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The aperture, sensitivity and precision of the AUGER Fluorescence Detector

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Abstract. Detecting the fluorescence yield of light emitted by Nitrogen when a high energy Cosmic Ray shower develops through the atmosphere, it is possible to perform a precise calorimetric measurement of the shower energy profile. Fluorescence detectors were used successfully in the past. In the Auger hybrid system they complement the information coming from the large Surface Detector Array providing an important validation of the methods used to determine the energy and the identity of the primary Cosmic Ray. The design parameters and the expected performance of the Auger Fluorescence Detector are discussed, with an overview of the factors determining their sensitivity and the precision of the measurements.

1 Introduction

Before analyzing the properties of the Auger Fluorescnce Detector (FD) I will briefly review some of the characteristics of the signal that we want to detect.

When a Cosmic Ray(CR) particle interacts in the upper levels of the atmosphere, originating a shower that then propagates down to earth, the charged particles in the shower excite the Nitrogen molecules and ions which decay emitting light in the near ultraviolet wavelength range. The process has a very low efficiency with only 5×10^{-5} of the shower energy being carried by fluorescence photons. The light is emitted isotropically with an yield which is proportional to track length and almost independent of the atmosphere altitude. Detecting this signal we can perform a measurement of the shower energy profile using the atmosphere as a calorimeter. The signal is however so weak that this technique can only be successfully applyed to study very high energy showers when background light levels are low.

There are two major sources of background: the first is coming from the diffused light of astronomical objects (sun, moon and stars). The overlap between the sky light spectrum and the fluorescence spectrum is small and optical filters can be used to reduce this kind of background. Even so, one can safely operate a fluorescence detector only in clear moonless nights. A second source of background is that coming from the Cherenkov light emitted by charged shower particles and beaming directly or scattered into the detector aperture. The Cherenkov component can be subtracted by an iterative method, but in practice a reliable measurement of the energy can only be performed when the Cherenkov component is a fraction of the fluorescence light detected.

I will discuss the properties of the FD as a stand-alone detector. However it should be kept in mind that in the Auger experiment the FD has an auxiliary function and some of the choices are dictated by the demand of optimizing the hybrid detector performance. This is the case for example of the positioning of FD telescopes on the site which is designed to provide an almost complete overlap between the Surface Detectors Array (SD) and the FD apertures without waisting FD aperture outside the SD area.

2 Aperture

The geometrical aperture for the SD in the southern site is :

$$A = \int d\phi \int_0^{\theta_{max}} S \times cos(\theta) \times d\theta = \quad (1)$$

$$= \pi \times S \times sin^2\theta_{max} \approx 7350 Km^2 sterad$$

for θ, the primary CR zenith angle, $\leq 60^0$. Accepting events with $\theta \geq 60^0$ will increase A by about 50%. With a 1.5 Km spacing between the SD detectors, the array will be fully efficient for energies of the CR primary, $E_{CR} \geq 10^{19} eV$. The number of FD stations (eyes) and their location on the site are therefore chosen so that all showers of energy $\geq 10^{19} eV$ that hit the SD, be seen by at least one eye. A further constraint comes from the need of limiting the systematic error in the measurements deriving from the uncertainty in the attenuation length of the atmosphere (λ_{At}) traversed by the light in

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Table 1. Event Rates expected at the Auger Southern Site compared to the expected rates from the HiRes Fluorescence detector

Energy(eV)	SD - South site events/year	FD- South site events/year	HiRes events/year
$\geq 3 \times 10^{18}$	15000	4700	
$\geq 10^{19}$	5150	515	387
$\geq 2 \times 10^{19}$	1590	159	170
$\geq 5 \times 10^{19}$	490	49	63
$\geq 10^{20}$	103	10	15
$\geq 2 \times 10^{20}$	32	3	4

its path (d_{DS}) from shower to the detector ($d_{DS} \leq 2\lambda_{At}$). The optimal FD configuration was determined by MC simulations, guided by the orographic constraints of the site.

The FD aperture is calculated asking that the showers seen by one eye leave on the detector a track of sufficient length to allow a precise determination of the geometry of the shower (typically an angular track length $\alpha_{tk} \geq 20^0$ for *monocular* events, that is for events seen by one eye only). α_{tk} depends on the shower direction and impact point and on the telescopes polar angle aperture. With a polar angle aperture of $\sim 30^0$ the constraint on α_{tk} is met by most of the showers hitting ground at a distance and with a direction such that the detected fluorescence light exceeds the detected Cherenkov light.

The acceptance times the effective running time gives the total exposure. The effective running time depends on what are the background conditions under which it is possible to run. If one runs between astronomical dusk and dawn (that is with the sun more than 18^0 below the horizon) one can in principle run 18% of the time. However weather conditions must be folded in. Fly's Eye averaged a 10% to 12% duty cycle and, from what we know, there is no real reason to expect that we can do much better in our southern site. One can play games with the moon, but also assuming that one can run with 80% of the moon being illuminated (which actually means that the brightness of the moon is $\leq$ 30% of full moon) the clear weather duty cycle would only increase from 18% to 27%. Conservatively we assume in what follows a duty cycle of 10%. To estimate the number of expected events/year we take, for the highest part of the CR spectrum, the one determined by the Agasa experiment and obtain the numbers given in Table 1.

3 Sensitivity and precision

The central eye has azimuthal symmetry and is built out of 12 telescopes each with an acceptance in elevation, $1.7^0 < \theta_{tel} < 30.3^0$ and in azimuth $\Delta\phi_{tel} = 30^0$. The peripheral eyes are not complete, being equipped only with the telescopes facing the SD. Basic elements of a telescope are the diaphragm, which defines the telescope aperture, the spherical mirror that must be dimensioned to collect all the light entering the diaphragm in the acceptance angular range and the camera, an array of phototubes positioned approximately on the mirror focal surface (Matthiae, 2001).

As the shower comes into the field of view of one telescope, an image is formed on the camera that tracks the trajectory of the shower as it develops through the atmosphere. The angular motion of the light spot depends both on the distance and on the orientation of the shower axis.

From each PM triggered one reads out amplitude and timing of the signal. From these data the characteristics of the shower can be reconstructed.

The sensitivity of the detector depends primarily on the signal (S) to noise (N) ratio. The signal is proportional to the diaphragm area; the background (B) is proportional to the pixel solid angle times the diaphragm area, hence:

$$\frac{S}{N} = \frac{S}{\sqrt{B}} \propto \frac{d_{dph}}{\alpha_{pix}} \tag{2}$$

where d_{dph} is the diaphragm diameter and, and α_{pix} is the angular diameter of a pixel (the area read out by one PM). The base-line design of the Auger FD detector has d_{dph} = 170 cm and α_{pix} = 1.5^0. Constraints on the diaphragm diameter come from the requirement on spot size. With a 170 cm diaphragm diameter the light spot angular diameter (from spherical aberration) is 0.5^0, small compared to the pixel size. The pixel size is chosen as a compromise between the requirement of achieving a low noise and that of keeping the cost at an acceptable level. It must be added that reducing the pixel size allows a more precise determination of the shower direction, while a relatively large size simplifies the signal analysis by reducing the number of interfaces at which the signal is split between more than one PM.

Table 2 lists typical signal to noise ratios calculated for the Auger FD.

E_p [eV]	R_P [km]	T [μs]	S/N
10^{19}	25	1.125	7.2
	20	0.9	19.4
	10	0.5	168
10^{20}	25	1.125	72
	20	0.9	194
	10	0.5	1680

Table 2. Calculated S/N ratio at shower maximum for vertical showers - the PM viewing angle is taken to be at 30^0 from the horizon. T is the transit time for a track that crosses the same PM along its diagonal (Argiro, 2000)

The crucial parameters that one wants to extract from the measurements of the shower profile are:

- energy of the primary CR
- direction of the primary CR and
- position of the shower maximum

The position of the shower maximum is a powerful indicator of the nature of the primary particle. It changes over a

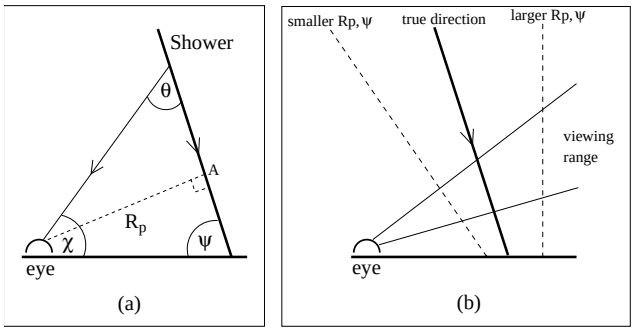

Fig. 1. (a) Geometrical parameters (R_p, Ψ) defining the shower axis within the Shower-Detector plane. χ is the viewing angle of one of the detector phototubes;(b) Reconstruction of shower axis of monocular events exemplifying the problems encountered when the information available is insufficient(see text): the full line shows the true direction of the shower axis while dashed lines show the topology of two solutions both compatible with the available data.

range of 100 gm/cm^2 for nuclei of A=1 to A = 56 and, of course, is dramatically different for weakly interacting particles. To have a reasonable sensitivity to the nuclear mass we need to measure the position of shower maximum to a precision level of $\leq$ 20 gm/cm^2. The Auger FD detector, as described above, allows this level of precision for the position of shower maximum and a measurement of the total energy to $\leq 10\%$. These values refer to a shower of E = 10^{19} eV. The measurement improves as the energy increases. The precision on the measurement of these two quantities depends however on the accuracy in the determination of the direction of the shower. The reconstruction of the shower geometry starts with the determination of the shower-detector plane (SDP) obtained by a fit of the triggered pixels directions, weighted by signal amplitude, to trial configurations. A precision of $\sim 0.25^0$ on the direction of the normal to the SDP is typically achieved. Once the direction of the SDP has been determined, for monocular events the firing time of the PMT's are used to determine the orientation of the shower axis within the SDP. The arrival time of light at a tube viewing the shower axis at an angle χ_i is:

$$t(\chi_i) = \frac{R_P}{c} tan(\frac{(\Psi - \chi_i)}{2}) + T_0 \qquad (3)$$

where R_P is the distance of closest approach of the detector to the shower axis, T_0 is the time at which the shower reaches the point of closest approach and Ψ gives the direction of the shower axis within the SDP (see Fig. 1a). When $tan\frac{(\Psi-\chi_i)}{2} \sim \frac{(\Psi-\chi_i)}{2}$, for all values of i, only two independent parameters can be determined and the reconstructed shower geometry is ambiguous (see Fig. 1b).

If the shower is detected by at least two eyes ($\sim 68\%$of the events of energy 10^{19} eV and $\sim 95\%$ of the events of energy 10^{20} eV) the direction of the shower is precisely reconstructed by the intersection of the SDP's determined from the two eyes. This discussion ignores the powerful handle coming from the knowledge of the shower impact point on ground, as derived from the SD data (Dawson, 2001).

So far we have discussed the precision of the measurements without taking into account systematic errors. We list in increasing order of importance 4 effects:

– Strictly speaking the fluorescence signal is proportional only to the energy of the EM shower. The non electromagnetic component is estimated to be in the range of 10% to 20% depending on primary mass and energy.

– If a very energetic particle enters the atmosphere at small zenith angle, the shower can reach ground before being completely absorbed. If only showers that hit ground well below shower maximum are accepted, the effect is small and can be reliably corrected for.

  In both these cases the energy measured gives a lower limit to the primary energy.

– The presence of a Cherenkov component in the detected signal will affect the energy integral and distort the shower profile. It is a more dangerous effect since, if not taken accurately into account, it can lead to an overestimate of the primary energy. The Cherenkov light beamed directly into the detector acceptance can be estimated from the known angular distribution of electrons in the shower. It is however more difficult to evaluate the fraction of Cherenkov light scattered into the detector acceptance by the aerosol molecules in the atmosphere.

– An insufficient understanding of the characteristics of the atmosphere along the light path between the shower and the detector is potentially the worse cause of systematic errors in the determination of the shower parameters. For this reason the Auger experiment plans to implement a sophisticated diagnostic program to monitor continuously the atmospheric conditions (Matthews, 2001).

It is estimated that the combined effect of the four systematics will contribute an error of $\leq 20\%$ to the measurement of the primary energy.

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