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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 underground detectors are not very ideal for the composition study because they were originally designed mainly 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.

Key words cosmic ray composition, 'knee' region, underground multimuon phenomena

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. In these aspects different models have been presented. They predicted different chemical composition at the 'knee' energies, 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 that are originally 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 detail, see below) obtained at the energy region $10^{15}-10^{16}$ eV. We are interested in the differences both in the absolute values 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

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sensitivity of the composition in the 'knee' region from multimuon events we propose a new approach paying more attention on utilizing these information as much as possible.

We may further discuss the difference 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 (the higher height of the first interaction in the atmosphere) and the lower average energy of mesons (larger number and larger angular spread of muons). In addition the iron nucleus fragmentation may also contribute a further lateral spread.

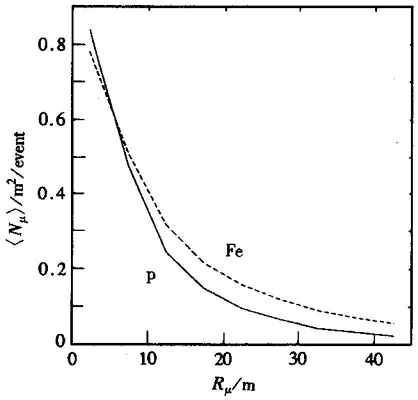

Fig. 1. The lateral distribution of $< N_\mu >$ from a p and a Fe sample in energy region 10^{15}—10^{16} eV.

In order to record these differences experimentally our basic demands are: using larger detector and setting up the detector 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.

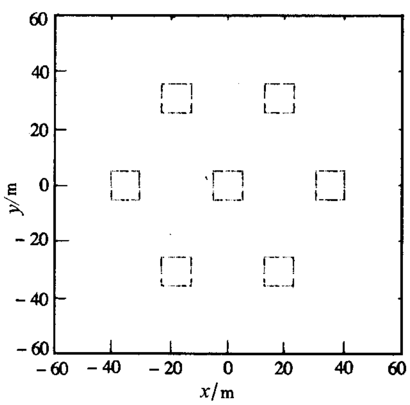

Fig.2. A schematic display of the detector array.

The whole facility is 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 (Fig. 2) and is assumed to be set up at a depth of about 50 m underground. RPC (Resistive Plate Chamber) is the first candidate for the detector, and used to measure the number of hitting muons for that a position resolution about 5 cm and an angular resolution about 1 degree are requested. Our simulation shows that on the average only 0.1% of muon pairs in an EAS event in the energy region 10^{15}—10^{16}eV have a mutual distance shorter than 5 cm. RPC also provides timing information of particle hitting which is used for the event trigger.

The physics expectation was obtained from a Monte Carlo. We used the Monte Carlo code developed in Beijing-Hong Kong[5] for the EAS simulation. For hadron-hadron collisions the minijet model is used which 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]. However, some less important effects are temporarily ignored, such as the fluctuation of muon energy loss in the rock and the single scattering with large angle. The detector efficiency is assumed to be 100%. It is also assumed that the multimuon events can be well reconstructed and the number of muons can be counted correctly.

Before giving the event selection criteria we first 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 the average number of muons hitting the 'outer' detector by a factor of 5.

In order to concentrate to the 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, $\langle N_{\mu}^{\text{outer}} \rangle$, must be equal to or larger than 7.

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

In both proton and iron incidence cases we dropped 240000 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, not including those events having larger zenith angles that are also useful for the composition study.

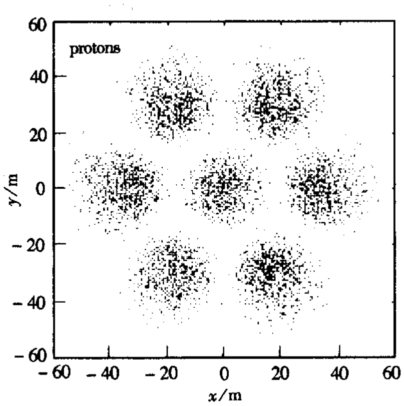

Fig.3. The core positions of events selected by $w = 5$ for p incidence case in energy regior 10^{15}—10^{16} eV.

To see the selection efficiency the 2-dimensional distribution of the core positions of events selected by $w = 5$ is shown in Fig.3 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 kept and measured. It should be noted that Fig.3 is for proton incidence case. For iron case the distribution is even more concentrated.

Then the results are seen in Figs. 4, 5 and 6. First, the distributions of the ratios for the number of muons of the 'central' detector over the average of 'outer' detectors are shown in Fig.4. The slopes of p events and Fe events are seen to be significantly different. Fig.5 is the distribution of the number of muons in 'central' detectors. In Fig. 6 is shown the same distribution of 'outer' detectors.

For the results shown in Fig. 4, 5 and 6 we discuss on the following aspects: First, the contamination from higher energy region ($10^{16}-5\times10^{16}$ 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. 4, 5 and 6 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. 4, 5 and 6. 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.

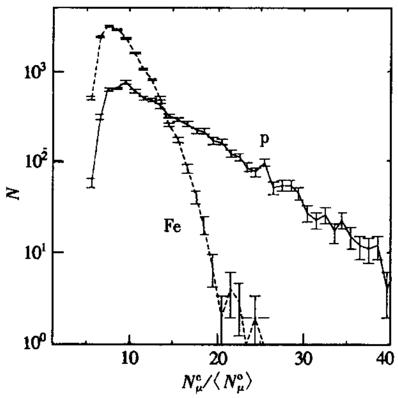

Fig. 4. Using $w=5$ the resulting distribution of $N_\mu^{\mathrm{central}}/<N_\mu^{\mathrm{outer}}>$ in energy cegion 10^{15}—10^{16} eV and $\theta=0°$—$20°$.

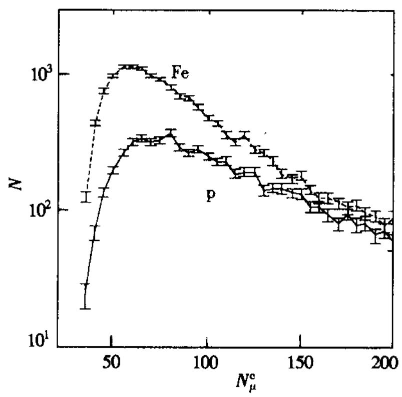

Fig.5. Same as in Fig.4, but for N_μ^{central}.

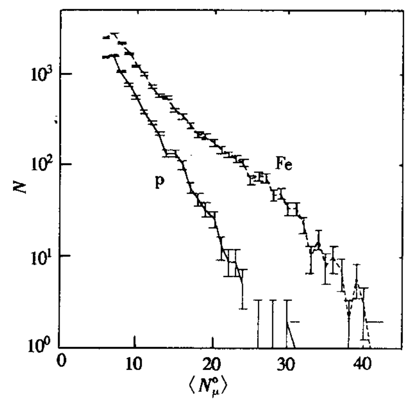

Fig.6. Same as in Fig.4, but for N_μ^{outer}.

In addition we have to consider the model dependence of the results. All above results were obtained by a special Monte Carlo code that uses minijet model. However, our analysis of the differences existing in features of proton events and iron events should be qualitatively correct for any interaction models. Some model dependences might exist that may change the slope and/or the intensity of Fig. 4, 5 and 6 somewhat, thus need to be checked. A better way for the self-calibration of a model used is suggested 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. 4, 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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通过浅层地下多μ事例研究“膝”区宇宙线成分的一种途径

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摘要　地下多μ现象的观测是研究“膝”区(10^{15}—10^{16} eV)宇宙线成分的一种重要方法．现有的地下探测器对于成分研究不甚理想，因为它们原本主要是为其它目的而设计的．我们提出一种新的途径：用一个探测器陈列在浅层地下观测多μ事例．这一方法对成分研究具有较高的灵敏度．

关键词　宇宙线成分　“膝”区　地下多μ现象

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