WDS'10 Proceedings of Contributed Papers, Part III, 107–110, 2010. ISBN 978-80-7378-141-5 © MATFYZPRESS

Mass Composition Study at the Pierre Auger Observatory

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Abstract. The Pierre Auger Observatory is built to measure extended air showers induced by cosmic ray particles. One of the main goals of the physical analysis is the determination of the mass composition. The measurement of the depth of the maximum, X_{max}, of the longitudinal development of the air showers will be described. The analysis deals with almost four thousand events above 10^{18} eV observed by the fluorescence detector of the Pierre Auger Observatory in coincidence with at least one surface detector station. The most actual results will be shown.

Introduction

Cosmic Rays (CRs) are permanent source of high energy particles reaching the Earth. The energy spectrum of CRs is wide, from about 10^9 eV up to about 10^{20} eV. The lower limit is caused by solar wind, which do not allow lower energy particles to reach the Earth atmosphere. The upper limit is known as so-called GZK effect (the CRs particles interact with microwave photons and loose their energy). The sources of the highest energy particles are still not known.

If the CRs particle reaches the Earth's atmosphere, it interacts with air and so-called extensive air shower is created. The shower contains all known particles, which can be split to 3 shower components - electromagnetic component, hadronic component and muonic component. The hadronic part continuously feeds the electromagnetic part (majority of shower energy is then in the electromagnetic part).

The basic features of the shower can be described by simple Heitler model [*Heitler*, 1949] for electromagnetic cascades. It supposes that at the beginning there is a photon with primary energy E_0. This photon creates a e^+, e^- pair with energy $E_0/2$ per particle. Electron (positron) can radiate a photon etc. The creation of new particles stops, when the energy per particle becomes smaller then a critical energy (the radiation and ionization looses becomes equal) - this point is called the maximum of the shower. After n interactions there will be 2^n particles with approximately the same energy $E_0/2^n$. In the shower maximum the number of particles will be equal $N_{max} = E_0/E_{crit}$. The position of the shower maximum in the atmosphere is called X_{max}, where X is the slant depth (units g/cm^2). The X_{max} can be than expressed as:

$$X_{max} = \lambda \ln(E_0/E_{crit})/\ln 2, \tag{1}$$

where λ is the splitting length.

The real air showers are not only electromagnetic cascades, but they are also hadronic showers, so the superposition model can be used ($E_0 \to E_0/A$), where A is the mass number of the primary particle (nuclei). The position of the shower maximum can be than expressed using following formula:

$$X_{max} \approx \lambda + X_0 \ln\left(\frac{E_0}{N E_{crit}^{\gamma} A}\right), \tag{2}$$

where N is the multiplicity, λ is the interaction length and X_0 is the radiation length. The position of the shower maxima is thus sensitive to energy of the primary particle E_0 and also to the mass of the primary particle A.

In current time, the mass composition of CRs with the highest energies is still unknown. This is due to the low statistics of such particles and also due to the results interpretation

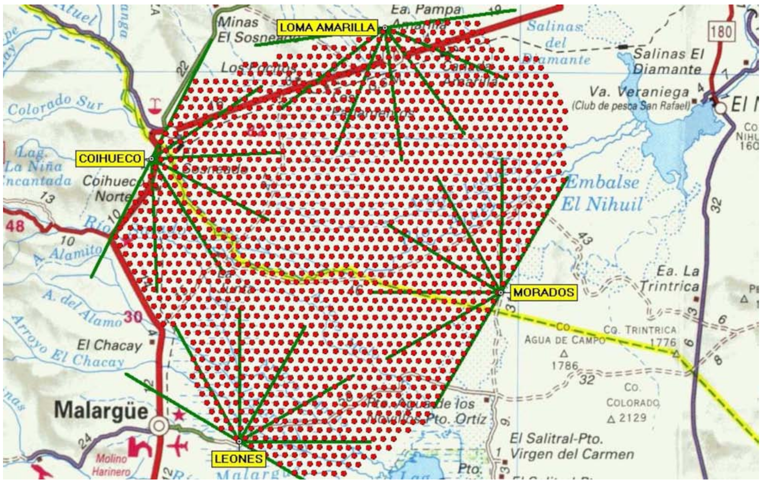

Figure 1. The schematic view of the Pierre Auger observatory. The red points represent the water cherenkov tanks. The yellow titles represent the four positions of the fluorescence detectors and the green lines represent the azimuthal fields of view of the individual fluorescence telescopes.

problems. The current interpretation of the measured showers is possible only with prediction from simulations, which are based on hadronic interaction models. These hadronic interaction models are based only on extrapolations from current accelerators data. The results of mass composition determinations are typically shown as a comparison of measured X_{max} with model predictions.

Pierre Auger Observatory

The Pierre Auger Observatory has been designed to investigate the origin and the nature of the ultra high energy cosmic rays (UHECRs). The observatory is a hybrid detector, which combine a measurement from surface detectors (SD) and fluorescence detectors (FD). The observatory is located in Southern hemisphere in Argentinian pampa, close to the city Malargüe, provincia Mendoza.

The surface array consists of about 1600 water cherenkov detectors to detect the particles of air showers on ground level. The detectors cover an area of about 3000 km^2 and each detector is 1.5 km apart from another one. Each water tank is filled with 12m^3 of clear water, has 3 photomultipliers and GPS module for precise timing.

The fluorescence detectors are placed at 4 positions to overlook the surface array. Six fluorescence telescopes are placed at each position - totally 24 fluorescence telescopes are used. The fluorescence detectors allow us to observe main part of the longitudinal profile of the air shower.

The observatory has been taking data since January 2004. The construction has been completed in Summer 2008. Details of the design, construction and performance of the Observatory can be found in [*Abraham et al.*, 2004; *Allekotte et al.*, 2008; *Abraham et al.*, 2009].

The fluorescence telescope measurement

The shower of secondary particles passes through the atmosphere and it excites the molecules of air (mainly N_2 molecules). During the deexcitation the fluorescence photons are isotropically emitted. These photons can be measured by the fluorescence telescopes. The amount of fluorescence photons is proportional to the energy looses of the air shower and the measured profile can be then described by so-called Gaisser-Hillas formula [*Gaisser and Hillas, 1977]:*

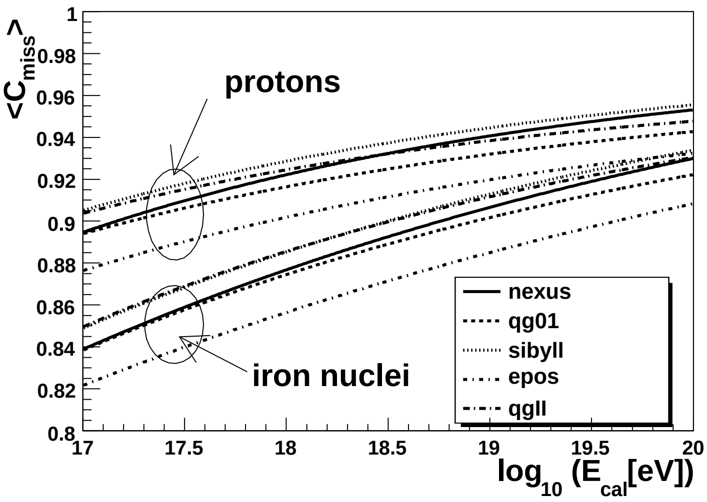

Figure 2. The ratio of the calorimetric energy to the primary energy (invisible energy correction $< C_{miss} >$) as a function of calorimetric energy for different high energy interaction models and primary particle types: protons and iron nuclei. Zenith angle $\Theta = 0°$. This picture is taken from [*Nyklicek and Travnicek 2009]*.

$$f_{GH}(X) = \frac{dE}{dX_{max}} \left(\frac{X - X_0}{X_{max} - X_0} \right)^{\frac{X_{max}-X_0}{\lambda}} \exp \left(\frac{X_{max} - X}{\lambda} \right), \tag{3}$$

where $\frac{dE}{dX_{max}}$ is the energy deposit at shower maximum, X_{max} is the point of the shower maximum and λ and X_0 are constants (sometimes identified as the interaction length and point of the first interaction).

The measured (calorimetric) energy is then obtained as an integral of the Gaisser-Hillas formula:

$$E_{cal} = \int_0^\infty f_{GH}(X)dX. \tag{4}$$

The determination of the calorimetric energy is independent of the Monte-Carlo (MC) predictions as well as X_{max} measurement. The only one thing, which is dependent on the simulations is the correction for the invisible energy (caused by neutrinos and muons, which are invisible for FD). The invisible energy correction is different for different primary particle types. Because the primary particle mass is unknown, the corrections is done as an average correction for protons and iron nuclei. The invisible energy correction given by different models of hadronic interactions is shown in the Fig. (2).

The mass composition study with FD

From FD data it is possible to directly determine X_{max} (from measured shower profile), the quantity which is sensitive to the primary particle mass. Due to the large shower by shower fluctuations, it is not possible to study the primary particle mass for each shower separately. For this reason the mean value of shower maxima ($< X_{max} >$) and RMS(X_{max}) are used for the mass composition studies. The proton shower penetrates deeper into the atmosphere (larger values of X_{max}) and have wider X_{max} distributions than iron nuclei.

This work is based on hybrid data (showers, which are observed simultaneously by FD and at least one surface detector) recorded between December 2004 and March 2009. The information from the surface detector is used to improve geometry reconstruction of showers measured by FD.

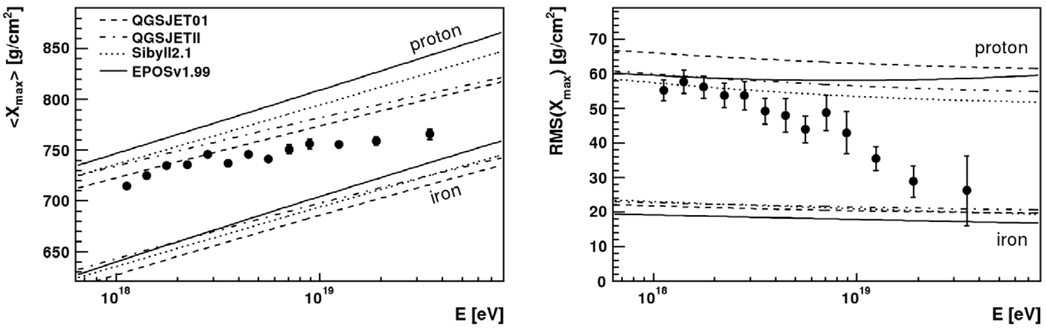

Figure 3. $< X_{max} >$ (left plot) and RMS(X_{max}) (right plot) as a function of energy from data compared to the air shower simulations using different hadronic interaction models.

The high quality data are selected from all measured data to allow the mass composition analysis. For more information about the selection criteria see [*Abraham et al., 2010*]. After all cuts, 3754 events remain for the mass composition analysis.

Fig. 3 shows measured data together with prediction from Monte-Carlo simulations. The right plot shows the mean shower maxima, the left plot shows RMS(X_{max}), both as a function of energy. The measured data are distributed in bins of $\Delta \log E = 0.1$ below 10^{19} eV and $\Delta \log E = 0.2$ above that energy. The last bin starts with energy $10^{19.4}$ eV and continue up to the highest measured energy.

The slope of measured $< X_{max} >$ data is not constant with energy. To describe the $< X_{max} >$ data is possible to use a broken line fit (below and above $10^{18.24 \pm 0.005}$ eV). The exact interpretation of the measured data is strongly dependent on the predictions of high energy interaction models, which are tuned to accelerator measurements at much smaller energy. With increasing energy the measured $< X_{max} >$ values indicates increasing average mass of the primary particle when confronted to any of the available models.

Conclusions

The fluorescence detector in combination with the surface detector of the Pierre Auger Observatory allows the determination of the primary energy of the cosmic rays, which is almost independent on the simulations (only small correction for the invisible energy). Also the X_{max} is determined directly from the data. The measurement of X_{max} is used for the mass composition studies. Above $10^{18.2}$ eV the measured data shows an increasing primary mass with energy.

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