# GAP-97-022, Auger project technical note:* Chemical Composition Studies with a Hybrid Detector

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**Abstract**

The proposed Pierre Auger Observatories for the highest energy cosmic rays will be hybrid systems, employing water Čerenkov ground arrays over-looked by atmospheric fluorescence detectors. The key experimental goals of the project are to determine the arrival direction, energy and primary particle type. This last is by far the most difficult to do, both experimentally, and interpretationally; excessive dependence on uncertain models must be avoided. Preliminary consideration of the problem is outlined in this paper.

## 1 Introduction

The Pierre Auger Project Design Report [1] calls for hybrid instruments employing the two established methods of detecting extremely high energy cosmic rays. Twin observatories will be built in the northern and southern hemispheres each consisting of a ground array of $1600 \times 10$ m$^2$ water Čerenkov tanks arranged in a hexagonal grid with spacing of 1.5 km. The arrays will be overlooked by optical sensors capable of remotely detecting the nitrogen fluorescence light produced by ionizing air shower cascades. Although the

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optical detectors will only function on dark, clear nights, the coincident data set will be crucial for calibrating and understanding the ground array; this will operate continuously providing $14,000$ km$^2$ sr of aperture. The goal of determining primary particle type will benefit particularly from the hybrid data set. Composition parameters extracted from the ground array can be cross-correlated with essentially independent information from the fluorescence device.

## 2 Anatomy of an Air Shower

An incoming cosmic ray particle undergoes an initial interaction in the upper atmosphere; an intense hadronic cascade ensues. At each generation approximately 1/3 of the available energy is transfered to an electromagnetic cascade by the prompt decay of neutral pions. The cascade proceeds until the charged pion energy has degraded to the point where decay to muons dominates over further multiplication ($\approx 20$ GeV); at this point the remaining hadronic energy is "dumped" into muons. The shower particles form a disc moving parallel to the primary cosmic ray direction, and growing in diameter as it moves down through the atmosphere. At ground level, and large core distances ($> 300$ m), the muons have GeV energies, while electromagnetic particles typically have $< 10$ MeV. While the muons propagate with relatively little deflection, the motion of the electromagnetic particles to large core distances can be thought of as a process of "diffusion".

Figure 1 shows a simulated longitudinal profile and lateral distribution of shower particles in an extremely high energy cascade [1]. The cascade is numerically dominated by the electromagnetic particles which grow in number and then decline when the critical energy is passed (50 MeV). The atmospheric depth at which the maximum development occurs is conventionally denoted by $X_{max}$, and expressed in units of g cm$^{-2}$ along the shower axis. A fluorescence detector measures the light given off by excited atmospheric nitrogen, and hence directly observes the longitudinal development of the shower along the intense central core. Fluorescence light is proportional to ionization energy loss, which is in turn approximately proportional to the number of charged particles. The surface array takes a 2-dimensional snapshot of the shower front as it intersects the ground plane. Since the core

[1] All simulation results in this paper were obtained using the Mocca cascade simulation [3] with the Sibyll hadronic interaction model [4].

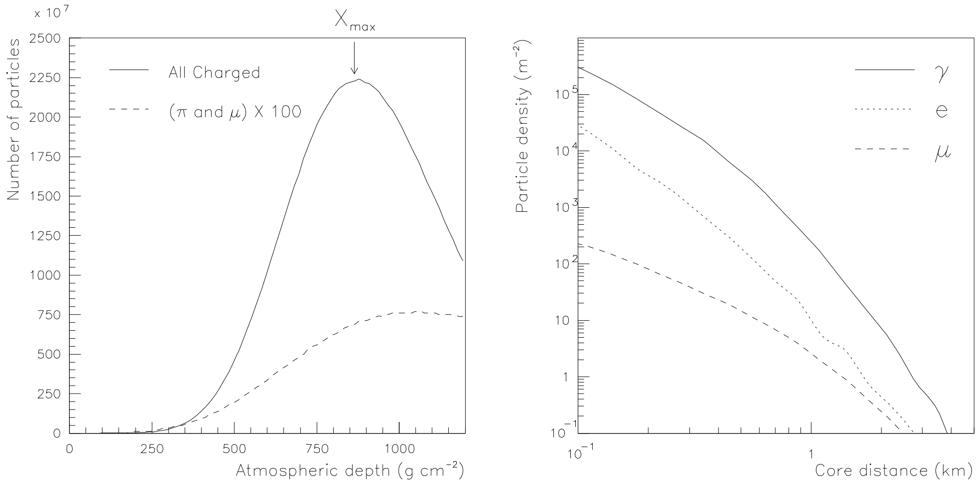


Figure 1: Simulated longitudinal and lateral profiles of a giant air shower. At left the number of charged particles is plotted against atmospheric depth. At right the lateral distribution is plotted for particles reaching ground level. Simulation parameters are $3 \times 10^{19}$ eV proton primary incident at 45 degrees to the zenith.

position is random with respect to the detector grid, in most instances there is no unit close to the shower core; measurements are made at a number of core distances (typically of the order of the array spacing).

# 3 Differences Between Proton and Heavy Nucleus Initiated Showers

The compositional sensitivity of all air shower detectors is inevitably crude since the nature of the primary is inferred in a highly indirect manner through the cascade it initiates. It is standard to discuss the separation power in terms of the ability to tell the difference between proton and iron initiated showers since these represent the limits of the probable candidates in more conventional astrophysical theory. In the final section some comments are made regarding the expected features of events initiated by gamma rays, while neutrino observations through near-horizontal air showers are discussed elsewhere in these proceedings.

As primary energy increases air showers penetrate more deeply into the atmosphere before reaching maximum; more cascade generations are required

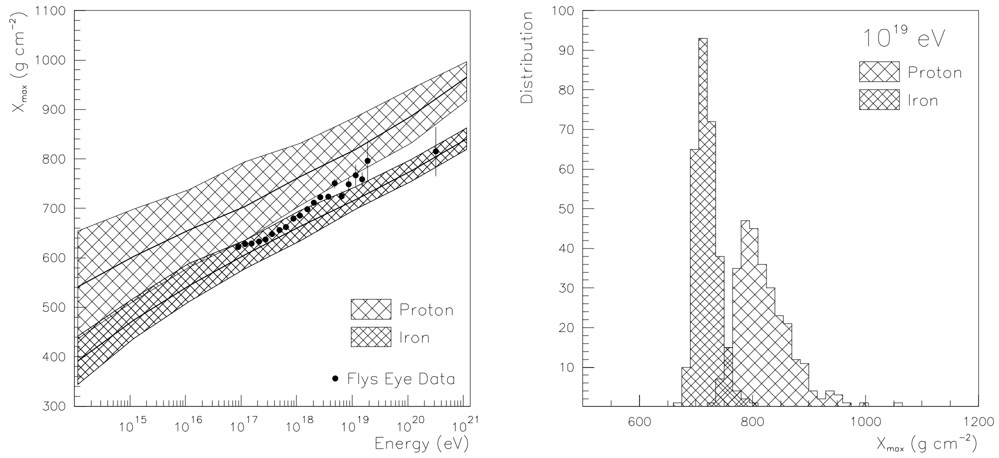


Figure 2: Depth of shower maximum versus primary energy is shown at left, while at right the distributions at $10^{19}$ eV are shown.

to degrade the shower particle energies. Primary nuclei rapidly fragment into their constituent nucleons — to first order this degrades the shower particle energy by a factor equal to the atomic mass $A$. Additionally the mean free path of nuclei is shorter. Hence nucleus initiated cascades *start earlier* and *develop more rapidly* than equivalent proton ones. Figure 2 shows simulated $X_{max}$ values plotted against energy [2]; the bands indicate fluctuations about the mean, and enclose the 10% and 90% points of the distribution. Fluctuations in $X_{max}$ are governed largely by fluctuations in the first interaction point, and hence by the mean free path (mfp) of the primaries. As the mfp falls with increasing energy $X_{max}$ fluctuations also become smaller; similarly fluctuations are smaller for heavy nuclei primaries compared to protons. This is why the $X_{max}$ separation between proton and iron initiated showers becomes more pronounced with increasing energy in figure 2.

Heavy nucleus initiated showers have a higher muon content compared to proton ones. Fewer hadronic cascade generations are required to reach the charged pion decay threshold, and hence a smaller fraction of the total energy is transfered to the electromagnetic channel.

[2] The Fly's Eye data points are taken from [2]; the error bars represent the experimental uncertainty in the mean value, not the spread. Also note that the lower energy points have an uncorrected experimental bias and so are not directly comparable with the simulation.

# 4 Composition Sensitive Observables

## 4.1 Fluorescence Detector

Fluorescence detectors measure $X_{max}$ directly on a shower-by-shower basis — a resolution of 20 g cm$^{-2}$ is expected for the Auger instruments. The Fly's Eye group have published evidence for a changing chemical composition between $10^{17}$ and $10^{19}$ eV based on $X_{max}$ measurements [5]. It should be noted that although the absolute value of $X_{max}$ for a given energy and primary type is model dependent, the *predicted differences between proton and heavy nuclei $X_{max}$ distributions are much more certain.* Hence a broad distribution within an energy band is indicative of a light or mixed composition, while a narrow one is a clear signature of heavy primary dominance; the right part of figure 2 illustrates this.

## 4.2 Ground Array

The most obvious difference between proton and heavy nucleus initiated showers at ground level is the muon to electromagnetic particle ratio. Unfortunately this is not easy to measure with low cost detectors, partly because the muon density is very low at large core distances (requiring large detector areas), and partly because traditional muon detectors use large quantities of shielding material. The Auger water tanks will have some ability to determine the fraction of their total signal coming from muons by exploiting the time dispersion of the shower front at large core distances. The muons have a much higher energy per particle, and hence produce large amplitude Čerenkov pulses. Using a Flash ADC waveform recorder these can be seen against a background of smaller, more numerous pulses from electromagnetic particles.

For the Auger arrays where the footprints of the bulk of events are fully contained within the array boundary the shower front curvature is a measurable parameter. Since a heavy nucleus initiated shower starts higher in the atmosphere the radius of curvature at ground level is greater — the shower front is closer to planar. For geometrical reasons the shower front is also thinner for early developing events, i.e. there is less time dispersion. Hence a so called "rise-time" parameter has been used to obtain composition sensitive information in the past [6], and is particularly effective for water Čerenkov detectors.

As shower particles move down through the atmosphere they spread out from the axis. The lateral density distribution slope is therefore a composition sensitive parameter, since early developing showers have passed through more atmosphere by the time they reach ground level. However, this is a small effect, and very difficult to measure with a sparse array of detectors.

## 5 Other Identification Possibilities

The discussion above is based upon distinguishing proton from heavy nucleus primaries. In the unlikely event that there is a significant fraction of gamma rays in the highest energy flux these will pair produce through interactions with the geomagnetic field at several earth radii. Magnetic bremsstrahlung would then produce a "swarm" of lower energy particles striking the upper atmosphere. The arrival direction of the particle and the LPM effect are important in determining the characteristics of such events [7].

Currently there is evidence for clustering of the highest energy cosmic rays suggestive of "point sources" [8]. If such clustering is confirmed it may become possible to use galactic and extra-galactic magnetic fields as a "magnetic spectrometer" to obtain information about the charge of the incoming particles.

## 6 Conclusions

The Auger Observatories will have compositional sensitivity and, at a minimum, will be able to split their whole data set into heavy-like and light-like fractions (assuming a mixed primary flux). The Hybrid data set, taken when the fluorescence detectors are operational, will allow detailed study and cross-check of composition parameters and is *crucial* to a proper understanding of the instrument. Detailed simulations of experimental data followed by event reconstruction is ongoing.

## Acknowledgments

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