

# The Fluorescence Detector of the Pierre Auger Observatory - a Calorimeter for UHECR

B. Keilhauer for the Pierre Auger Collaboration

*Universität Karlsruhe, Institut für Experimentelle Kernphysik, Postfach 3640, 76021 Karlsruhe, Germany and*

*Observatorio Pierre Auger, Av. San Martín Norte 304, 5613 Malargüe, Argentina;  
<http://www.auger.org/auger-authors.pdf>*

**Abstract.** The Pierre Auger Observatory is a hybrid detector for ultrahigh energy cosmic rays (UHECR) with energies above  $10^{18.5}$  eV. Currently the first part of the Observatory nears completion in the southern hemisphere in Argentina. One detection technique uses over 1600 water Cherenkov tanks at ground where samples of secondary particles of extensive air showers (EAS) are detected. The second technique is a calorimetric measurement of the energy deposited by EAS in the atmosphere. Charged secondary particles of EAS lose part of their energy in the atmosphere via ionization. The deposited energy is converted into excitation of molecules of the air and afterwards partly emitted as fluorescence light mainly from nitrogen in the wavelength region between 300 and 400 nm. This light is observed with 24 fluorescence telescopes in 4 stations placed at the boundary of the surface array. This setup provides a combined measurement of the longitudinal shower development and the lateral particle distribution at ground of the same event. Details on the fluorescence technique and the necessary atmospheric monitoring will be presented, as well as first physics results on UHECR.

**Keywords:** Cosmic Rays, Extensive Air Showers, Fluorescence Emission

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## INTRODUCTION

Ultrahigh energy cosmic rays (UHECR) are a continuous particle flux arriving at the Earth's atmosphere with strongly decreasing rate at highest energies. At energies above  $10^{18}$  eV, their origin is expected to be extragalactic. However, even after several years of measurements, the major questions remain unanswered: where and how do these particles obtain such high energies and what is their elemental composition. For resolving the enigma about UHECR, experiments are designed for measuring the primary energy and type of cosmic rays as well as their arrival directions.

Entering the Earth's atmosphere, cosmic rays initiate extensive air showers (EAS). The primary particle of an EAS, which is the actual cosmic ray particle, interacts with a nucleus of air molecules. This hadronic interaction yields new secondary particles which will interact themselves with nuclei of air molecules. A growing cascade of secondary particles develops in the Earth's atmosphere, which is called an extensive air shower. After an initial phase of particle multiplication, the number of charged particles in the shower falls due to energy losses. For inclined showers with moderate primary energy, only some of the overwhelming amount of particles reaches the Earth's surface. These particles can be observed by particle detectors at ground. For UHECR with nearly vertical incidence, the maximum of shower development is reached close to ground or

even “below” ground.

Another detection technique arises from the energy losses of EAS in the atmosphere. The energy deposited in the air excites molecules of the atmosphere where particularly the excitation of nitrogen molecules is of interest. The de-excitation of nitrogen molecules is partly proceeding through the channel of fluorescence emission. So a light track of the air shower in the UV-wavelength region between 300 and 400 nm can be detected by adequate telescopes. This enables a calorimetric measurement of the deposited energy of EAS which can be used to obtain the primary energy of the cosmic ray.

## **THE PIERRE AUGER OBSERVATORY**

The Pierre Auger Observatory is currently the only data-taking experiment for the detection of UHECR but still under construction. The first part nears completion in the Pampa Amarilla, near Malargüe, Argentina [1]. The second part will be installed in Colorado, USA. Each site of the observatory is designed as a hybrid detector, which consist of particle detectors at ground and fluorescence telescopes. This configuration ensures at least in dark nights the possibility of simultaneous detection of air showers with two different detection techniques.

In May 2006, about 1100 of the total 1600 water Cherenkov tanks, as particle detectors, have been deployed in the Pampa. The spacing of the tanks is 1.5 km and finally an area of 3000 km<sup>2</sup> will be covered. Within these detectors, energetic electrons and muons induce flashes of Cherenkov light which are recorded by three photomultipliers inside the water-filled tank. The duty cycle of this system is nearly 100 % [2].

The second detector component is fluorescence telescopes. Four stations are located at the boundary of the surface array each consisting of six telescopes. A single telescope has a field of view of roughly 30° × 30° with a minimum elevation of 1.5° above horizon. Each station in total has 180° in azimuth observing the atmosphere above the surface array. The telescopes are built with a *Schmidt* optics with an UV-filter for reducing the background light. This system is operated during the one week before and after new moon at night. Therefore, the duty cycle reaches only 15 % of the surface detectors. The camera in the focal point consists of 440 photomultipliers each covering 1.5° [3].

Data taking started in January 2004 with a continuously increasing detector. Until June 2005, an exposure of 1750 km<sup>2</sup> sr yr could be achieved [4].

## **EXTENSIVE AIR SHOWERS**

The development of extensive air showers in the atmosphere is strongly fluctuating from shower to shower. Nevertheless, some systematic behavior is correlated with the energy and type of the primary particle. High-energetic showers penetrate deeper in the atmosphere than lower-energetic ones. Vertical showers develop deeper in the atmosphere than more inclined ones. And also proton-induced air showers develop deeper than air showers induced by more heavy nuclei like iron. The shower development is described

according to the amount of traversed air which is the *atmospheric depth*  $X$  given by

$$X(h_0) = \int_{h_0}^{\infty} \rho_{air}(h) dh, \quad (1)$$

with  $h$  as geometrical height and  $\rho_{air}$  as the altitude-dependent air density<sup>1</sup>.

As the density of air is quite low at higher altitudes, the height of first interaction is strongly fluctuating. The incoming particles represent the projectiles and the resting air nuclei are the target similar to the setup in fixed-target accelerator experiments. In the case of nuclei, not all nucleons of the projectile interact with the target, most of them are only spectators [5].

In general, the description of EAS can be divided into three particle components: the electromagnetic, muonic, and hadronic. If the incoming particle is a nucleus, high energy hadronic interactions produce mostly nucleons, charged and neutral pions, and kaons. The  $\pi^{\pm}$  and  $K$  mesons have relatively long lifetimes of  $10^{-8}$  s, thus they can interact with air nuclei or decay depending on their energy [6]. If the  $\pi^{\pm}$  decay before interacting, they give rise to the muonic component accompanied by neutrinos:  $\pi^{\pm} \rightarrow \mu^{\pm} + \nu$ . Many of the muons reach the Earth's surface due to the relativistic time dilatation of their lifetime of  $2.2 \times 10^{-6}$  s and small energy loss. Those which decay, produce parts of the electromagnetic component:  $\mu^{\pm} \rightarrow e^{\pm} + \nu + \bar{\nu}$ .

If the incoming particle is an electron or positron, energy loss due to Bremsstrahlung is one of the most dominant processes. The emitted high-energetic photons create new pairs of electrons and positrons. In one radiation length, their energy is attenuated by the factor  $1/e$ , which is approximately the same as the  $1/e$  attenuation of a gamma-ray beam due to pair production. In air, the radiation length  $X_0^{air}$  is about  $37 \text{ g/cm}^2$ . The particle multiplication is large and the electromagnetic component is the most numerous part in EAS. This electromagnetic part of an air shower can also be induced by the decay of a  $\pi^0$  into two photons [7]. Losing more and more energy, these particles reach the critical energy which describes the equality of the energy loss due to radiation and the loss due to ionization. Since ionization energy loss is about  $2.2 \text{ MeV/g/cm}^2$ , the critical energy in air is 81 MeV. The interplay of particle production and energy loss yields in a shower maximum and closer to ground the shower starts to die out. Only some of the electrons and positrons reach the Earth's surface.

The overall longitudinal shower development, as simulated with CORSIKA<sup>2</sup> [8], is shown in Fig 1, where a proton-induced shower with  $10^{19}$  eV is plotted. On the left side, the development in terms of energy deposit of a vertical shower is displayed and on the right side, the particle number for a  $45^\circ$  inclined shower.

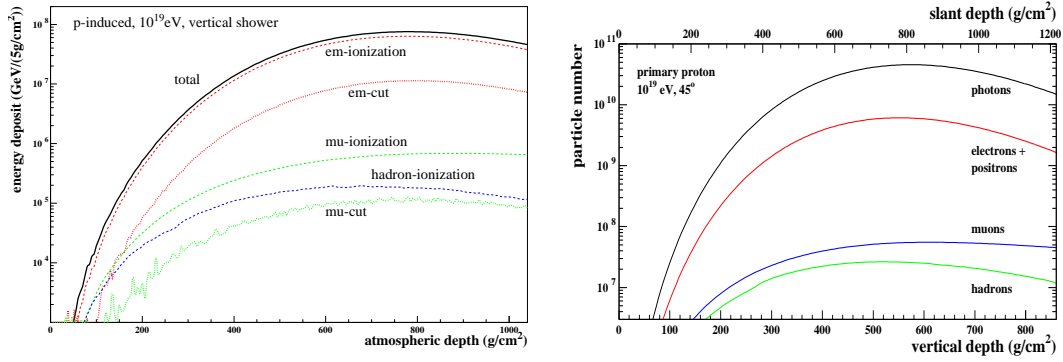
The position of the shower maximum is a good indicator for the properties of the primary particle. The particle number at shower maximum is proportional to the primary energy  $E_0$  and the atmospheric depth of the position of shower maximum is proportional to  $\ln(E_0/A)$ , where  $A$  is the mass of the primary.

Using the fluorescence technique, the energy deposit of an air shower is measured by the amount of emitted fluorescence light. However, integrating the whole energy deposit

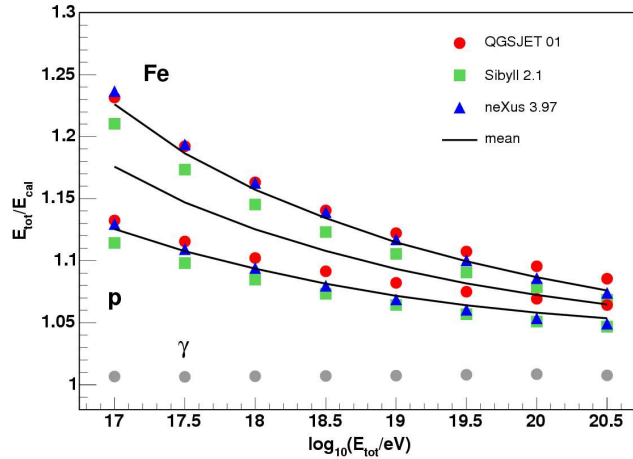
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<sup>1</sup> Here written for a vertical particle trajectory.

<sup>2</sup> COsmic Ray SIMulations for Kascade and Auger



**FIGURE 1.** Simulated proton-induced extensive air shower with  $E_0 = 10^{19}$  eV. Left: The overall deposited energy versus atmospheric depth is shown for the vertical case. The contributions from the electromagnetic, muonic, and hadronic part of air showers are separated. The contributions labeled by 'cut' are due to simulation limitations but can be added to the local energy deposit [9]. Right: The particle numbers of major contributions vs. atmospheric depth is shown. The shower inclination angle is  $45^\circ$ , therefore the slant depth is indicated at the top of the frame [10].

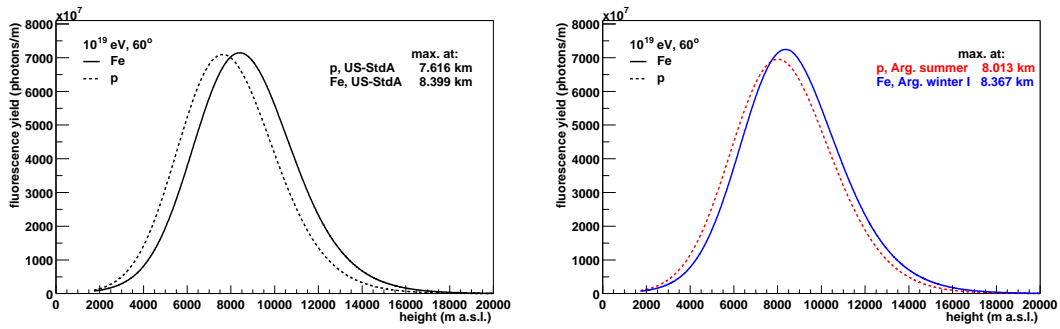


**FIGURE 2.** Correction factor for the energy which is not detected by fluorescence telescopes in dependence on primary energy and type of air shower. The missing energy is related to mainly neutrinos and muons as secondary particles in the air shower cascade [11].

will not result in the total primary energy. The energy deposit is only that of the charged particles but the energy carried away by neutrinos is not detected. Therefore, one has to perform a correction to obtain the total primary energy, which depends on the energy and type of cosmic rays, see Fig. 2.

## CALIBRATION SYSTEMS

The atmosphere is an integral part of any detector system using extensive air showers. The longitudinal and lateral development is affected by local atmospheric conditions

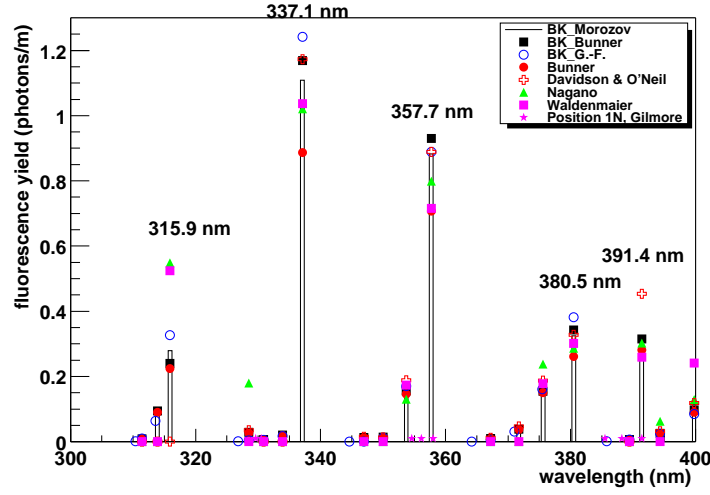


**FIGURE 3.** Left: Fluorescence yield profiles for p- and Fe-induced EAS in the US Standard Atmosphere with  $E_0 = 10^{19}$  eV and  $60^\circ$  inclination. The fluorescence yield is the sum of all emitted photons between 300 and 400 nm [9]. Right: Fluorescence yield profiles for p-induced EAS in Argentine summer and Fe-induced EAS in Argentine winter both with  $E_0 = 10^{19}$  eV and  $60^\circ$  inclination. The fluorescence yield is the sum of all emitted photons between 300 and 400 nm [9].

such as layering of air density and temperature. The optical signal of extensive air showers is even more influenced by the atmosphere, in the emission and transmission towards the detector.

Several calibration systems have been installed at the site of the Pierre Auger Observatory in Argentina. The *Central Laser Facility* [12] and the *Lidar stations* at each telescope station [13] are detecting the optical transmission conditions of the atmosphere. The absolute *drum* calibration determines the detector response [14]. Atmospheric variables like air temperature, pressure, and humidity are obtained by meteorological radio soundings [15]. From these data, the altitude and time dependent air density can be derived which is important for the reconstruction of the longitudinal air shower profiles of the calorimetric measurement using air fluorescence emission. Varying atmospheric conditions affect the conversion of atmospheric depth, as the characteristic quantity for the air shower development, to geometrical altitude, as reconstructed from fluorescence telescope data. Systematic variations of the position of shower maximum as seen by the telescopes due to changing air density profiles have been found [16]. In Fig. 3, the position of shower maximum for simulated proton- and iron-induced showers are shown on the left side for conditions like in the US Standard atmosphere [17]. On the right side, the same simulated showers are plotted for the case that the proton shower would develop in the Argentine summer atmosphere and the iron shower in winter conditions. The separation between the positions of maximum in the US Standard atmosphere as seen by the fluorescence telescopes is significantly reduced.

The uncertainties on the reconstructed energy of air showers from the fluorescence measurement are still quite large. Currently, known uncertainties for the signals in the PMT camera are 5 % for the light collection and 12 % from the absolute detector calibration [3]. However, the latter will improve in the near future. For the reconstructed photons at the telescope, the Auger experiment has to cope with 2 % uncertainty in the geometry reconstruction for hybrid events and with 10 % from aerosols in the atmosphere. The correction for the missing energy yields 3 % uncertainty and the



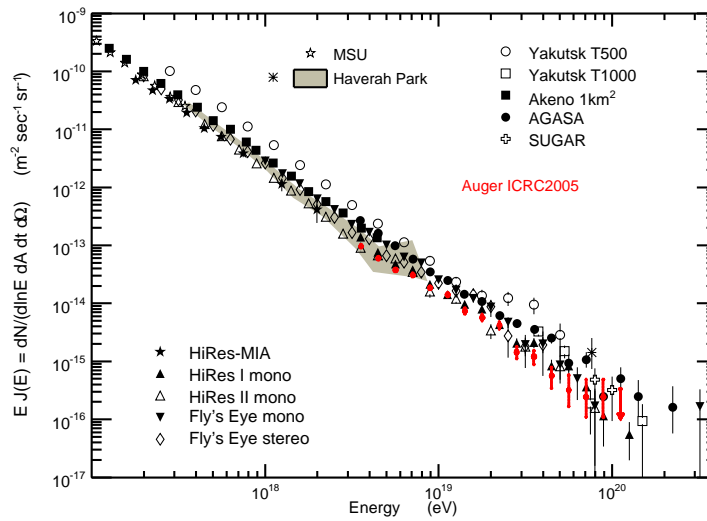
**FIGURE 4.** Fluorescence yield spectra of several calculations and measurements for 0.85 MeV electrons as exciting particles. The bars indicate the preferred calculation by the authors of the referenced article [18]. All calculations by the authors are labeled with “BK\_name”, where *name* indicates the authors of the input parameters.

varying air density profiles 2 % for monthly models for the site of the Auger experiment.

A very important quantity for the energy reconstruction is the fluorescence yield. The emitted light is mainly coming from 18 strong emission bands in the 2P system of nitrogen molecules for the wavelength range between 300 and 400 nm and one emission band in the 1N system. It is assumed that the fluorescence yield is proportional to the local energy deposit of an air shower

$$Fl.Yield_{\lambda} = \varepsilon_{\lambda}(p, T) \cdot \frac{\lambda}{hc} \cdot \frac{dE}{dX} \cdot \rho_{air} \left[ \frac{\text{photons}}{\text{m}} \right], \quad (2)$$

where  $\varepsilon_{\lambda}(p, T)$  is the fluorescence efficiency in dependence on air pressure and temperature. Strong efforts in improving laboratory measurements of the main variables of the fluorescence emission are ongoing as well as of theoretical descriptions of the molecular processes. A comparison of current experimental data and calculations for the fluorescence yield is given in Fig. 4 [18]. The yield is given for a 0.85 MeV electron as the exciting particle in US Standard atmosphere conditions at sea level. The uncertainties for individual wavelengths are large. For the overall wavelength region, some of the discrepancies cancel out and the uncertainty for the total fluorescence yield between 300 and 400 nm is about 15 % for air shower applications. However, the wavelength-dependent light transmission coefficients and detector response necessitate a good knowledge of the fluorescence yield of the individual emission bands. A world-wide cooperation of several groups will improve the accuracy of the most important variables linked to nitrogen fluorescence emission in air in the near future [19].



**FIGURE 5.** Primary cosmic ray flux [20]. Shown is a selection of previous measurements [21] together with the data from the Pierre Auger Observatory as presented at the ICRC 2005 [4].

## COSMIC RAY ENERGY SPECTRUM

Based on the data taken with the Pierre Auger Observatory between January 2004 and July 2005, a cosmic ray energy spectrum could be derived [4]. All events with zenith angle between  $0^\circ$  and  $60^\circ$  have been taken into account. The *time average area* of the continuously growing array has been  $660 \text{ km}^2$  which is about 22 % of the final size of the southern part of the experiment. Applying several quality cuts, a full efficiency could be reached above 3 EeV and 3525 events above  $10^{18.5} \text{ eV}$  could be collected by the surface array. The analysis has been performed using the following procedure. Since the surface array could collect much more event data, this higher statistics should be used. The zenith angle correction for these data is done with the *constant intensity cut* method [4]. Without fluorescence data, the energy reconstruction of the surface array events would depend on air shower simulation with its considerable uncertainties arising from different hadronic interaction models. Therefore, the energy is determined from the sub-sample of hybrid events. An energy conversion factor is derived by comparing the reconstructed energy of hybrid events, based on the calorimetric energy measurement with the fluorescence telescopes, with the surface detector signal at 1000 m from the shower core. Finally, the exposure of the growing array is calculated. The estimated energy spectrum can be seen in Fig. 5 together with previous measurements.

Statistics is still limited for the first data taking period and systematic uncertainties are quite large. So, based on that data, no decision can be made about the characteristics of the spectrum in the GZK cutoff region. Whether there is a systematic difference in the energy reconstruction for the fluorescence method and the surface detector method will be subject of detailed investigations. The Pierre Auger Observatory with its hybrid technique intends to resolve this uncertainty together with the investigations of the fluorescence processes.

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