

The Pierre Auger Observatory at 10^{18} eV

Bruce R. Dawson

Physics Department, University of Adelaide, Adelaide SA 5005, Australia

E-mail: `bruce.dawson@adelaide.edu.au`

Abstract. The Pierre Auger Observatory was primarily designed for studying the energy region beyond 10^{19} eV, but a significant aperture, and significant physics, is accessible at energies down to around 10^{18} eV. In this paper we describe the physics studies planned for this region, including a description of the experimental techniques.

1. Introduction

The Pierre Auger Observatory has been collecting data in a routine way since January 2004, while construction of the full array is being completed. The experiment's main focus is understanding the nature and origin of the highest energy cosmic rays, those with energies beyond 10^{19} eV. At these energies the flux is expected to be predominantly extragalactic, and a series of measurements is planned to confirm this and improve our current understanding. Measurements of the primary particle energy spectrum, mass composition and anisotropy, as well as searches for gamma-rays and neutrinos, are either underway or planned.

The Observatory's unique attributes of enormous collecting area, and "hybrid" detectors are designed to overcome both the statistical and systematic uncertainties that have traditionally been part of this difficult experimental area. The combination of an array of water Cherenkov detectors with a series of four fluorescence detectors offers an opportunity to measure cosmic ray air showers with two independent techniques, each with their own strengths and different systematic uncertainties.

The hybrid detector also offers opportunities to push down the observatory energy threshold to around 10^{18} eV, the subject of this paper. This is an energy region with interesting physics, perhaps the region where the galactic sources of cosmic rays lose dominance, and extragalactic sources take over. Auger has plans to study this energy region with the existing infrastructure, and may also "enhance" the observatory with this target in mind.¹

2. The Observatory

The Pierre Auger Observatory is located in the province of Mendoza in Argentina, close to the town of Malargue at the foot of the Andes mountains. On this elevated plain (1400 m.a.s.l.) the collaboration is deploying an array (the "surface detector" or SD) of 1600 water Cherenkov detectors on a 1.5km triangular grid, to cover a total area of 3000 km². Each detector, a 12-tonne tank of water viewed by three photomultiplier tubes, is an autonomous unit, with solar

¹ After this talk was given, the collaboration approved two enhancements - HEAT, an extension to the viewing elevations of FD telescopes at one site; and AMIGA, an infill array of water tanks with additional buried muon detectors. Both have relevance to measurements of the spectrum and composition of lower energy cosmic rays.

power, electronics, GPS clock and data communications hardware in place. The Observatory’s fluorescence detectors (FD) are arranged in four sites, or “eyes”, at positions on the perimeter of the array. Each FD eye consists of 6 Schmidt telescope systems, each with a $30^\circ \times 30^\circ$ field of view, a 2.2 m diameter entrance diaphragm, and a camera consisting of 440 photomultiplier tubes. The SD detects air shower particles at ground level 24 hours per day, and the FD operates during dark nights and detects nitrogen fluorescence light from air showers as they propagate through the atmosphere. The observatory is designed such that both the FD and SD are fully efficient at detecting 10^{19} eV showers over the entire 3000 km^2 area of the array. The efficiency is smaller at lower energies, but still large and useful, as we will discuss.

As of September 2006 the Observatory had 990 of the 1600 SD tanks and three of the four FD eyes in operation. Construction will be completed at the end of 2007. At the time of writing, the integrated exposure ($\text{m}^2 \text{ s sr}$) of the SD is already three times that of the AGASA experiment.

3. Physics Motivation around 10^{18} eV

There is a general, though not unanimous, consensus that cosmic rays with energies around the knee of the energy spectrum (10^{15} - 10^{16} eV) originate within the Milky Way, while those at the highest energies are extragalactic. We believe we know of galactic sources (supernovae) capable of accelerating particles to knee-energies and somewhat higher [?], but we struggle to identify more powerful sources within the galaxy for the highest energy particles. No strong galactic anisotropy has ever been observed. This is understandable at knee-energies because of the known galactic magnetic fields, but it does also seem to suggest that the sources of the highest energy particles are elsewhere in the nearby Universe.

Results from the successful KASCADE experiment [?] show that the spectral knee is probably composed of a series of knees associated with different mass components of the cosmic ray flux. This is observed for lower mass components, with hints of similar behaviour at higher masses. One interpretation is that there is rigidity-dependent escape of cosmic rays from either the acceleration source, or the galaxy, and this leads to the spectral knee. As a result, the average cosmic ray mass increases with increasing energy through the knee.

Several scenarios are possible for the transition from galactic sources to extragalactic sources, and some have particular predictions for the shape of the spectrum, and the average mass of particles through the transition region. Several of these possibilities have been explored by Hillas (eg [?]) and Berezhinsky and collaborators [?]. An important energy region is between $10^{17} - 10^{18.5}$ eV. The details of the spectrum and mass composition in this region could be important in discriminating between models of the transition. Data exists in this region, but results on mass composition (for example) are not yet conclusive [?].

Specific experiments are being built to explore this energy range with better sensitivity than in the past (eg KASCADE-Grande), but Auger also has some capability in the region, with improvements planned in the near future.

4. “Low” energy apertures of Auger components

The key to an Auger aperture at the relatively low energies around 10^{18} eV is an efficient and noise-free trigger in the surface detector tanks. In the surface detector alone, this can provide significant aperture at 10^{18} eV with three-tank triggers. Coupled with the fluorescence detector, hybrid triggers (1 tank + one fluorescence eye) are achievable at even lower energies.

The SD trigger system is described in detail in [?]. There are various levels of trigger, but in the context of the low energy aperture the most important is the local tank trigger known as the T2. This itself is an OR condition between two possible triggers. The “threshold” trigger requires each of the three PMTs in a tank to observe a signal above 3.2VEM in a particular 25ns time bin, where 1 VEM, or “vertical equivalent muon”, is the signal observed for a vertical muon traversing the tank. The other possible trigger is known as the “time over threshold”

or ToT trigger, and it requires 13 bins in a 120 bin ($3\mu\text{s}$) window to be above 0.2 VEM in at least 2 PMTs. The “threshold trigger” is required for sensitivity to fast ($< 200\text{ ns}$) signals expected from inclined showers where only the prompt muons have survived. This trigger makes up the bulk of the 20Hz T2 rate from a tank, and is mostly noise. In contrast, the ToT trigger contributes about 1.6Hz to the T2 rate, most of it from real showers. It is the trigger most relevant to the low energy aperture.

The single tank T2 triggers are sent to the central data acquisition system where real-time higher level triggers are formed, either between tanks, or between tanks and fluorescence detectors. Later, offline checks of the physical characteristics of triggers are performed, resulting in two common forms of the so-called T4 trigger. The 3ToT trigger requires a compact arrangement of 3 tanks with ToT triggers; the 4C1 trigger requires a compact combination of 4 tanks with any T2 trigger condition (details in [?]).

In Figure ?? we show characteristics of these two types of array T4 trigger. The 3ToT triggers are the most numerous and extend to low energies. The 4C1 triggers are important for the inclined showers with tight shower front structure.

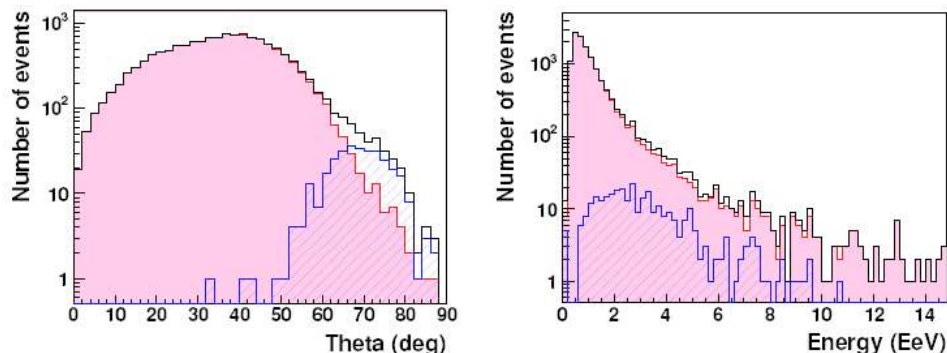


Figure 1. Characteristics of SD array T4 triggers, in terms of the shower zenith angle (left) and energy (right)[?]. Pink shaded areas represent 3ToT triggers; blue shaded areas for 4C1 triggers. Showers satisfying both trigger criteria are included in the 3ToT histograms.

Simulations of the trigger have resulted in the SD aperture curves shown in Figure ?. We see that requiring a 3ToT trigger gives full triggering efficiency across the array at an energy of $3 \times 10^{18}\text{eV}$, while requiring 4 tanks with ToT sets the threshold at $7 \times 10^{18}\text{eV}$. Note that the aperture in the turn-on region is mass-dependent. In principle this undesirable feature could be used to study mass composition around 10^{18}eV , provided that simulations and the detector were well understood. Other mass composition sensitivity is present in this low energy region, for example in the signal rise-time at a fixed distance from the core, as demonstrated in [?].

Turning to the hybrid aperture, we note that only one triggered SD tank is required to provide a constraint on the FD reconstruction of the shower geometry, an important step in deriving good FD estimates of energy and mass. The single-tank energy threshold is clearly lower than the energy required to trigger three tanks. This is illustrated in Figure ??, where the hybrid triggering aperture is shown for a particular time (October 2004) in the evolution of the detector. The hybrid aperture is determined largely by the FD triggering efficiency, since the single tank SD threshold is so low in energy. Thus, high quality hybrid data is available below 10^{18}eV . Mass composition biases exist in this low energy region for both the SD and FD, and so care must be taken.

The angular resolution of the SD detector alone has been studied using hybrid events [?] (given the superior hybrid angular resolution of about 0.5°). It is found that acceptable resolution

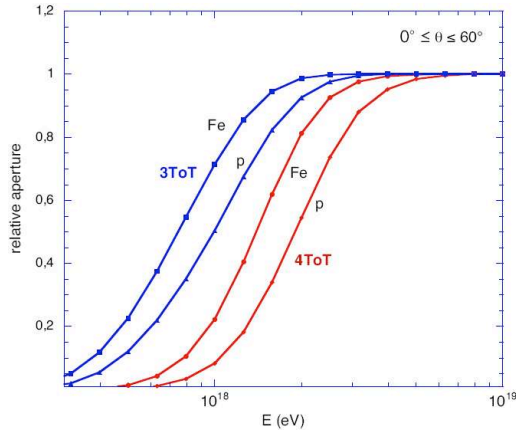


Figure 2. Relative aperture of the SD array as a function of energy for 3 and 4 tank ToT triggers. The aperture in the turn-on region is mass dependent[?].

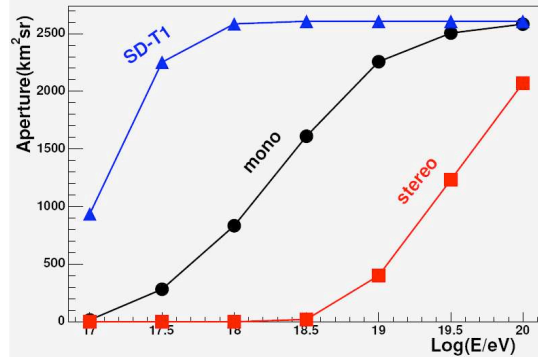


Figure 3. Hybrid trigger aperture as of October 2004 for single and multiple-eye triggers. The SD line shows the efficiency for a single-tank trigger [?].

is achieved even for the low-energy 3 tank events. The angular resolution (the space angle containing 68% of the 3D probability distribution) is better than 2.2° , improving to 1.7° for 4 tank events (energies of 3-10 EeV) and 1.4° for energies above 8 EeV. Studies of the SD energy resolution at these and higher energies is in progress. For those events seen by the hybrid detectors, good quality angular and energy resolution is expected at energies at and below 10^{18} eV. Angular resolution of 0.5° is accompanied by statistical energy resolution of 10-15% and resolution in depth of maximum (X_{\max}) of about 40 g/cm^2 [?].

5. “Low” Energy Physics Studies - existing and in the future

The most important “low” energy study undertaken so far by Auger has been the investigation of anisotropy claims around the Galactic Centre at energies around 10^{18} eV [?]. Despite much improved statistics compared with the AGASA and SUGAR analyses, no excesses were observed.

In progress is the study of mass composition using hybrid data and the depth of maximum, X_{\max} . It is hoped that the energy range will extend from around $10^{17.5}$ eV to beyond 10^{19} eV in this first analysis. Care is being taken in understanding the triggering biases present in the experiment, including those related to the limited field of view (elevation range 2° to 30°) of the FD telescopes. Composition analyses of SD data will certainly follow.

The main focus of Auger will continue to be the highest energy particles, but there is also considerable interest in the physics at around 10^{18} eV and below. Work is continuing to exploit the low energy aperture that we have for “free”, while work is beginning on the low-energy Auger enhancements (AMIGA and HEAT), mentioned in the footnote on page 1 of this article.

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