Pierre Auger Observatory: status and prospects

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The Pierre Auger Observatory is the next generation ground based cosmic ray detector fully devoted to the study of the ultra-high energy cosmic rays (UHECR) with energies above 10^{19} eV. Cosmic rays in this energy range were the main topic of this international workshop where many pending questions on their nature and origin were emphasized. The Auger Observatory, with its unique features (unprecented statistical power, hybrid detection possibilities, full sky aperture, excellent sensitivity for all zenith angles...), will bring in a decisive step, if not definitive answers, in the understanding of one of the most puzzling phenomena of modern astrophysics.

KEYWORDS: Cosmic rays, ultra high energies, ground arrays

§1. Introduction

A few years ago, it became obvious to the community working in the fields of high energy astrophysics and cosmic rays that the ultra-high energy cosmic ray puzzle called for a new generation of detectors. The fact that there is such a puzzle was the object of the present ICRR workshop. In the following, we shall try to give a compact description of the first next-generation experiment, the Auger Observatory.

For its designers and builders, the Auger Observatory is the ideal (and for the time being, unique) tool to unveil (conclusively?) the mystery of the origin and/or nature of the UHECR. Let us give a few arguments in favour of such a presumptious statement. When completed, i.e. with a site in each hemisphere, the Observatory can be considered as a single detector having a full sky coverage, an almost compulsory feature to be able to study weak anisotropies (e.g. for sources accumulating in the galactic halo). The detector is “hybrid”, meaning that some 10% of the events will be observed both with a ground array and a fluorescence telescopeThis article will be restricted to the parameters and performances of the ground array. The optical component of the Obsevatory (the Fluorescence Detector) and its hybrid aspects are treated by Paul Sommers in these proceedings.. This unique feature improves the detector’s performance in many aspects: cross-calibration of the two components, improving the energy and angular resolution; two independent methods for the reconstruction of the air-shower (and hence a weaker dependence on models used for simulation); an increased number of observables related to the incident cosmic ray’s nature, therefore a stronger lever to study the chemical composition (e.g. by a multi-dimensional analysis), etc. The use of Cherenkov tanks rather than scintillators for the ground array increases the angular acceptance to values much larger than the usual 60°. Actually, showers with zenith angles up to 90° can be detected, although with poorly estimated energies. The specific case of tau neutrinos and angles even larger than 90° is mentioned in section 4.4[1)]). This allows the opening of a new window for UHE neutrino astronomy, in an energy range where the Earth becomes opaque to neutrinos and makes life harder for underwater or under-ice neutrino telescopes. Finally, maybe the most important performance needed for this physics is the necessary statistical power. Large statistics are needed for good spectrum reconstruction (a necessary indicator of the operating production mechanism), anisotropy studies and chemical composition studies. The complete Auger observatory, with its two sites, will have an aperture of more than 14,000 km^{2}sr, nearly two orders of magnitude above the largest operating ground array (AGASA) and 15 to 40 times that of the most powerful existing fluorescence detector (HiRes).

§2. Brief history of the Auger Observatory

The idea of having a detector with the largest possible aperture to yield the largest statistics is indeed straight-

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forward. The delicate step was to design a detector with the optimum combination of four parameters: statistical power; optimization in the appropriate energy range; technical feasibility; acceptable cost. From these derive all the other constraints.

The first steps towards the actual Auger detector design germinated in the minds of the two present Auger spokespersons, James W. Cronin and Alan A. Watson in 1991, during the International Cosmic Ray Conference in Dublin. Quite soon, they became convinced that aiming for a ground array of 5000 km^2 was the right direction to explore. The appropriate, although ugly, acronym P5000 was then temporarily coined for the project. Another transient name was envisaged later when the "hybrid" option was decided. The geometry of an hexagonal ground array with one (Fly's) Eye (fluorescence telescope) in the middle generated the name of "Cyclops" for the detector. Cronin and Watson came finally with the proposal that rather than using complicated acronyms one could just give credit to the pioneer of the discovery of giant air-showers$^{2)}$ (in the late thirties), the french physicist Pierre Auger. Transforming the name into an acronym such as "A Unique Giant Eas Recorder" was rejected. Therefore the right spelling for the Observatory's name is Auger and not AUGER.

In April 1992, an international workshop titled "Techniques to Study Cosmic Rays with Energies Greater than 10^{19} eV" was held in Paris at the Jussieu Campus.$^{3)}$ This workshop can no doubt be considered as the collective starting point of the Auger project. The aim of the workshop was multifold: to review the experimental situation in the field, to overview the theoretical motivations and to come up with any idea, however crazy, which could possibly be of use in the design of a future detector. More than nine years later, while the Auger teams are starting the installation of the first elements of the detector in the Argentine Pampa, it is interesting to note that many of the ideas envisaged then are still the baseline parameters of the detector. Many decisive steps in the progress of the project followed, the most important ones being the six-month working group meetings at Fermilab in 1995 (from which conclusions are recorded in the 250 page Design Report) and the two collaboration meetings in 1995 and 1996 where the (respectively southern and northern) sites were chosen. It is during the "working group" period that the main important options were defined, namely the use of the Cherenkov tanks rather than scintillators or resistive plate counters, the hybrid concept, and the splitting of the array in two sites so as to have a full sky coverage.

§3. Main parameters of the Ground Array

The full Auger Observatory will consist in two sites of 3000 km^2 each. The ground array stations are to be distributed with a regular spacing of 1.5 km between each over sites whose shape -initially supposed to be hexagonal- has to be adapted to the undulations and access conditions of the field. The two sites were chosen on the basis of a list of specifications of which the most important were the size (and flatness of the landscape for easier hertzian communication), the latitude (between 35 and 40° North and South for optimum sky coverage), the altitude (around 1400 m, an altitude close to the shower maximum for a vertical shower to minimize statistical fluctuations), dry atmosphere, clear skies and low light pollution for the optical component (and partly for the solar power). After two years of prospecting entrusted to a team of two young physicists (K.Gibbs and A.Letessier-Selvon) and visits to some 15 sites, the choice was the following. Northern site: Millard County, Utah, USA (39.1° N and 112.6° W); southern site: Malargüe, Mendoza, Argentina (35.2° N and 69.2° W). A prototype observatory called the engineering array (EA) is already built on the southern site (see below).

Detector stations. Each surface detector is a 3.6 m diameter, 1.2 m high roto-molded plastic tank, filled with filtered and de-ionized water. The internal walls of the tank are lined with a highly reflecting and diffusing material (Tyvek). The charged particles (mainly electrons - including those from Compton scattering and photon conversion - and muons) produce Cherenkov light in the water that is detected by three phototubes installed on the top of the tank. The phototubes tested on the EA are 8" and 9" in diameter and produced by three different firms: Photonis XP1802, Hamamatsu R5912 and ETL 9354. The reference signal is that produced by a muon crossing the full height of the water column (therefore called vertical equivalent muon or v.e.m.) and is typically about 90 photo-electrons when the signals from the three PMs are summed.

Solar power. The possibility of powering the ground array by industrial electricity was envisaged and abandoned on the basis of excessive extra cost for the project (a likely increase of 50%). Therefore, and very early in the development of the project, the use of solar power was decided, with the inevitable conclusion that there would be a very strict power consumption budget. The somewhat arbitrarily fixed 10 watts for the whole electronics is still the baseline value now. There are two 12 volt 100 Ah battery units per station. They are powered by two 12 V nominal solar panels (actually providing 17 volts each) operating in series to produce 24 V. Each panel has a power rating of about 50 Wp after 20 yearsWp is the industry designation for a power output with a standard illumination, with a warrantee that reflects this 20 year lifetime.

Detector electronics. Each detector station includes a slow control board the role of which is to monitor the relevant physical parameters: phototube high voltage and currents, temperatures from several parts of the station, battery voltage and currents, cloud detectors, atmospheric pressure, slow control board voltages. The sensors are read through a 12 bit ADC. Two inputs are left free for unforeseen use. In the EA phase, the full monitoring data are sent to the Central Data Acquisition System (CDAS). With the full detector, these may be pre-processed locally and only averages and warnings sent to CDAS if the deviations are in excess of pre-loaded values.

The electronics and gains of the phototubes are designed so that one can collect signals as close and as far as possible from the shower core (e.g. from 1 to 10^5 pho-

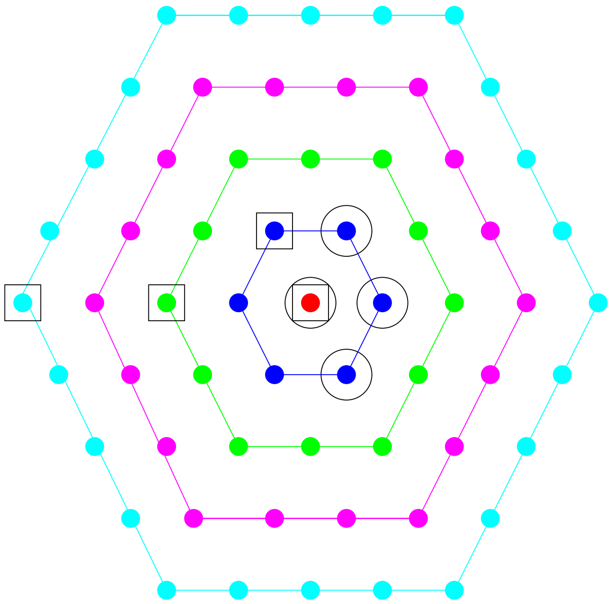

Fig. 1. The four concentric hexagons around a central station. A T3 trigger is generated if two T2s are found in the first two hexagons in time with the T2 from the center, plus an additional one in any of the four hexagons. The circles and squares show two different T3 geometries.

toelectrons in a 25 ns time slot) without requiring a too sophisticated system. The linear gain range of the PMs is required to be $10^5 - 10^6$ (with an operational value of 2×10^5). Each of the three PMs has two outputs, one (with a low gain amplification) from the anode, another (with a high gain amplification) from the last dynode. The outputs are read with six 10-bit flash-ADCs cycling with a frequency of 40 MHz. The dynamic range thus obtained is 15 bits (taking into account an overlap between the two ranges). This allows data at distances from the core of the expected highest energy showers in the range of 500 m to several kilometers to be recorded.

The *physics trigger* is actually a set of patterns of detector stations in which a pre-defined amount of energy is deposited within a pre-defined time window. There are three levels of on-line triggers. The first level trigger (T1) is a hardware trigger generated by the front-end electronics (ASIC), an alert saying that the tank has seen a signal above the background threshold defined so that the rate is less than 100 s^{-1}. The second level (software) T2 trigger is built by the station controller. It is generated whenever the energy deposit/time combination exceeds preset values: either a large amount of energy in a short time or a smaller amount of energy (typically the equivalent of 4 vertical muons crossing the tank) over a larger time window. The T2 trigger rate is constrained to remain below 20 s^{-1}. The corresponding data (FADC traces) are stored into local buffers and a short information on the address, the time stamp and the total amplitude is sent to CDAS. The central trigger system then checks if there are several neighbouring tanks having sent T2 signals “in time”. Neighbours of a given station include tanks belonging to the four “hexagons” surrounding the station. *In time* means time windows ranging from 5 μs to larger values depending on the number of hexagons considered. Fig.1 shows the geometry of the four hexagons around a station where a T2 signal was emitted, together with two patterns that would generate a central third level trigger (T3). If a T3 is found, all these tanks are requested to send the contents of their buffers to CDAS. The maximum rate of T3 triggers is expected to be 0.02 s^{-1} and is mainly limited by the telecom bandwidth. Data collecting from the stations can also be triggered by an external signal. The external message may be that of the Fluorescence Detector (FD) whose 3rd level trigger is used to promote T2 signals from the tanks whose positions are close to the shower core as calculated on-line by the FD software. It is also envisaged that the T2 information from the full array will be collected on reception of a message broadcast by satellites observing gamma-ray bursts.

With such a trigger system, the efficiency of the ground array is 0:30:98% for energies of 1:3:10 EeV and showers with zenith angles smaller than 45°. For angles larger than 60°, the efficiency at the intermediate value of 3 EeV improves significantly (50% to 80% for angles going from 70° to 80°).

Communications. Data from the detector stations are transferred to the CDAS in a two-step process. The first step is the communication between the local stations and base station units (BSU) installed on collector towers situated near the FD buildings (in principle, four of them). The available ISM bandwidth is 1.2 kbps per station which is well adapted to the T2 trigger rate (24 bits per event and 20 events per second and per station). The BSUs then transfer the data through a microwave link, each link with a data flow capacity of 2 Mbps. The CDAS interface to the microwave links, called the Post-Master, can deal with a rate of about 2 Mbps coming from the full array. The physics events are typically 5 kB data blocks. Therefore, the total amount of data expected to be recorded at the central station should be less than 150 MB/day, including calibration data (about two-thirds of the total). These values are all for the full array and do not include the FD.

A satellite Internet link will transfer daily all data to a series of mirror sites where the analysis will take place. For the EA period, a 128 kbps satellite link (IMPSAT) connects the Malargüe site to Buenos-Aires and then the data is sent to Fermilab via the Florida International University through optical fibers. Finally the other mirror sites are served by Fermilab through the high-energy physics networks.

§4. Global performance of the ground array

4.1 Aperture

Based on a total area of 3000 km^2, the aperture of the Auger ground array is (for one site) 7350 $km^2 sr$, when we take 60° as the maximum zenith angle. Since, as was stated in the introduction, a Cherenkov tank is sensitive to particles penetrating its volume at any angle, the value given here can be considered as a lower limit. However, one should keep in mind that showers with very large zenith angles will be difficult to fully analyze in a model independent way (see below).

4.2 Energy resolution

Below 60°, the energy resolution is weakly dependent on the energy and zenith angle. As the energy increases from 10 to 100 EeV or more, its rms value is expected to slightly improve from 12 to 10% or lessTo be strict, this error does not include part of the systematic errors coming e.g. from the shower model adopted.. This result is almost independent on the nature of the primary particle, with slightly better resolution for showers generated by heavy nuclei because of smaller shower-to-shower fluctuations. At larger zenith angles, the electromagnetic component of the shower is more or less totally absorbed and for the energy measurement one has to rely mainly on the lateral distribution function for penetrating muons. Therefore, in this range we expect the reconstruction to be more strongly model-dependent, and the systematic errors to dominate.

4.3 Angular resolution

The measurement of the incident cosmic ray's angle is made by fitting an adapted curve to the shower front (in most cases a simple plane is sufficient) reconstructed from the arrival time of the particles on the array stations. This of course is a totally model-independent measure, and the precision on the angles depends on a few parameters: the number of stations hit by the shower front particles i.e. the projection of the front on the ground (which depend on the zenith angle and the primary energy); the fluctuations on the arrival time of the particles (therefore the thickness of the shower front); the precision on the *relative* synchronization of the detector stations (the interpolated and corrected GPS pps). The average angular resolutionAll the values given here for the angular resolution mean the uncertainty which contains 68% of all events. for a hadronic shower at 30° for all energies in the detector's optimum energy range (> 10 EeV) is about 1°. This is obtained with a timing precision of about 15 ns (GPS pps interpolated with a 100 MHz clock). This resolution improves with the energy (0.5° at the same angle above 100 EeV), and with the incident angle (0.3° at $\theta = 80°$, all energies).

For gamma induced showers (if there are any at these energies) the situation is somewhat more complicated. For photons unconverted in the geomagnetic field (see next section for details) the resolution will clearly be worse: e.g. 3° at $\theta = 30°$.

4.4 Composition analysis

The number of known stable particles that can propagate over large distances and then be detected on earth are quite limited in numbers: nuclei (heavy or light, with special emphasis on protons), photons and neutrinos. In the search for a solution to the UHECR puzzle, several authors invoke exotic particles or interactions (meaning not yet established with experimental evidence). Such models are called for mechanisms which would violate the GZK cutoff. Examples are: neutrinos whose cross-sections on nuclei are substantially increased by graviton exchanging interactions;4) massive stable new particles (e.g. a baryonic state bound by a light gluino5)) with a mass larger than the proton, hence moving the GZK threshold to higher energies; vortons6) (stable, superconducting cosmic string loops); magnetic monopoles,7) and so on. Here we shall limit our comments to standard particles and interactions.

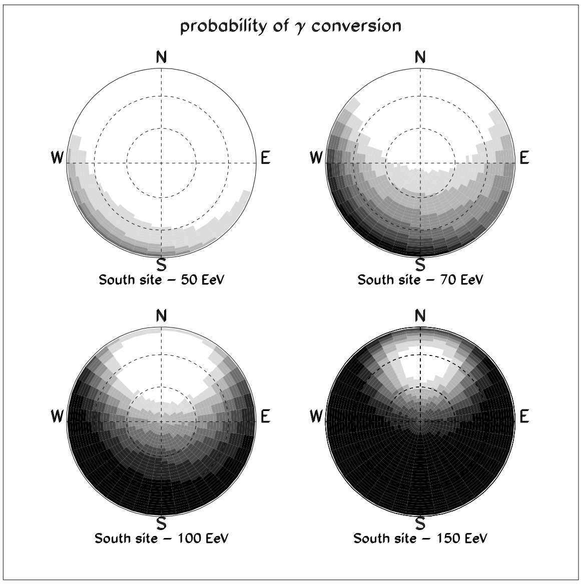

Fig. 2. Photon conversion probabilities as a function of the direction in the earth's frame of reference as seen from the southern Auger site.9) The conversion probabilities range from 100% (black areas) to 0% (white zones).

Different particles leave different fingerprints on the EAS parameters. Two such parameters are the position of the shower maximum $X_{\max}$ and the relative muon content of the shower at ground level (which of course depends on the slant-depth $X = X_0/\cos\theta$ where X_0 is the vertical atmospheric depth at the altitude of the detector). The shower maximum can be measured directly by the fluorescence detector. Only the ground array can measure (to some extent and at large distances from the shower core) the muon content by the analysis of the the flash-ADC traces. Other indicators such as the shower front curvature, rise time of the signal detected by the array stations, steepness of the lateral distribution functions (LDF) are parameters to use in a multidimensional analysis of the nature of the primary cosmic ray. However, all simulation and reconstruction studies show that the discrimination between heavy and light nuclei (the most likely ones to be found in the incident samples being iron nuclei and protons) will be possible only on a statistical basis. This is due to physics: the depth at which the shower maximum occurs (and the parameters which derive from it and are measured by the ground array) is a strongly fluctuating parameter and its values, even for extreme cases such as protons and iron nuclei, have such an overlap that only their average over large numbers will be distinguishable.

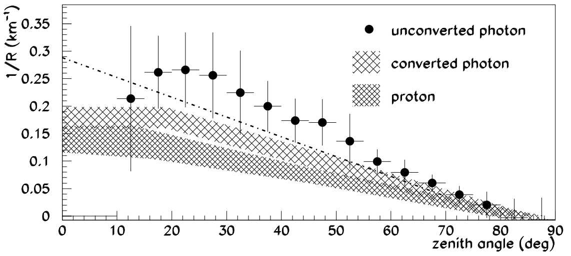

Fig. 3. Shower-front curvature as a function of the zenith angle for photons and protons.[9)]

The situation improves dramatically for gammas and neutrinos, strong signatures of exotic processes (top-down mechanisms) if found in large proportions at extreme energies.

The identification of UHE gammas is based on two physical phenomena: photon conversion in interactions with the geomagnetic field and the LPM effect. Gamma rays with energies E_γ propagating through a magnetic field with a transverse component $B_\perp$ have a large probability of converting into electron-positron pairs if the product $E_\gamma B_\perp$ is large. This happens in particular for $E_\gamma \gtrsim 10$ EeV for typical values of the geomagnetic field. The conversion occurs at altitudes of several thousands kilometers (therefore well above the atmosphere). The e^+e^- pairs then undergo energy loss by magnetic bremsstrahlung and so on. By the time the secondary electrons and photons reach the atmosphere, they all have energies less than a few EeV. The development of this pre-shower in the atmosphere is like that of a superposition of several low energy electromagnetic showers.

However, whenever the incident gamma arrives with its direction parallel to the field vector, the conversion becomes negligible and the gamma penetrates the atmosphere with its full energy. Then a second phenomenon, the Landau-Pomeranchuk-Migdal (LPM) effect, takes over. This effect consists in a decreasing of the cross-sections of electromagnetic processes with the energy of photons/electrons and the density of the propagation medium. It becomes dominant over the Bethe-Heitler processes for particles with typical energies of around 100 EeV even in the rarefied layers of the upper atmosphere.

Fig.2 shows how these effects operate[9)] at a given place, namely at the site of the southern Auger Observatory. One can see how the gamma conversion probability depends on the energy of the photons and their direction in the earth's reference frame. The dashed circles show the directions with zenith angles of 30 and 60 degrees. One can see that for all values of the gamma ray energy, the conversion probability is zero in a direction close to 50° North. UHE gammas coming from this direction will deeply penetrate the atmosphere before starting to shower. Therefore their geometry compared to those coming from the other directions will be quite distinctive and detectable. As an example, Fig.3 shows how the measurement of the shower-front curvature is expected to distinguish between converted and unconverted gammas and protons. The sample used for this figure includes gammas of all energies between 30 and 300 EeV with a uniform distribution in $\log(E)$. The fluctuations are indicated by the error bars (unconverted photons) or the hatched surfaces. The dotted line shows the separation of what can be considered as high and low curvature populations. The use of this variable makes it possible to separate protons from photons over a large range of zenith angles (at least up to 60°). With the use of the curvature, as well as the steepness of the LDF or the muon content of the EAS, it is expected that a 5-10% contamination by UHE photons of a sample of protons will be detectable.

The detection of neutrinos in the same energy range with a ground array is based on the fact that a particle penetrating the atmosphere tangentially to the earth will be absorbed by an enormous amount of matter:[11)] more than 800 radiation lengths, about 350 nuclear interaction lengths. For horizontal airshowers (HAS) the atmosphere is therefore equivalent to a good beam-dump. Using cross-section values extrapolated from lower energy data,[10)] the probability that UHE (anti)neutrinos interact in such a thickness of air is larger than 10^{-4} above 0.1 EeV, which is far from being negligible. Moreover, this energy range is just above the limit accessible to the neutrino telescopes for up-going neutrinos, since above 10^{16} eV the earth becomes opaque to them. It was therefore interesting to see what a giant ground array such as Auger can do with the detection of UHE neutrinos. The studies are based on EAS incident with a zenith angle above 75 degrees and energies between 0.1 and 100 EeV. For neutrinos above 1 EeV, the acceptance of the ground array is more than 10 km^3 water equivalent. The background to the expectedly weak neutrino signal is of course the numerous hadronic showers incoming at large angles. However, and with the same methods as in the case of UHE gammas (in particular the shape of the shower front and the signal risetime) it is expected that even a few neutrino events per year should be detectable.

An equally interesting case is that of the tau-neutrinos if neutrino oscillations as observed by Super-K and SNO are confirmed. With a maximum mixing, and given the large propagation distances, it is expected to have equal proportions of the three neutrino species incident on earth, if the ν_μ/ν_e ratio at the source is 2/1. In this case, it becomes very interesting to look for tau neutrinos through their interaction in the ground (i.e. with zenith angles larger than 90°) producing a τ. In our energy ranges, the taus can propagate over tens of km before decaying (or interact with the earth and start an iterative process). If the decay occurs in the volume of air above the ground array, the direction of the showers could, at least statistically, give indications to discriminate them from the "standard" HAS.

Detailed studies were made[1,12)] to estimate the performance of the Auger ground array with respect to neutrino detection. Fig.4 is a summary of recent studies where the sensitivity for one event per year and per

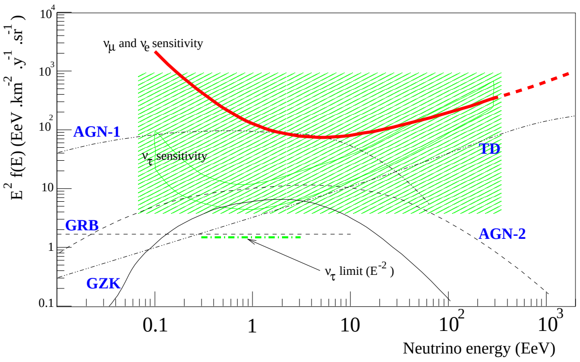

Fig. 4. Sensitivity of Auger to neutrino detection.$^{1)}$ The ν_μ/ν_τ flux estimates are from$^{13)}$ and are divided by a factor 2 to take into account the full mixing hypothesis. See text for comments.

decade is shown for ν_μ/ν_e (top thick line) and ν_τ (shaded area). The curves limiting the shaded zone on this figure are for deep-inelastic scattering with strong energy loss (top) and no such loss (bottom). The expected event rate depends of course on the models of UHE neutrino production. Whenever the sensitivity curve lies for more than one decade below the flux curves, it is expected to observe more than one event per year. For models considered as being solid$^{13)}$ such as the so-called GZK neutrinos (those produced as secondaries of the interactions of UHECR with the 2.7 K microwave background, full line on the figure) the detection rate appears to be rather low. For more speculative estimates (GRBs, AGN etc) several events per year should be detected. The horizontal line shown as the "ν_τ limit" is the 90% confidence level limit (background-free detection) achievable with five years of data taking with Auger for an E^{-2} flux between 0.3 and 3 EeV.

§5. Status and prospects

The Collaboration decided to phase the construction of the southern site in two steps. During 2001, the prototype hybrid system called the Engineering Array (EA) was built. It consists of 40 tanks covering an area of about 50 km^2 and two elements of fluorescence telescopes overlooking the area equipped with the tanks. The EA aims to test all the technical issues (including those where the final choice is still open) before the launching of the final production. A critical design review in October 2001 will finalize the design, wherever options were left open, and the deployment of the full observatory is expected to start then and be completed by the end of 2004.

The northern site is not funded yet. It will be submitted for approval to the various national agencies when the physics data from the southern site start to come in.

At the time this article was written, the first UHECR events were observed by the prototype flurescence telescopes. Working with laser shots at 26 km the FD crew has calculated roughly that we can see showers down to $1-2\times10^{18}$ eV at that distance. This is at or better than specification.

Acknowledgements

The data presented here come from unnumerable sources within the Auger collaboration. Those who provided this information will know that my deep gratitude goes to them. Special thanks to Alan Watson for his careful reading of the manuscript and his comments, to Pierre Billoir and Jim Cronin for their in-depth studies of reconstruction issues and for making them available to the collaboration. Many of these data and much more can be found on the Web, and especially in the 'Technical and Scientific Notes' section of the Auger page:
`http://www.auger.org/admin/`

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