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Studying the cosmic-ray composition at the knee region with EMMA

T. Räihä[a], C. Shen[b], L. Ding[e], I. Dzaparova[g], T. Enqvist[b], H. Fynbo[h], T. Jämsén[c], S. Karpov[g], P. Keränen[d], A. Kurenya[g], H. Laitala[a], M. Lehtola[a], J. Narkilahti[a], S. Nurmenniemi[a], J. Peltoniemi[a], V. Petkov[g], H. Remes[a], M. Roos[f], J. Sarkamo[a], A. Yanin[g] and Q. Zhu[e]

(a) CUPP, University of Oulu, Finland
(b) CUPP, Pyhäsalmi, University of Oulu, Finland
(c) Sodankylä Geophysical Observatory, University of Oulu, Finland
(d) Department of Physics, University of Jyväskylä, Finland
(e) Institute of High Energy Physics, Chinese Academy of Sciences, Beijing 100039, China
(f) Department of Physical Sciences, University of Helsinki, Finland
(g) Institute of Nuclear Research of the Russian Academy of Sciences, Moscow, Russia
(h) Department of Physics and Astronomy, University of Århus, Denmark
Presenter: T. Räihä (Tomi.Raiha@oulu.fi) and C. Shen (shen@sun3.oulu.fi) fin-tomi-R-abs1-he12-poster

We are developing a new underground cosmic-ray experiment EMMA (Experiment with MultiMuon Array). It measures the multiplicity and lateral distribution of high-energy muons for studying the composition of primary cosmic-rays at the knee region. Our preliminary analysis of simulated events shows that due to different method used, EMMA can provide comprehensive and new information on the composition of cosmic-rays within a few years of running.

1. Introduction

The flux of high-energy cosmic-rays decreases substantially in the energies 10^{15} - 10^{16} eV in the so-called knee region. It may be related to cosmic-ray acceleration or propagation, or both. Also the composition of cosmic-rays may change around the knee.

The information of the cosmic-rays origin at the knee energies is lost due to galactic magnetic field. It is important to know the cosmic-ray composition at the knee energies itself. The study of the composition can also give us more information of the origin, acceleration and propagation mechanisms of high-energy cosmic-rays since it is difficult to study these directly.

2. EMMA detector

EMMA will be located in the underground laboratory of CUPP (Centre for Underground Physics in Pyhäsalmi) in Pyhäsalmi mine in Finland [1]. The detectors have two possible locations, 210 m and 85 m underground. We will use muon chambers used previously at CERN.

At the first phase EMMA will consist of two or three detector units of about 50 m^2 each. The distance between the detectors will be 14 m or 25 m depending on the location, respectively. We start from the 85 m level due to better statistics and later on may have a possibility to expand the caverns in most suitable depth.

The overburden filters all electromagnetic components, hadrons and the lower energy muons, but leaves a good signal of high-energy muons, produced at high altitudes close to the primary collision.

EMMA measures the multiplicity and lateral distribution of high-energy muons, which can be used to deduce the composition of cosmic-rays at the knee region. Many cosmic-ray experiments with different experimental setups have deduced indirect information of the composition at primary energies around the knee, but the results do not allow firm conclusions. The proposed EMMA experiment differs significantly from other experiments because it can obtain information of the lateral distribution of the high-energy muons originating close to the first interaction. Hence EMMA can shed light on the composition and air-shower development from a different point of view.

3. Muon lateral distribution

The first interaction height is an average higher for heavier than for lighter primary cosmic-rays. Higher interaction leads to a larger spread of the air-shower. Also a larger fraction of the secondary high-energy mesons decay into muons before scattering, since the atmosphere is sparser at these heights. It is experimentally known that the more massive the primary is, the more secondaries it produces in average. Secondaries are less energetic, and so they more probably decay before scattering. Finally, all this leads to a fact that the heavier primaries produce more muons and with wider spread than lighter ones on the ground. In Fig.1 we show the results of our simulation for the lateral distribution of muons with energy higher than 160 GeV.

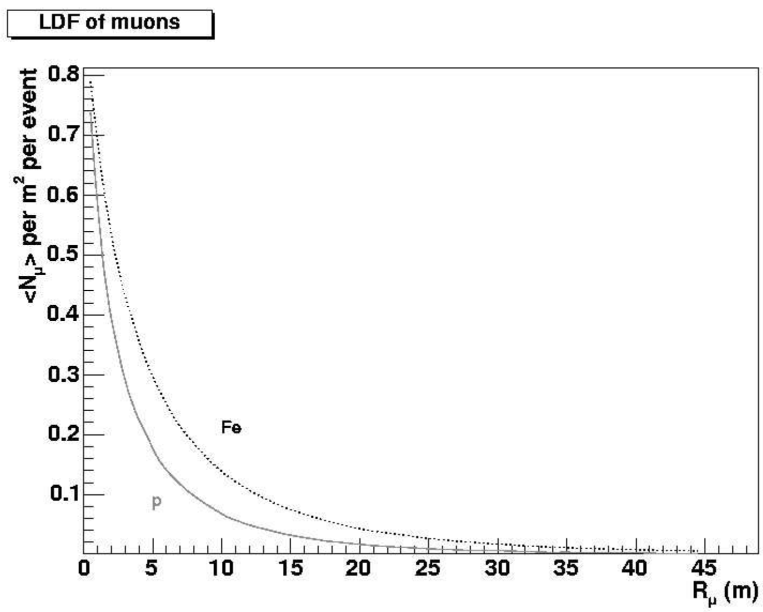

Figure 1. Lateral distribution of muons with energy higher than 160 GeV, originating from proton (lower curve) and iron (upper curve) initiated showers with energy of 1-10 PeV. The corresponding detector level is 210 m.

4. Preliminary analysis of simulated data

With detailed Monte Carlo air shower simulation program CORSIKA [2] we have simulated four samples of air showers in two energy regimes: below the knee (3 PeV) samples of 60 000 air showers initiated by protons and iron nuclei with spectral index 2.7 and above the knee samples of 30 000 proton and iron nuclei initiated showers with spectral index 3.1. These samples are combined to obtain the integrated particle flux corresponding roughly to ten months of data taking. For simplicity, we have assumed all showers to be vertical and we have cut off all particles below 160 GeV corresponding 210 m detector level.

By using suitable selection criteria we select only those events that have both energy in the interval we are interested in (below and above the knee) and the shower core close to or inside either of the detectors, to be able to define the muon lateral distribution. If we assume that the measured data will be a linear combination of the pure iron and pure proton simulated data, the primary composition can be deduced from the selected showers. The energy resolution of EMMA in this preliminary analysis is somewhat moderate: there is contamination outside of the selected energy range, leading into systematic errors, estimated to be of the order of 10%. At higher altitude at 85 m level due to higher muon multiplicity the systematic errors of energy resolution are expected to be smaller.

For example, in the two-component model for the primaries, assuming the true composition of 50% of iron nuclei and 50% of protons, we can measure the average primary mass below the knee with the accuracy $\langle \ln A \rangle$ = 2.01 $\pm$ 0.10 (1σ(stat. only)), corresponding to a ten months' running time and above the knee with the accuracy $\langle \ln A \rangle$ = 2.01 $\pm$ 0.17 (1σ(stat. only)), corresponding to a 30 months' running time. The average primary mass is defined as

$$\langle \ln A \rangle = \Sigma_i r_i \ln A_i, \tag{1}$$

where r_i is the relative abundance of the element with the mass number A_i. This accuracy, estimated straightforwardly, is comparable with many other experiments that study the composition of cosmic-rays around the knee region.

The analysis performed is preliminary. A more thorough analysis with inclined air showers and with proper muon propagation in the rock with Geant4 simulation code are subject to a future study.

5. Schedule and hardware

The prototype of EMMA is planned to run by the end of the year 2005. The experiment is then constructed unit by unit, so that all modules start taking data after installation. We expect to that by the end of 2007 we have 100 m^2 detector area taking data.

The EMMA will be constructed of the muon chambers used in the former DELPHI detector. The muon planks of drift chambers, 3.65 x 0.8 m and 3.65 x 1 m, will be assembled in two layers with 2.5 m in between, forming two 50 m^2 detectors. The gas mixture 7% CO_2 and 93% Ar is tested and found out to work well. Front-end electronics is the original used in Delphi detector which consists of discriminators and amplifiers. Data acquisition is done via VME-system. We are making flexible and programmable trigger electronics suiting all potential physics motivation.

6. Summary

The EMMA is a new kind of cosmic-ray experiment studying the high-energy muon multiplicities and lateral distribution underground. These muons, originating close to the first interaction, can shed light on the air-shower development in the early phase and composition of the primary cosmic-rays. The experiment is planned to start data taking by the end of the year 2007. EMMA is cost-effective, since it is planned to use muon chambers of the former DELPHI detector and it is placed in already existing caverns.

7. Acknowledgements

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References

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