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Acceptance and Angular Resolution of an Infill Array for the Pierre Auger Surface Detector

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Abstract. The Pierre Auger Observatory has been designed to study the highest-energy cosmic rays in nature ($E \geq 10^{19}$ eV). The determination of their arrival direction, energy and composition is performed by the analysis of the atmospheric showers they produce. The Auger Surface Array will consist of 1600 water Cerenkov detectors placed in an equilateral triangular grid of 1.5 km. In this paper we show how adding a "small" area of surface detectors at half the above mentioned spacing would make it possible to lower the detection threshold by one order of magnitude, thus allowing the Observatory to reach lower energies where the cross-over from galactic to extragalactic sources is expected. We also analyze the angular resolution that can be attained with such an infill array.

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1. Introduction

Cosmic rays are observed in a wide range of energies spanning more than eleven decades, from energies below 1 GeV up to more than 10^{20} eV. Up to the so-called knee ($\sim 10^{15}$ eV), the energy spectrum follows a simple power law with an exponent equal to -2.7, consistent with galactic supernova acceleration of charged nuclei. Above the knee the composition becomes heavier and the slope becomes steeper, with a spectral index of -3.1, as lighter nuclei with large rigidity cannot be efficiently accelerated by supernova remnants anymore. Above a few times 10^{17} eV,

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the spectrum shows at least two additional features: the second knee and the ankle (see Fig. [1]).

The second knee, where a second steepening brings the spectral slope to -3.3, has been observed in the vicinity of 4×10^{17} eV by Akeno [1], Fly's Eye stereo [3,4], Yakutsk [2] and HiRes [7]. The physical interpretation of this spectral feature is uncertain at present. The ankle, on the other hand, is a broader feature that has been observed by Fly's Eye [3,4] around 3×10^{18} eV as well as by Haverah Park [5] at approximately the same energy. These results have been confirmed by Yakutsk [2] and HiRes [7]. AGASA also observed the ankle, but they locate it at higher energy, around 10^{19} eV [6]. More than one physical interpretations are possible, and they are all intimately related with the nature of the second knee. The ankle may be the transition region between the galactic and extragalactic components, the result of pair creation by protons in the cosmic microwave background [12], or the result of diffusive propagation of extragalactic nuclei through cosmic magnetic fields [11].

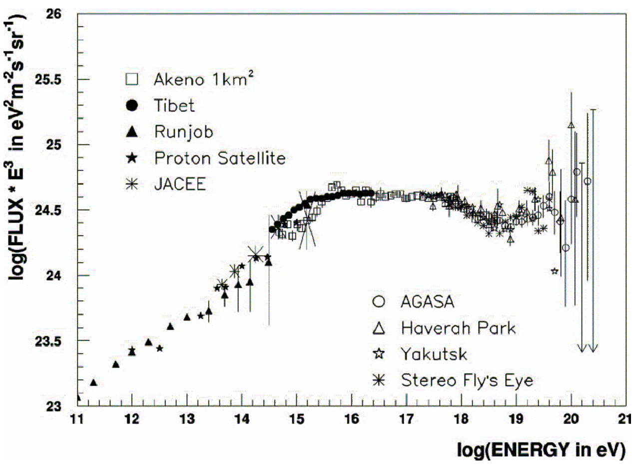

Fig. 1. Compilation of all particle cosmic ray spectrum showing its main features: the knee, the second knee and the ankle. Extracted from Ref. [18].

Clues for understanding the origin of these features can be found in the observed changes in composition along this energy region. From the KASCADE experiment [17], it is established that the cosmic ray composition is heavy, probably iron dominated, at 10^{17} eV. From there upwards in energy, there are strong evidences that it changes back to a lighter composition [8], although it is disputed what the actual rate of change is, and what the average mass is at, say, 10^{19} eV [9]. In order to pinpoint the correct model, both a reliable, high quality spectrum with a well calibrated absolute energy and a detailed composition study are required.

As of today, the forefront experiment in the ultra-high energy cosmic ray arena is the Auger South Observatory in Malargue [10]. Although Auger is able to reconstruct events with energies as low as 10^{18} eV, and is fully efficient above 3×10^{18} eV [22], this experiment has been optimized for the highest energies, i.e., above 10^{19} eV. On the lower side of this regime, Kascade-Grande is expected to operate up to 10^{18} eV, but with very good statistics and energy resolution up to only a few times 10^{17} eV.

In this note we analyze how an upgrade of the Pierre Auger Observatory could bridge the gap in the spectrum between the aforementioned experiments, extending their coverage to this scientifically interesting energy region. Such an upgrade, consisting of an "infill" of surface detectors at smaller spacing, can be achieved with small additional effort and at a relatively low cost. This infill array needs to cover a much smaller area than Auger due to the much higher flux at low energies.

We present the results of our calculation of the acceptance for different infill configurations, with the objective of finding an optimum layout. As a first step towards the characterization of such an infill array, we also calculate, by means of shower and detector response simulations, the angular resolution that can be achieved for different detector spacings.

Although extremely high energy particles originating in Galactic sources are unlikely, particles in the energy range from few times 10^{17} eV to few times 10^{18} eV cannot be discarded either as a result of acceleration [16] or trapping of the extragalactic component and subsequent p-p and p-γ neutron production [13]. Observing the Galactic Center in this energy range with high statistics and high angular accuracy is necessary to validate or discard these models. The Auger Observatory, located in the Southern Hemisphere and with full view of the Galactic Center, is the ideal experiment for this task.

2. Tools

We generated a library of extensive air showers using the Monte Carlo simulation code Aires 2.6.0 [19]. Two types of primaries (proton and iron) were considered, arriving with three characteristic zenith angles: $0°$, $30°$ and $45°$ and with five different energies: $10^{17.5}$ eV, $10^{17.75}$ eV, 10^{18} eV, $10^{18.25}$ eV and $10^{18.5}$ eV. For each energy, zenith angle and primary composition, 50 showers were simulated with a uniform azimuthal distribution. Each of these showers was injected randomly five times on a triangular array of 37 Auger-like surface detectors, with a spacing of 1500 m between detectors, thus covering an area of 52 km^2. By adding detectors to this array, new triangular arrays can be formed with (a) 866 m, (b) 750 m and (c) 433 m spacing between neighbouring detectors.

The response of these arrays was simulated using the code SDSim (v3r0) [20]. The same trigger algorithm and threshold levels of Auger surface detectors were used[15]. The energy, arrival direction and lateral distribution of the incoming shower were reconstructed for each event using the standard Auger reconstruction package (CDAS Er v4r2)[21].

3. Results

3.1. Trigger Efficiency and Acceptance

The acceptance of the different arrays was calculated using the trigger probability as described in [15]. From the simulated events that trigger at least 4 detectors, a lateral distribution function (LDF) is adjusted to the signals recorded in the detectors. Then the trigger probability $P(S)$ is obtained, as a function of the signal S expected from the LDF at each detector. Given this probability, the array trigger efficiency can be obtained as a function of zenith angle, core position and energy. The acceptance is then calculated by integrating over core position and solid angle and taking into account the efficiency. Fig. [2] shows the relative acceptance for proton (open symbols) and iron (full symbols) primaries and for different detector spacings.

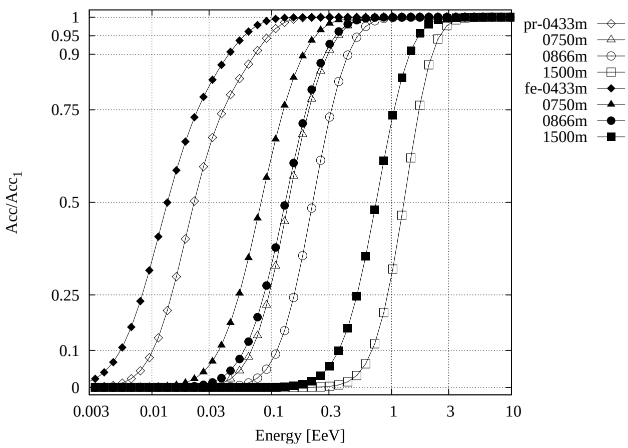

Fig. 2. Relative Acceptance for different infill configurations, for proton (*open symbols*) and iron (*full symbols*) primaries.

Fig. [2] shows that an array with a separation of 750 m between detectors allows the detection of showers of 0.36 EeV with a 95% efficiency, thus lowering the detection threshold of the original Auger array (1500 m spacing) by nearly one order of magnitude.

3.2. *Angular Resolution*

Understanding the angular resolution of a detector is fundamental for the study of arrival directions and the understanding of eventual anisotropies that might be detected in the data. We define the resolution as the 3-dimensional angle α between the real ($\hat{R}_{real}$) and reconstructed ($\hat{R}_{rec}$) arrival directions, given by:

$$\sin\alpha = \|\hat{R}_{rec} \times \hat{R}_{real}\| \tag{1}$$

Fig. [3] shows the dependence on detector spacing of the 68% CL value of α's distribution for different shower energies, for iron (left) and proton (right) primaries. Note that for the energy of interest in anisotropy studies related to the Galactic Center ($\sim 10^{18}$ eV), the angular resolution for events detected by an infill array of half the Auger spacing will be 2 times better, with values close to 1^o both for proton and iron.

The number of showers detected by the array with the larger spacing (1500 m) at the lowest simulated energy (0.32×10^{18} eV) is too small, severely limiting their statistical significance. Therefore, these results are not shown.

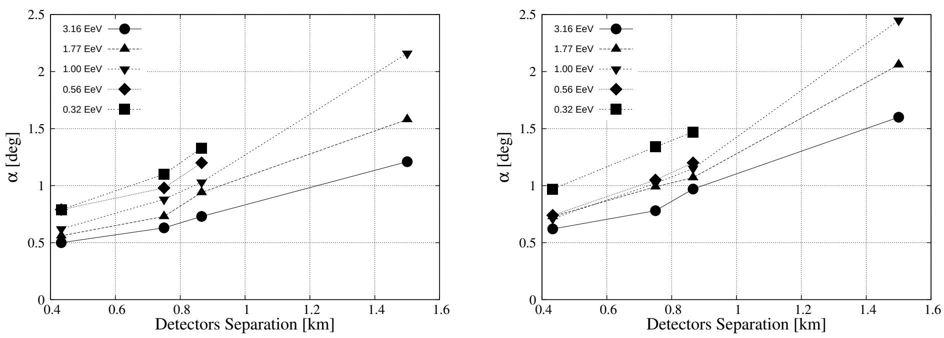

Fig. 3. 3D angle as function of detector spacings for iron (*left*) and proton (*right*).

In Figure [4] we present the 68% confidence level for the arrival direction reconstruction error, α, as a function of the mean number of triggered stations for proton and iron primaries. As expected, as the average number of stations participating in the reconstruction chain increases, the resolution on the arrival direction is proportionally better. The values of α corresponding to 3, 4 and 5 stations are in good agreement with the empirical results for the Auger surface array detector [23].

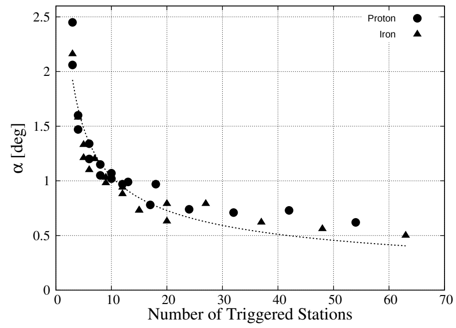

Fig. 4. 3D angle as function of the mean number of triggered stations for proton (*circles*) and iron (*triangles*).

4. Conclusions

By performing full simulations both of the shower development and the detector response, we show that upgrading the Pierre Auger Observatory by embedding a set of additional detectors in a small area of the full observatory could reduce in one order of magnitude the energy detection threshold, greatly expanding the scientific scope of the original experiment. In particular, an infill array forming a triangular grid of detectors with a spacing of 750 m would allow an independent determination of the spectrum and an assessment of the corresponding composition evolution in the astrophysically interesting region of 3×10^{17} to 3×10^{18} eV.

Additionally, such infill array would also allow a better characterization of the main Auger surface detector, since individual events could be independently reconstructed with two non-overlapping sets of triggered detectors. The data coming from an infill array would also serve to further validate the end-to-end simulation and reconstruction processes. There is work in progress suggesting that both the shower core position and the energy are significantly better reconstructed with an infill array.

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