Cosmic Rays
Pierre Auger Observatory

After ten years of successful running, the decision for a major upgrade of the Auger experiment on the Argentine Pampas has been made. The key element of the upgrade is the installation of a plastic scintillator on top of each existing surface detector station. It will provide a complementary measurement of the showers allowing the reconstruction of muons and electromagnetic particles. The surface scintillator detector stations (SSD) will be deployed over the full 3,000-km² area of the overall surface detector.

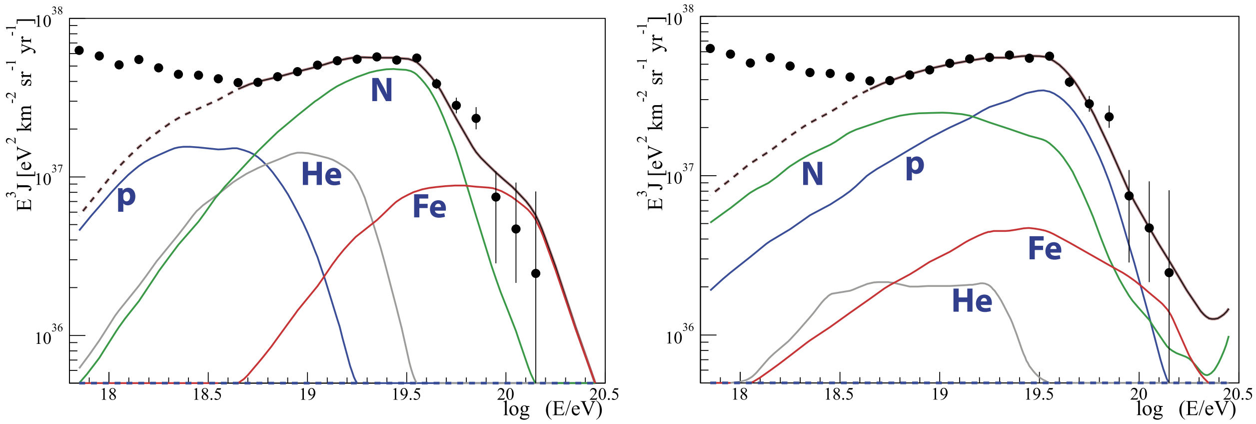

Figure 1. Fits of the cosmic ray flux at the highest energy for the maximum energy (left) and GZK (right) scenarios.

Management
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Ultra-high-energy cosmic rays are the most energetic particles we know, exceeding the LHC energy by many orders of magnitude. Yet we neither know their sources, the physics that is needed to generate them, nor the physics that governs their interactions with the air in our atmosphere. The Pierre Auger Observatory was built to resolve these mysteries. It is the world's largest cosmic ray observatory located on 3,000 km^2 near Malargüe in the province of Mendoza in Argentina.

The origin of ultra-high-energy cosmic rays

The Pierre Auger Collaboration had already definitively shown that the energy spectrum of cosmic rays exhibits a sharp drop around 10^{20} eV. This drop is compatible with the Greisen-Zatsepin-Kuz'min (GZK) cut-off, above which ultra-high-energy cosmic rays interact with photons of the 2.7 K cosmic microwave background and will loose their energy when traveling over inter-galactic distances.

However, recent measurements by the Pierre Auger Collaboration have cast doubt on this to be the only explanation. Where for the GZK cut-off explanation the highest energy cosmic rays are thought to consist mostly of protons, extrapolation from energies just below this regime seems to indicate domination by heavier elements. This is illustrated by fits of the particle spectrum at the highest energy using the two models mentioned in Fig. 1, which both describe the data quite well, despite the completely different particle type composition.

The crux of the answer lies in knowing the particle composition of cosmic rays at the highest energy. The current technique in Auger that was explicitly designed to determine this composition by fluorescence detection of air showers can only be used in pitch dark nights, which is only 10% of the day on average. The Nikhef group pioneers both the use of the already existing Auger surface detector and the use of the entirely new radio detection technique in determining the cosmic ray composition, ultimately on an event-by-event basis.

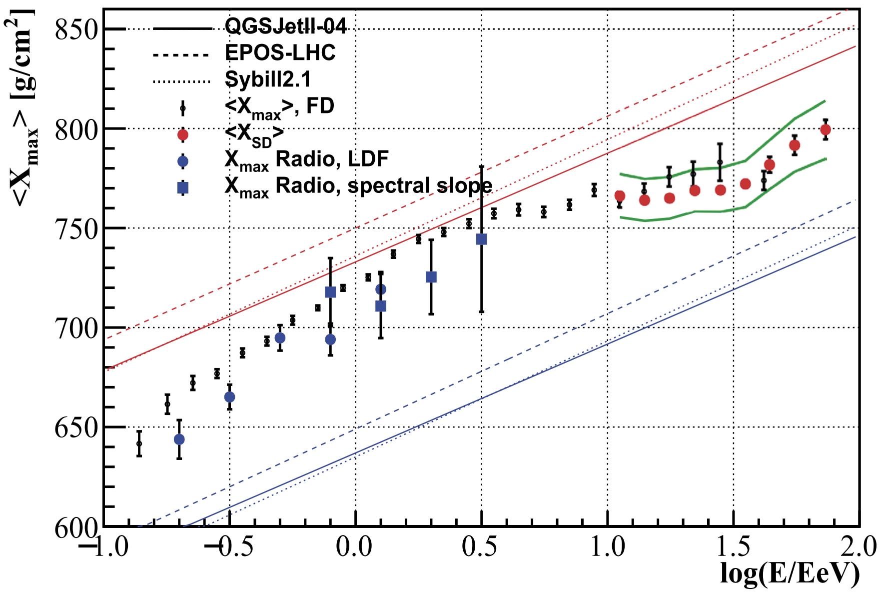

Figure 2. Cosmic ray average penetration depth in grammage, X_{max} as a function of energy. The small black points are published data from the Auger fluorescence detector. The full red dots are the preliminary measurement using the Auger surface detector. The green band around them is the systematic uncertainty on these points. The blue square points are the preliminary pulse length measurements of the radio detection. The blue dots are from the radio detection Cherenkov ring radius measurements. The estimation of the systematic uncertainty on these points is ongoing research. The lines are prediction from various air shower simulation models: full lines from QGSJetII-04, dashed lines from EPOS with LHC tuning and dotted lines from Sybill2.1

Cosmic ray composition from the Auger surface detector

The Auger Surface Detector consists of about 1,660 water Cherenkov tanks of 12 ton water each. These tanks are spaced by 1.5 km to cover a surface of 3,000 km^2 in total. When high-energy particles at the end of the air showers pass through the water they make Cherenkov radiation that is observed by three photomultipliers that look down in the water of the tank. For ultra-high-energy cosmic rays, many tanks are hit. The particle flux in a collection of tanks is fit as a lateral density profile and its normalisation renders the energy of the incoming cosmic ray. Depending on the direction of the incoming cosmic ray, the water tanks are hit at different times by the air shower front. From timing reconstruction the arrival direction of the incoming cosmic ray can be determined.

At the same energy light and heavy cosmic ray particles have different interactions with the atmosphere. Light particles, *in extremum* the proton, have a smaller cross section with air molecules than heavy elements, such as nitrogen or even iron nuclei. Therefore, light cosmic rays have the development of their shower deeper into the atmosphere than heavier nuclei. Moreover, the interactions with heavier cosmic rays invoke a more rapid shower development than with lighter ones. And in addition, heavier elements tend to produce significantly more muons, especially also at the early stage of the shower, than light cosmic rays.

The penetration depth of the shower in the atmosphere can be assessed by carefully studying the shower front when it arrives at ground. The front is an hyperbolic surface, where the focal area points back to the points on the shower axis where the particles in the shower were produced. This *curvature* can be measured using the timing of the tanks that are hit. The shower thickness is produced by the different arrival times of particles that are produced relatively early in the shower that arrive early and particles formed at the end of the shower that arrive later. Using the *rise-time* of the signal in the tanks is a measure of the ratio of early particles, mostly muons and late particles mostly electrons, positrons and photons.

Combining the curvature and rise-time, promising first preliminary results have been produced on the already available Auger surface detector data of the past decade. A resolution of better than twice that of the fluorescence detector can be attained for a factor of nearly ten more data. A publication is in preparation in which this is used to provide data points on composition at significantly higher energy than any such measurement previously. The preliminary measurement is shown in Fig. 2.

Surface detector upgrade

To improve significantly on the composition determination by the surface detector it will be upgraded with electronics with a better timing resolution and a new detection layer will be installed. Together with the Cherenkov tank the new detection layer will allow the muon flux to be distinguished from the flux of electromagnetic particles. These improvements will lead to a composition resolution of the surface detectors that is similar to that of the existing fluorescence detector, but with a 24 hours per day duty cycle.

Nikhef is involved in the design of the new detection layer, which is called the scintillator surface detector (SSD). It consists of a 1 cm thin plane of nearly 4 m^2 of scintillator, read out with wave length shifting fibers that collect the signal onto a single photomultiplier (see Fig. 3). The readout of the photomultiplier is integrated in the new surface detector electronics.

Figure 3. The scintillator surface detector (SSD) as seen on top of the Cherenkov tank. It consists of a 1 cm thin plane of nearly 4 m^2 of scintillator, read out by a single photomultiplier.

The new electronics and the SSD will be installed in 2017 and 2018, at which time the Auger Observatory smoothly rolls into the new mode of operation without stopping data taking and with negligible efficiency loss.

Cosmic ray composition from radio detection

The position in the atmosphere where the radio wave signal from extensive air showers is created is one-to-one correlated to the penetration depth of the shower in the atmosphere. This fact can be used in at least three different ways to determine the incoming cosmic ray mass composition. A curved shower front can be reconstructed, with a focal area that corresponds to the penetration depth of the air shower. The radio pulse duration for an observer is a measure for the distance and the projection angle of the emission area of the air shower. This duration, in the form of a spectral slope, can be used together with the knowledge of the distance of the observer from the air shower axis to estimate the penetration depth of the air shower. In a third method, it is used that the radio wave emission peaks in a Cherenkov cone around the air shower axis. By measuring the radius of this Cherenkov cone the emission region and thereby the penetration depth of the air shower can be estimated.

Nikhef plays the leading role in the latter two techniques, the pulse length and Cherenkov radius measurements. The pulse length method is published in Stefan Jansen's PhD thesis (2016) and the Cherenkov ring radius method is published in the PhD theses of Anna Nelles (2014) and Johannes Schulz (2016).

Figure 2 shows the measurement of the average penetration depth in grammage, X_{max}, as a function of the measured energy of the air showers. The standard Auger surface detector reconstruction is used for the energy determination. The figure shows the published Auger fluorescence detector data points, together with Nikhef preliminary measurements from the surface detector and from the two methods in radio detection pioneered by Nikhef. The theoretical predictions vary considerably in absolute value between models. However, the slope of the average X_{max} as a function of energy is always the same and the distance between the average X_{max} for protons and iron is also very similar in the different models.