An Approach to Study the Cosmic Ray 'Knee' Composition from Underground Multimuon Events at a Shallower Depth

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Abstract

The observation of underground multimuon phenomena is an important way for the study of the cosmic ray composition in the 'knee' region ($10^{15} - 10^{16}$ eV). It is noticed that the existing deep underground detectors are not very ideal for the composition study because they were originally designed for other aims. A new approach having higher sensitivity for this study by observing multimuon events using a detector array in a shallower depth underground is presented. This approach is suggested by a Monte Carlo simulation and the problem of model dependence is discussed.

1 Introduction

It is a common thought that the appearance of the 'knee' in the cosmic ray all-particle spectrum is mainly related with the origin, acceleration and propagation of galactic cosmic rays. As one of fundamental problems of cosmic ray physics this topic has been discussed for decades. Different models have been presented that predict different chemical compositions at the 'knee', and could only be identified by the experimental evidence on the composition. In recent years some new experimental efforts have been devoted to this topic using multi-parameter measurement of extensive air showers (EASs)[1], shower maximum measurement by Cerenkov radiation[2] and underground multimuon measurements at a depth about 1 km[3].

In an EAS muons are decay products of hadrons produced in hadronic and nuclear interactions induced by a cosmic ray nucleus incident to the atmosphere. Normally thousands of muons are produced in an EAS with a 'knee' energy. For incidences of different nuclei with same energy, as commonly recognized, the number of muons, its lateral distribution and its energy spectrum are statistically different. These features can be seen in Fig.1 which are from a sample of Monte Carlo events (for details, see below) obtained at the energy region $10^{15} - 10^{16}$ eV. We are interested in the differences both in the absolute intensities and in the slopes of proton and iron distributions. However, only very few of produced muons can penetrate to a deeper depth underground, say 1 km, thus one loses most information there. In order to increase the observational sensitivity of the composition in the 'knee' from multimuon events we propose a new approach paying more attention on utilizing these information as much as possible.

2 Detection Consideration

As shown in Fig.1, comparing with proton events, muons in iron events have following features: larger total number, less concentration to the core, and smaller number density gradient in the lateral distribution. These features are naturally resulted from, compared with the proton case, the larger cross-section (higher first interaction height), lower energy per nucleon and the lower average energy of mesons (larger number and larger angular spread of muons). In addition the fragmentation of iron nucleus may also contribute a further lateral spread.

In order to record these differences experimentally our basic demands are: using a detector array with larger area and set up it at a shallower depth underground to record more muons; having good position resolution and multi-track reconstruction efficiency to give more precise number of hitting muons; being able to choose those events for that shower cores hit (or very close to) a detector and to measure the number gradient of muons with several detectors surrounding it.

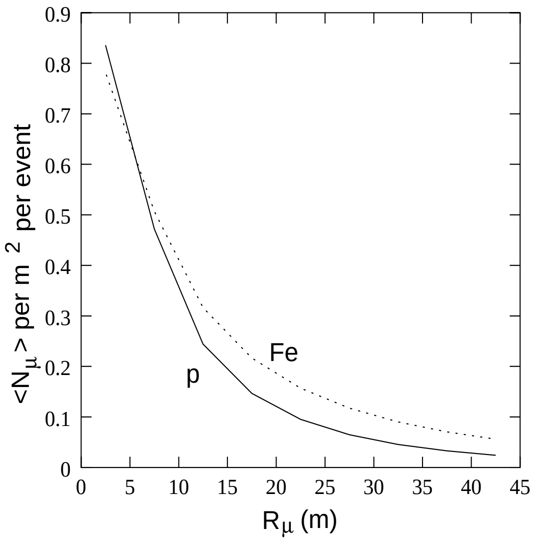

Fig.1 The lateral distribution of $< N_\mu >$ from a p and a Fe sample at $10^{15} - 10^{16}$ eV

As an example, the whole facility may be proposed to consist of 7 identical detectors each with an area of 100 m^2, arranged as a hexagonal array with one detector located in the centre and other six in six corners with a mutual distance of about 35 m and is assumed to be set up at a depth of about 50 m underground. RPC (Resistive Plate Chamber), taking its fast timing, good space resolution and cheaper cost per unit area, is suggested as the detector to measure the number of hitting muons for that a position resolution about 5 cm and an angular resolution about 1 degree are requested.

3 Monte Carlo Event Generation

The physics expectation was obtained by a Monte Carlo. We used the code developed in Beijing - Hong Kong[5] for the EAS simulation. A minijet model for hadronic interactions is used that was well adjusted to reproduce the existing hadron collider data. A superposition model is adopted for the nucleus-nucleus interactions. For hadron-air nucleus inelastic interactions an $E^{0.05}$ cross section law is taken to suit other cosmic ray data.

All muons with energies higher than 50 GeV are traced in the Monte Carlo till they reach the sea level. When they penetrate underground an average energy loss that include the ionization, bremsstrahlung, pair production and photonuclear interactions is taken into account[6]. The multiple scattering is also evaluated[6]. It is assumed at present stage that muons hitting detectors could be recorded with efficiency 1 and multimuon events can be well reconstructed.

In order to describe the event selection criteria we define the 'central' detector and the 'outer' detectors. Any one detector in the array could be the 'central'. If the one in the center position of the whole facility is the 'central' the six surrounding it are 'outer'. If any one of other six is the 'central' other three most close to it are 'outer'.

The event selection criteria are:

(1) There are at least one muon hitting for every 'outer' detector;

(2) The number of muons hitting the 'central' detector is equal to or larger than w times the number of muons hitting any one of the 'outer' detectors, and we take w=5.

In order to concentrate our study in the 'knee' region the contamination of those events that satisfy the selection criteria (1) and (2) but come from lower energy region (say, from $10^{14} - 10^{15}$ eV) must be ruled out. Fortunately, when we use (1) and (2) in this energy region, the distributions of the average number of muons in the 'outer' detectors for both proton and iron cases are dropped rapidly, meaning that these events could be cut by adding a new criterion:

(3) The average number of muons hitting outer detectors, $< N_\mu^{outer} >$, must be equal to or larger than 7.

Hereafter we briefly call criteria (1), (2) and (3) as $w = 5$.

4 Result Expectation

In both proton and iron incidence cases we dropped 240,000 simulation events with energy from 10^{15} eV to 10^{16} eV in a circle area with a radius of 55 m from the center of the array. In this sample the zenith angles are only distributed from 0 to 20 degrees. This sample is equivalent to a data set of 500 days operation. It should be mentioned that those events having larger zenith angles are also useful for the composition study.

To see the selection efficiency the 2-dimensional distribution of the core positions of events selected by $w = 5$ is shown in Fig.2 which shows that w=5 could select events with core position inside or very close to the 'central' detector. Therefore, the composition sensitivity existing in the core region and in the density gradients of muon lateral distributions could be measured. It should be noted that Fig.2 is for proton incidence case. For iron case the distribution is even more concentrated to each detector.

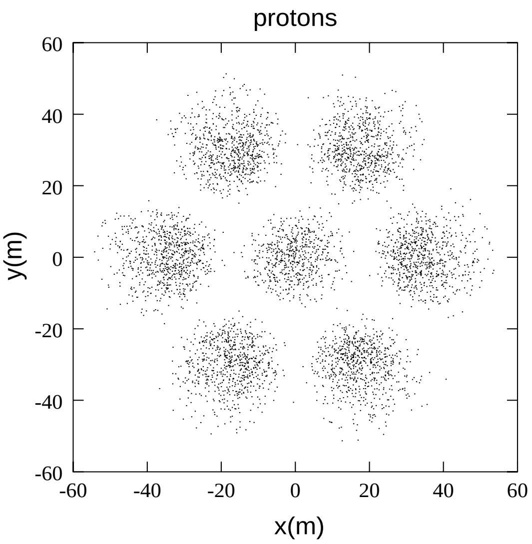

Fig.2 The core positions of events selected by $w = 5$ for p incidence case at $10^{15} - 10^{16}$ eV

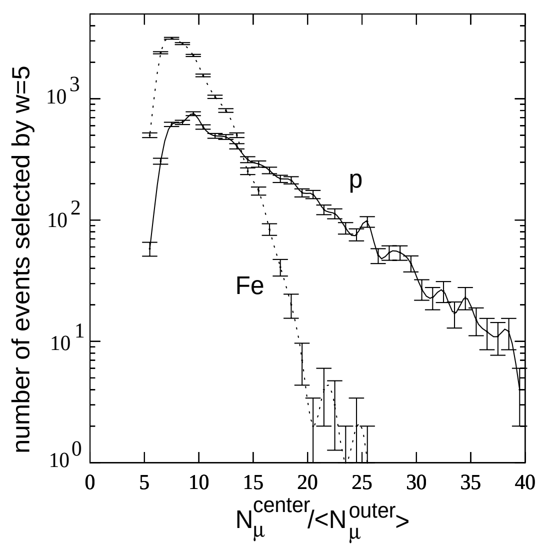

Fig.3 Using $w = 5$ the resulting distribution of $N_\mu^{central}/ < N_\mu^{outer} >$ at $10^{15} - 10^{16}$ eV and $\theta = 0° - 20°$

One of the results is seen in Fig.3 that is the distribution of the ratios for the number of muons of the 'central' detector over the average of 'outer' detectors in each event. The slopes of p events and Fe events are seen to be significantly different.

5 Discussion and Summary

For the result shown in Fig.3 we discuss on the following aspects: First, the contamination from the higher energy region ($10^{16} - 5 \times 10^{16}$ eV) was analysed. It can not be removed by a straightforward way. But due to the much lower event flux in this energy region the distributions of Fig.3 are shown not to be essentially influenced by it. Second, the simulation results for events with zenith angles from 20 to 40 degrees also show the similar sensitivity. Due to the larger acceptance 200 days' exposure can give similar results as shown in Fig.3. Third, the 50 m depth, the 100 m^2 detector area, the 35 m distance between detectors and the value 5 for w are all chosen with simplified quantitative considerations. More analyses are needed to achieve optimized values.

An important problem we have to consider is the model dependence of the results. It is emphasized that the differences existing in features of proton events and iron events as discussed above should be qualitatively correct for any interaction models. Some model dependences might exist that may change the slope and/or the intensity of Fig.3, thus need to be checked. Indeed, our recent simulations using CORSIKA-QGSJET[7] and COSMOS[8] showed such differences. Thus we suggest a self-calibration way for the model checking that is to see, after taking all detection efficiency into Monte Carlo data, whether the experimental data cross the crossing point of proton curve and iron curve giving by the model simulation as shown in Fig.3, and whether the model simulation in 10^{14} eV energy region where the composition has been known by direct measurement could give the consistent results with multimuon data.

In summary, we proposed an approach to select the core part and to measure the number gradient of multimuon events in the 'knee' energy region at a shallower depth underground. For the event selection criteria w=5, the corresponding distributions are shown to have higher composition sensitivity.

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