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Ultra high energy cosmic rays simulated with CONEX code

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Abstract.
Today, many experiments around the world (Auger Observatory, Telescope Array, and soon Jem-Euso experiment...) are tracking ultra-high energy cosmic rays. They try to collect some exceptional data that would lift the veil on this type of cosmic rays , mainly to answer why does their energies exceed the GZK cutoff without pointing to astrophysical sources close to our galaxy. Furthermore, we do not really know neither the identity nor the acceleration processes that can provide them with such colossal energy. We have performed, using the CONEX program version 2r6.40 coupled to different hadronic interaction models (QGSJET01, EPOS LHC , SIBYLL 2.1 and QGSJETII-04) simulations focused on the slant depth X_{max} of the maximum of the shower longitudinal profile and the charged particle number N_{max}. Theses parameters and their fluctuations are very sensitive to the primary particle mass (identity) and energy. The obtained results are compared for proton and iron primaries at the energy range 10^{18} – 10^{21} eV.

1 Introduction

1.1 Primary cosmic rays

Primary cosmic particles with energy higher than 10^{18} eV are called Ultra High Energy Cosmic Rays (UHECRs). At present, these kind of rays have been measured by two biggest experiments: Auger observatory and Telescope Array (TA).

By studying closely the UHECRs spectrum, one can notice two important features:

- a flattening at arround 5×10^{18} eV, the so called 'ankle' [1]. Its origin is not perfectly clear. It seems to be either a signature of ultra-high energy primary protons interactions with the Cosmic Mirowave Background (CMB) [2, 3], or a transition from a galactic to extragalactic sources, or even a transition from an extragalactic proton component to a different extragalactic heavy nuclei one...
- a strong decrease or cut-off at about $5{\times}10^{19}$ eV. This cutoff predicted by Greisen, Zatsepin and Kusmin (GZK) [4, 5] is mainly due to the energy attenuation of protons in the photopion-production interactions with the CMB.

The identities of these UHECR with energies above the GZK cutoff remain unknown. Discovering their sources will certainly reveal the most energetic astrophysical accelerators in the Universe.

When penetrating in the Earth atmosphere, the UHECR collides with the nitrogen or oxygen nuclei and produces a large cascade of secondary particles called extensive air shower (EAS).

1.2 Extensive Air Shower

At the begining of the evolution of this EAS, the successive interactions increase the number of its particles, hence a decrease of the average energy per particle: it is the developpement phase. However, along their travel, the secondary particles lose progressively their energy by ionising the air, and the less energetic of them will stop. When the mean energy per particle falls below a critical value, the number of secondaries in motion decreases: it is the extinction phase.

When passing from one phase to the other the number of particles reaches a maximum value, N_{max} at the slant depth position X_{max}. This later parameter is often used to reconstruct the elemental composition of the primary cosmic rays (primary particle identification). The analysis of simulations based on this parameter X_{max} will probably allow us to interpret recent and future experimental data (e.g. TA, Auger observatory and soon JEM-EUSO).

2 Simulation method : CONEX code

The physical characteristic quantities of the UHECR, such as their masses, their energies, and their arrival directions, are possible to measure only indirectly. These parameters can be deduced from the properties of the extensive air showers (huge nuclear-electromagneticcascades) generated when the UHECRs enter into the earth's atmosphere. Monte Carlo simulations of these EAS, which take into account all the natural physical phenomena occurring during their evolution, could reliably predict these cascades of myriad particles. The CORSIKA code (COsmic Ray SImulations for KAscade) [6] is one of the best programs describing perfectly the EAS using the Monte Carlo method.

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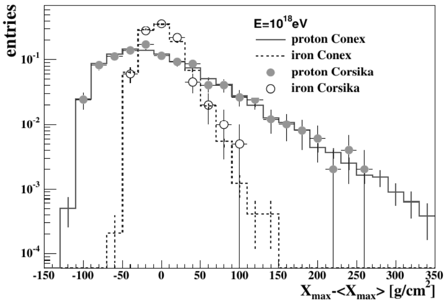

Figure 1. fluctuations of the shower maximum depth X_{max} around the mean shower maximum depth $\langle X_{max} \rangle$ for a primary energy of 10^{17} to 10^{20} eV [7].

Table 1. Comparation between Monte Carlo simulations and Cascade Equations (CE) by CONEX and CORSIKA codes results [7]

Monte Carlo (MC) simulations	Cascade Equations (CE)
Realistic	Fast
Flexible	Mean behavior
fluctuations	No fluctuations
slow	Limited to analytic formula

Unfortunately, for UHECR the execution time of such a program becomes unreasonable despite the use of its THINING option based on a weighted sampling algorithm. In order to circumvent this difficulty, we have used CONEX program version 2r4.37 [8, 9] coupled to different high energy hadronic interaction models EPOS LHC, QGSJETII-04, QGSJET01 and SiBYLL 2.1. and default low energy hadronic interaction model UrQMD 1.3. CONEX is a hybrid simulation code that is suited for fast one dimensional of shower profiles, including fluctuations. It combines Monte Carlo (MC) simulation of high energy interactions with a fast numerical solution of cascade equations (CE) for the resulting distributions of secondary particles. For a given primary mass, energy, and zenith angle, the energy deposit profile as well as charged particle and muon longitudinal profiles are calculated. Furthermore an extended Gaisser-Hillas is performed for each shower profile similar to what is implemented in CORSIKA. The shower simulation parameters, profiles and fit results are written to a Root file [10]. So CONEX quickly determines the EAS profile including fluctuations. A comparison of the two methods both used in CONEX code, Monte Carlo and the numerical resolution of the cascade equation, is shown in Table-1.

Pierog [7] mentioned (fig. 1) a good agreement of CORSIKA and CONEX programs when calculating the fluctuation of the maximum longitudinal profile, $X_{max} - \langle X_{max} \rangle$, for primary proton and iron nuleus at 10^{18} eV.

3 Simulation results

CONEX options involved in our simulations are the following:

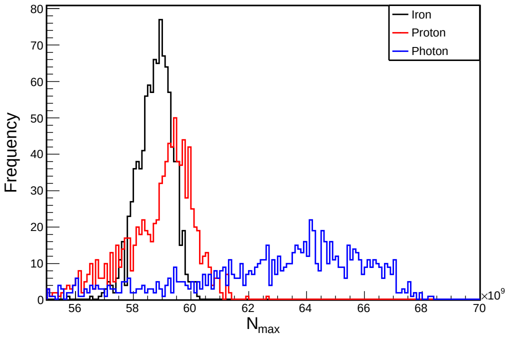

Figure 2. The N_{max} distribution for primary proton, photon and iron (primary energy10^{20} eV).

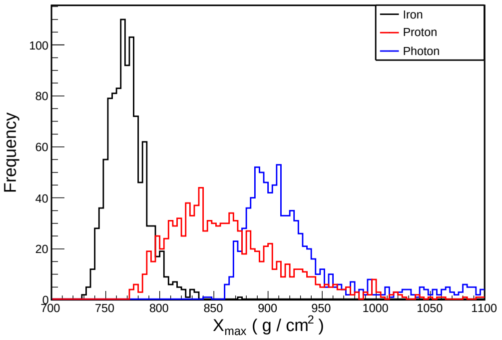

Figure 3. The X_{max} distribution for primary proton, photon and iron (primary energy10^{20} eV).

- Primary particle : proton, iron;
- Primary particle energy : 10^{18} - 10^{21} eV;
- Zenith angle : $\theta = 0 - 70°$;
- Energy cutoff: default values;
- Event number: 500 – 1000;
- Hadronic interaction Model: EPOS LHC, QGSJETII-04, QGSJET01 and SiBYLL 2.1.

First, we have studied the maximum charged particle number profiles distibution , N_{max} (fig.2), and the shower maximum slant depth, X_{max} distribution (fig.3), for primary cosmic-ray protons, iron nuclei and γ-photons at energy equal to 10^{20} eV . One can see that the fluctuation of the N_{max} and the X_{max} parameters is much more pronounced for a primary proton than a primary iron nuclus. We have also plotted the variation of N_{max} (fig.4) as a function of the primary proton and and iron nucleus energies. For both primary particles (proton and iron nucleus) the higher the energy the wider the maximum longitudinal profile number N_{max}. There is no significant difference in the two primary particles N_{max} values. This can be explained by the superposition model used for cosmic ray nuclei. This model treats a nucleus interaction of mass number A and energy E as A proton interactions each with energy E/A.

Figure 5 shows the variation of the charged maximum slant depth X_{max} with the primary proton and iron nucleus

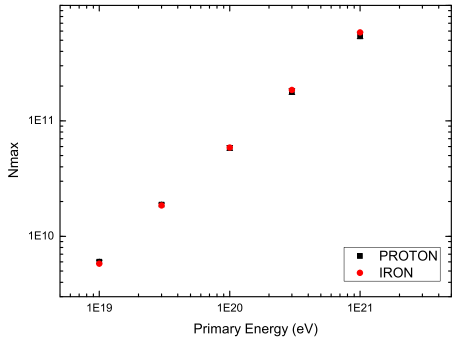

Figure 4. The maximum charged particles number N_{max} as function of the primary enery (proton, iron) of energy 10^{20} eV.

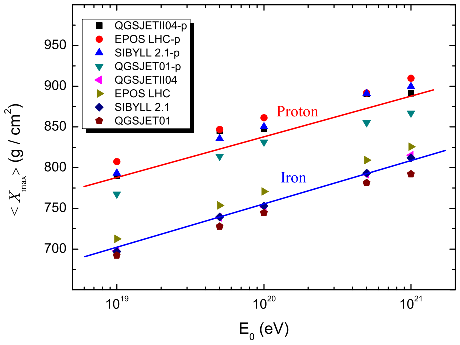

Figure 5. The variation of the charged maximum slant depth X_{max} with the primary proton and iron nucleus energy for different high energy interaction models.

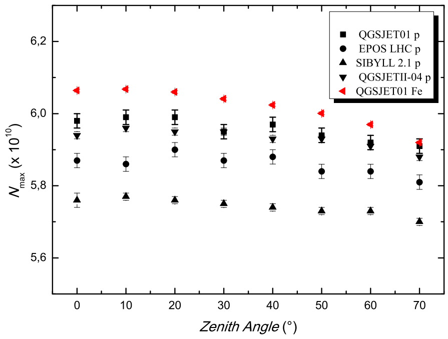

Figure 6. The maximum charged particles number N_{max} as function of the zenith angle of primary proton (Black) iron (red) with energy equals $10^{20}eV$.

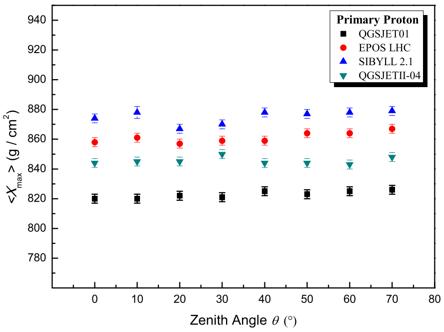

Figure 7. The maximum charged particles number N_{max} as function of the zenith angle of primary proton (Black) iron (red) with energy equals $10^{20}eV$.

energy. In all the energy range ($10^{19} - 10^{21}$ eV), we noticed a difference of aproximatly 100 g/cm^2 between the two primary particles X_{max} values. As we know, this parameter is directly related to the primary particle mass. When comparing the experimental data with such simulations, this should probably lead to the identification of the nature of UHECRs.

Moreover, we have studied the variation of N_{max} (fig.6) and X_{max} (fig.7) versus the zenith angle for a primary proton energy of 10^{20} eV. The discrepancy between the different high energy hadronic models regarding the N_{max} parameter is negligible (<5%). However, X_{max} parameter is influenced by the choice of the high energy hadronic model. The discrepancy, in case of primary proton, between the different models is about 60 g/cm^2.

4 Conclusion

For a better understanding of the properties of ultra high energy (UHE), we have used CONEX code to simulate the interaction with atmosphere of primary nuclei (iron, proton) and photon with energy range 10^{19}eV to 10^{21}eV. The most interesting quantities for this purpose are the distributions of the X_{max} parameter and the number of charged particles N_{max}. X_{max} depends strongly on the high energy hadron interaction models which induce large uncertainties in primary particle identification. The next step is to use our recorded data (CONEX) as input ones for the Jem-Euso experiment simulation code (Offline). The study of the fluorescence signal intensity profile will shed more light on the primary mass and energy.

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