Cosmic ray studies at the upgraded Pierre Auger Observatory

The proposed project aims at an experimental study of cosmic rays and hadron interactions at energies above 10^{18} eV. Particles with such high energies - several orders of magnitude higher than the energies achieved in man-made particle accelerators - reach the Earth from deep Cosmos. With our currently available technology, the Large Hadron Collider accelerator would have to be scaled to the size of the orbit of the planet Mercury to reach these energies. We don't know where in the Universe are their sources, or how they are accelerated to the extreme energies observed. Nevertheless, there is no doubt that these particles with enormously high energies really do arrive to us from the Cosmos; their origin and acceleration mechanism are one of the greatest puzzles in the present–day astrophysics.

The flux of ultra-high energy cosmic rays is extremely small. Less than one particle per century arrives in an area of a square-kilometer. Therefore, it is necessary to build a huge detector to be able to observe them. Moreover, the ultra-high energy cosmic rays are observed only indirectly, through observations of so-called extensive air showers induced by the cosmic rays. What can be observed are the cascades of secondary particles moving in the atmosphere and finally reaching the ground. For experimental studies of such showers, a giant array of cosmic ray detectors was constructed: the Pierre Auger Observatory. The Observatory is located near the town of Malargue in the province of Mendoza, Argentina. It is a hybrid detector that combines a network of Surface Detectors with a Fluorescence Detector. The Surface Detector stations are water-Cherenkov detectors placed 1.5 km apart. Each station, powered by solar batteries, measures signals induced by the particles entering the water tank. The observatory consists of 1660 particle detectors, which form a gigantic network covering about 3000 km^2. A second detection system uses the faint glow (fluorescence) caused by the collisions of shower particles with air molecules. On dark, moonless nights, finely tuned light sensors can measure this fluorescence light. A collection of light sensors pointing around the sky makes an effective air shower detector, observing an air shower as a trace of light across the sky. The total amount of light depends on the number of particles in the shower, which in turn depends on the energy of the primary cosmic ray particle initiating that shower in the atmosphere. The system consists of 4 fluorescence detectors, each containing 6 telescopes.

The results obtained so far with the Pierre Auger Observatory have dramatically advanced our understanding of ultra-high energy cosmic rays, however some of the findings are very surprising and their interpretation is difficult within the current cosmic ray paradigm. One such thing is the observation of suppression of the cosmic ray flux around 4×10^{19} eV. Such a feature is predicted as a result of interactions of cosmic rays with the cosmic microwave background (which is a remnant of the Big Bang) and is known as the Greisen-Zatsepin-Kuzmin (GZK) cutoff. However, the experimental data on the cosmic ray composition collected by the Pierre Auger Observatory suggest that the suppression of the spectrum may not be caused by just the GZK cutoff, but this feature can be interpreted as a manifestation of the limit of the particle acceleration at the source, with the maximum energy proportional to the particle charge. These studies show that ultra-high energy cosmic rays are not just protons and/or iron nuclei, but that there is a significant component of intermediate mass nuclei in the observed cosmic rays. Composition determination of ultra-high energy cosmic rays (preferably on event-by-event basis) is the key to resolve this issue.

Most reliable studies of the cosmic ray composition are currently possible with the observations from the Fluorescence Detector, which only can operate on dark, moonless nights, and in good weather conditions. Such a limit of the observation time translates into a smaller statistics of the collected data, allowing the most accurate mass composition studies so far, covering only energies up to 4×10^{19} eV, i.e. just below the flux suppression region. At the same time, the Surface Detector data extends to beyond 10^{20} eV. However, determining the composition of cosmic rays based solely on the Surface Detector was so far difficult due to large systematic uncertainties related to modeling hadronic showers and to limitations of reconstruction algorithms. Therefore, Pierre Auger Collaboration decided to enhance the capabilities of the surface array of particle detectors, which collects data continuously. This upgrade will allow more reliable measurements of the air shower particles at the ground level, in particular the separation of signals from the muonic and electromagnetic components.

The results of the proposed project will contribute to a significant progress in the studies of the composition of the ultra-high energy cosmic rays, which will bring us closer to the final explanation of their nature and origin. Detailed analysis of the air shower development, supported by precise measurements from the upgraded detectors, will also allow us to study the nuclear interactions and test various interaction models at energies much higher than those attainable in particle accelerators on Earth.