EMMA – A New Underground Cosmic-Ray Experiment

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Abstract

A new type of cosmic-ray experiment is under construction in the Pyhäsalmi mine in the underground laboratory of the University of Oulu, Finland. It aims to study the composition of cosmic rays at and above the knee region. The experiment, called EMMA, will cover approximately 150 m\textsuperscript{2} of detector area. The array is capable of measuring the multiplicity and the lateral distribution of underground muons, and the arrival direction of the air shower. The full-size detector is expected to run by the end of 2007.

Key words: cosmic rays, composition, muon lateral distribution, muon multiplicity, air shower, underground experiment

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1 Introduction

Due to a slight change observed in the cosmic-ray energy spectrum in the energy interval of $10^{15} - 10^{16}$ eV, it is believed that the origin, modification in the chemical composition, acceleration mechanism or propagation of cosmic rays (or a combination of these) changes. Up to this energy, so called knee region, most cosmic rays are supposed to be produced inside the galaxy, and are also confined by the galactic magnetic field.

At these high energies the source cannot be observed directly and the cosmic-ray composition is used as a tool to investigate the origin of the cosmic radiation. The direct composition measurements are no longer practical at or above the knee and the method is solely based on the measurement of extensive air showers, i.e. the secondary particles created in the atmosphere and detected by large arrays on the ground.

The origin of the knee has been one of the fundamental problems of cosmic-ray physics, and it has been discussed for decades. Several models have been presented predicting different composition at the knee energies, and could only be identified by the experimental evidence on the composition. Some new experimental efforts have been devoted to the study of cosmic rays in recent years. These experiments are based, for example, on multi-parameter measurement of extensive air-showers, on shower maximum measurement by Čerenkov or fluorescence detectors and on underground multimuon measurements (see, for example, Ref. [1] and references therein). Their conclusions, however, have so far been diverse, implying the need for further studies, especially using different approaches. The results are also known to be strongly model dependent.

EMMA (Experiment with MultiMuon Array) uses a different approach. It is not the first underground cosmic-ray experiment (see, for example, Refs. [2,3,4,5,6]), but it differs significantly from previous underground experiments with its ability to measure the lateral distribution function of underground muons. In EMMA the composition analysis is based on the lateral distribution of high-energy muons and on their multiplicity. The muons detected by EMMA are generated in the upper part of the air shower close to the primary interaction.

2 Experimental details

The present experiment will be carried out at the depth of 85 metres in the Pyhäsalmi mine (owned by the Inmet Mining Corporation Ltd., Canada), which is situated in the middle of Finland.
The EMMA detector array consists of drift chambers (muon barrel (MUB) detectors) previously used in the LEP–DELPHI experiments at CERN [7]. The setup is able to measure the arrival direction of the air shower, the muon multiplicity and their lateral distribution. This is carried out by an array of separate detectors with the total detector area of about 150 m². Part of the array is in two layers with a vertical distance of 2.5 metres between the layers in order to obtain the direction information (see Fig. 1 for details).

Most of the drift chambers have an active volume of 365×20×1.6 cm³. A plank consists of seven chambers (partly overlapped) having an area of approximately 3 m². The layout of Fig. 1 requires 60 planks. The drift chambers operate in the proportional mode, with Ar:CO₂ (92:8) nonflammable gas mixture. Due to the safety issues, the gas mixture does not contain CH₄. Each drift chamber can provide up to three signals, one anode signal and two delay line signals (near and far), which can be used to localise the positions of particles passing through the chambers. The measured position resolution of the chambers in our setup is about 1 cm and 3 cm along the drift direction and along the drift line, respectively.

Recycling the old muon barrel detectors provides a the possibility to build the array at low costs. Also the use of existing caverns of the mine reduces the costs. The data-acquisition electronics is build by ourselves or bought as new.
3 Data analysis

3.1 Muon tracking

An important part of the data analysis software is the muon tracking routine. As it is obvious that an observed shape of the shower partially depends on the angles it hits the detectors, the shower can only be reconstructed by determining the angles of individual muons. In EMMA the shower reconstruction will be carried out by tracking muons as they hit simultaneously to two detector planes (the three double-layer units shown in Fig. 1).

The simulated performance of the muon tracking routine is illustrated in Fig. 2 using an example where eight simultaneous muons penetrate two detector planes with a randomly chosen shower angle. The tracking code employs an automatic routine which connects the pairs in two planes and rejects pairs too far from the average angle.

The tracking routine will be tested with real cosmic-ray muon data at the surface in the end of 2005 and in the beginning of 2006 using system similar to Fig. 2, and it will be further developed.
3.2 Locating core position

In order to reconstruct the lateral distribution of underground muons and their multiplicity, the core of the air shower has to be located accurately (i.e. within metres). A two-dimensional fit routine was developed for the extraction of the core location. The routine was tested with simulated air-shower samples. Depending on the hit position of the core, it can be extracted with an accuracy better than three metres in most cases if the core hits the detector unit or between them. If the core is elsewhere, the accuracy is weaker and the distribution slightly biased, but this can be corrected for. In the current version of the core-location software the routine uses model-dependent lateral distributions. However, we are developing a routine that works in the model-independent way, which would allow a direct comparison between measured lateral distribution and different model predictions.

3.3 Extracting composition

The multiplicity measurements at distances between 20 and 30 metres from the core position are expected to be the optimal cases for separating different cosmic-ray primary particles. As the core is located and the lateral distribution is fitted for each shower, the measured lateral distributions are used to extract the composition information as a function of the primary energy. The number
Fig. 4. The separation of primary cosmic-ray composition and energy, in two-dimensional plot of $\rho(1 \text{ m})$ versus $\rho(20 \text{ m})$. See text for details. The plot is based on simulations of proton and iron primaries with energies of 1, 3 and 10 PeV.

of muons at the core can be used as an indicator for the primary energy. The energy resolution of EMMA according to this preliminary analysis is somewhat moderate.

4 Expected results

As no experimental results have been obtained yet, expected results based on simulations are introduced in this section to present some of the performance of the EMMA array. The simulations serve, at the same time, also a way to develop and further improve the methods to analyse and to interpret the data. The air-shower simulations and particularly the data analysis methods are still preliminary but they already indicate the good capabilities of the EMMA array.

According to cosmic-ray air-shower models (e.g. CORSIKA & QGSJET [8,9]) the lateral distribution, or its gradient, of high-energy muons is sensitive to primary cosmic-ray particles and their energies, and to hadronic interactions. Also the muon multiplicity is sensitive to the energy. The simulated (using CORSIKA & QGSJET) lateral distribution functions of muons are shown in Fig. 3 for three discrete energies of 1, 3 and 10 PeV for proton- and iron-initiated showers, being the most relevant for the present experiment. Only muons with energies above 50 GeV are included in Fig. 3.
The method of the cosmic-ray composition study in the present work is illustrated in Fig. 4 where the separation of two primary cosmic-ray particles with three different energies is shown. The figure is generated by fitting the lateral distribution functions to muons in an air shower and extracting the muon densities at distances of 1 and 20 metres ($\rho(1 \text{ m})$ and $\rho(20 \text{ m})$, respectively) away from the located core position. The composition and energy of the primary cosmic ray can then be extracted, for example, using variables $\rho(1 \text{ m})$, which is related to the energy, and $\rho(20 \text{ m})$, which is related to the composition.

In reality, different groups (or groups of elements) in the plot would be less pronounced than those simulated and shown in Fig. 4. This is due to poorer statistics and an uncertainty related to the core position determination, and also continuous cosmic-ray primary energy spectrum (Fig. 4 shows only three discrete energies for only two primary particles).

The effective area of the array determines recorded statistics. The area in the EMMA experiment is expected to be between 100 m$^2$ and 1000 m$^2$. Fig. 5 shows the expected numbers of air showers collected as a function of cosmic-ray primary energy.
5 Summary

A new underground cosmic ray experiment EMMA is under construction and it is expected to start recording data in the full scale by the end of 2007. With a partial-size array the data recording can be started by the middle of 2006. The analysis of simulated air showers shows that the primary cosmic-ray composition could be resolved (with a two-component model) at and above the knee energies. A possibility for the model-independent way of the determination of the muon lateral distribution would allow to improve high-energy interaction models. Due to new method used, the EMMA experiment could provide comprehensive (and perhaps new) information on the composition of the cosmic rays at the knee region within the next few years.

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