detector \(^1\) and is currently being exploited in its successor, the high resolution Fly’s Eye (HiRes) \(^2\), as well as in the Auger Observatory \(^3\), now in construction stage, and the Telescope Array \(^4\). It is also the basis of planned experiments that will look for atmospheric UHECR showers from satellites \(^5\), and which are likely to provide the next generation of UHECR detectors. Although the technique has been completely successful, there are unsolved discrepancies between the UHECR spectrum measured with it and with the more conventional techniques that sample the shower front as it hits the ground. The measurements of the cosmic ray spectrum above \(5 \times 10^{19} \text{ eV}\) with the HiRes experiment give results which differ at the 2 to 3 sigma level from those obtained with the AGASA air shower array \(^6\). In this respect the Auger observatory, being a hybrid experiment that combines both the fluorescence and the shower front sampling techniques, is a crucial step for solving the discrepancies and for the future of UHECR measurements.

Fluorescence detectors use mirrors to collect light produced by all the charged particles in the shower front as it propagates through the atmosphere. Different depths of the shower are observed from different arrival directions which are viewed by different photo-detectors of an imaging camera in the focal plane of the mirror. A procedure must be devised to compare the light emission curve as a function of depth to that expected from an air shower, from which important properties such as shower energy can be inferred. As fluorescence technique experiments measure the light emitted at different depths in shower development, they perform a calorimetric measurement of energy deposition, and are in principle more reliable for establishing shower energy.

The technique has other difficulties, particularly those associated to light transport in the atmosphere which is complex and changing with time, and also because the fluorescence light emission mechanism itself is subject to uncertainties. In this article we discuss the relation between the emission process and the shower development. We argue that there are geometric effects associated to shower development that can have important implications in the procedure to compare light emission to shower development, with important consequences for the determination of shower energy. This idea is not new, it was already discussed over a decade ago by M. Hillas \(^7\).

The depth distribution of the collected photons in a fluorescence telescope \(N_{\gamma}^{\text{tot}}(X)\), where \(X\) is measured along shower axis, is often converted to the number of charged particles \(N_e(X)\) at the corresponding depth. In this way the longitudinal shower profile can be obtained after correcting for attenuation and geometrical effects associated to the characteristics of the detector and the orientation of the shower with respect to it,

\[
N_e(X) = \frac{N_{\gamma}^{\text{tot}}(X)}{\frac{1}{Y \Delta X} g_{\text{atten}} g_{\text{area}}},
\]

where \(g_{\text{atten}}\) takes into account the attenuation of the fluorescence photons in the atmosphere, and \(g_{\text{area}}\) accounts for the collection area of the mirror (see Eq.(6.2) in Ref.\(^8\)). Here \(\Delta X\) is the segment of the shower viewed by the telescope which is measured along the shower axis, and \(Y\) is the fluorescence yield for air.

The amount of fluorescence light emitted by a particle of charge \(e\) is usually assumed to be isotropic and proportional to the energy loss by ionization. The fluorescence yield for nitrogen, \(Y\), measured in photons/m, is concentrated in the Ultra Violet (UV) range of the spectrum, and must be experimentally determined. Most of the data used relies on two experiments \(^2\), \(^10\). In the most recent experiment, electrons were fired onto an air target of a given length. The yield is obtained dividing the number of emitted photons per incident electron \((N_e)\) by the length \((d)\) of the visible portion of the electron beam in the direction of the beam axis \(^10\).

\[
Y_{\exp} = \frac{N_e}{d}.
\]
The experimental result is that on average about five UV fluorescence photons are emitted when a particle of charge $e$ passes through one meter of air at standard temperature and pressure [10].

The shower energy has been determined in the past by integration of the longitudinal profile of the shower [8, 11], applying Eq. 1 to obtain it, and fitting it to an adequate depth development function [12]. The numerical value of this integral is just the track length of the charged particles in the shower. Since the integral is performed in the direction of the shower axis, the calculated track length corresponds to the sum of all the charged particle track lengths projected onto the shower axis. We have referred to this track length as the total projected track length in a different context [13]. This track length is known to be proportional to the shower energy,

$$E_{\text{em}} = \alpha \int_0^\infty N_c(X) dX,$$

where $\alpha$ is a constant that can be related to the ionization loss rate. Its numerical value has been obtained from Monte Carlo simulations [11] and is usually given the value $\alpha \sim 2.19$ MeV/g cm$^{-2}$. We have performed a detailed simulation of 1 TeV electromagnetic showers in air using the GEANT 4 [14] package, following particles down to a very low kinetic energy threshold of 10 keV. These simulations produced a numerical value $\alpha = 2.25$ MeV/g cm$^{-2}$. For the sake of clarity we adopt in the following the standard value of $\alpha = 2.19$ MeV/g cm$^{-2}$, keeping in mind that any uncertainty in $\alpha$ translates directly into a systematic error in the determination of shower energy. It is also important to note that an accurate determination of $\alpha$ by Monte Carlo simulations should take care for the backward-going particles in the shower. We have obtained that $\sim 3-4\%$ of the contribution to the track integral in Eq. 3 is due to backscattered particles.

The main idea of this article refers to the relation between energy loss in a shower and the value of the projected track length. It is well known that as the shower develops charged particles degrade their energy, they suffer more scatterings and they acquire transverse momentum. In other words their paths become less aligned with shower axis. However both the energy loss and the fluorescence yield of charged particles are defined per unit length measured along the particle travel direction. If the fluorescence light is used to infer the number of shower particles in a given depth interval, and the fluorescence yield is assumed to be proportional to energy loss, account must be taken that the energy loss of particles depends on $\Delta L$, the average track length traveled by the shower particles regardless of the particle direction in a given depth interval $\Delta X$ measured along the shower axis. While $\Delta L$ is measured along the particle direction, $\Delta X$ is measured along the shower axis. One expects the ratio of $\Delta L$ to $\Delta X$ to increase as the shower develops and the average energy of the shower particles decreases. This ratio can be thought as the average value of $\sec \theta$ for all tracks, $\theta$ being the angle between the particle direction and the shower axis.

We have performed shower simulations in air to calculate the relation between $\Delta L$ and $\Delta X$ as a function of atmospheric depth. Air showers initiated by photons have been simulated using the GEANT 4 [14] and the ZHS [15] packages. It is worth noting that we have obtained that the results of both simulations in air, under the same conditions, agree at the 1% level. We define a factor $f$ as the ratio of the total to the projected track length. We have found that $f$ in a shower is significantly different from 1. Moreover it increases with shower age as expected. In Fig. 1 we show the dependence on depth (expressed in terms of shower age) of $f$ as obtained in electromagnetic showers for 1 TeV showers. The effect can amount to a 25% ($f = 1.25$) correction at the end of the shower. We have also obtained that the correction is energy independent which is not surprising since showers are known to have very good scaling properties. A reference value of the effect is given by $f = 1.18$ at shower maximum $s = 1$.

It is worth noting that this effect is not seen in experiments that measure the Čerenkov light emission from a shower. The kinetic threshold energy for Čerenkov emission in air is around 21 MeV. At this energy the deflection angle is very small and the correction (expressed as $(f - 1) \times 100$) is less than 1%. We also show in Fig. 1 the calculated value of $f$ for showers with threshold energy of 21 MeV. The ratio is seen to be very small at all stages of shower development. In figure 2 we show $f$ at shower maximum as a function of the kinetic energy threshold introduced in the simulation. At a kinetic en-
energy threshold of 3 MeV the correction is around 1.06 and goes rapidly to 1 at higher energies. For a kinetic energy threshold of 10 keV it increases to about 1.18. For showers initiated by hadrons the effect must be similar because they can be considered as a superposition of electromagnetic showers initiated from photons from neutral pion decays at different depths. To a reasonably good approximation the lateral distribution of hadronic showers around maximum does not change very much with depth and corresponds to that of an electromagnetic shower of age \(s \simeq 1\). We can expect \(f \simeq 1.18\) for these showers around shower maximum.

The same effect has to be kept in mind in experiments that measure the photon yield applying Eq. (2). The electrons traveling through Nitrogen a distance \(d\) will be scattered, and as a result the path they travel will be longer than its projection onto the beam axis depending on the electron’s energy. Providing that \(d\) is sufficiently short, an electron does not deviate much from the incident direction, and its total track length is approximately equal to the length of the visible portion of the beam. The ratio of the track lengths will actually depend on electron energy and must also be taken into account in the calculation of the yield. We have simulated electron paths in air using the GEANT 4 package, propagating a 1.4 MeV electron along a distance of 30 cm along the direction of movement of the incident electron, to roughly reproduce the conditions of the experimental setup in [10]. These simulations predict an average ratio \(f_{\text{exp}} = 1.02\) between the total track length and the track length projected along the electron’s incident direction. This value is significantly smaller than the typical value of \(f\) obtained in shower simulations and as a result corrections should be made to account for these factors.

Assuming that the fluorescence light emitted is just proportional to the track length of charged particles in a shower, we introduce an effective value of the yield \((Y_{\text{eff}}(X))\) which is dependent on depth and takes into consideration the fact that charged particles do not travel parallel to shower axis. Let us consider that the fluorescence yield \(Y_{\text{exp}}\) is obtained in a given experimental setup for which the ratio of total to projected track lengths is given by \(f_{\text{exp}}\). The effective yield that should be used in air shower experiments is given by:

\[
Y_{\text{eff}}(X) = \frac{f(X)}{f_{\text{exp}}} Y_{\text{exp}}. \quad (4)
\]

In other words \(Y_{\text{exp}}\) must be corrected by a factor \(f(X)/f_{\text{exp}}\) which is \(\sim 1.16\) near maximum, assuming \(f_{\text{exp}} = 1.02\).

The deduced value of the number of shower particles, \(N_e(X)\), must be inversely proportional to the effective yield which now measures the emission in terms of depth along the shower axis. Since \(f(X) > f_{\text{exp}}\) for most depths, using the experimental yield without this correction to estimate the shower energy will lead to an overestimate of the electromagnetic shower energy. This translates directly into a systematic overestimate of the energy which is deposited in the atmosphere in the form of charged particles (mainly electrons and positrons).

Moreover since \(Y_{\text{eff}}\) is in general depth dependent, ignoring the correction factor can also affect other observables such as the position of shower maximum. We can roughly estimate an upper bound of the expected effect on the calculation of the depth of shower maximum. The number of particles as a function of depth obtained without correcting for this effect would be \(\tilde{N}_e(X) = f(X)N_e(X)\), where \(N_e(X)\) is the actual number of particles. Using a simple parameterization of \(f\) from figure [11] and the Greisen parameterization for \(N_e(X)\) one obtains a depth of maximum which is deeper by \(\Delta X_{\text{max}} \approx 4\) g/cm\(^2\). This effect was already noticed in [11]. Our upper bound estimate is compatible with the shift of 3 – 4 g/cm\(^2\) between the depth at which the fluorescence light emission reaches maximum and the depth at which \(N_e\) is maximum, obtained in [10] for hadronic showers.

The result is independent of energy. This implies, for instance, that the elongation rate, the derivative of \(X_{\text{max}}\) with respect to the logarithm of the energy, is unchanged by this effect. Finally, the change of \(f\) with depth for showers induced by hadrons is expected to be less important because the lateral distribution function of hadronic showers is known to be less dependent on depth. In any case an iterative process taking this small effects into account could be implemented to avoid such systematic effects.

We have shown that the fact that charged particles in a shower do not travel parallel to the shower axis has important implications in the fluorescence light output of a shower in the assumption that the fluorescence yield is only dependent on distance traveled by the individual particles. The light output per unit charged particle (as
measured in the plane containing the shower axis perpendicular to the direction of observation) increases as the shower develops in the atmosphere since the individual particles travel in larger angles with respect to the shower axis as the shower develops. In a conventional approach the deduction of the depth development curve of the shower from the detected light needs to take these effects into account. This can be made through an effective yield which is to be obtained in a detailed simulation. Proposals to directly compare the data to the light outputs generated by simulated showers are at an advantage to take such effects into consideration in a consistent way [17]. Alternatively it has been recently proposed to directly measure the energy deposited in fluorescence light in order to estimate the shower energy [18]. Such an energy determination would also not be subject to the corrections discussed here. However, any determination of the number of particles through the fluorescence technique has to be corrected by the factor discussed here.

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