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A Monte Carlo study to measure the energy spectra of the primary heavy components at the knee using a new Tibet AS core detector array and a large underground muon detector array

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Abstract: The first phase experiment of the Tibet hybrid experiment to measure the energy spectrum of the light components (proton and helium) strongly suggested that the knee region should be dominated by heavy components. A large underground muon detector array (Tibet-MD) is being planned for the next phase experiment. In this paper, the capability of the measurement of the chemical components with use of the Tibet-AS+MD is investigated by means of an extensive Monte Carlo simulation in which the secondary particles are also propagated through the AS + MD array. Our simulation shows that the new installation is powerful enough to study the chemical composition at energies around and over the knee.

Introduction

The energy spectrum of observed cosmic rays is expressed by a power law from about 10^{10} to 10^{20} eV with a slight change of slopes between 10^{15} to 10^{16} eV. The break of the all particle spectrum at around several times 10^{15} eV is called the "knee". The chemical composition of the cosmic rays at the knee is considered as a key information to understand the cosmic-ray acceleration and the propagation in the galaxy [1].

The first phase of the Tibet hybrid experiment to measure the energy spectrum of the light components (proton and helium) strongly suggested that the knee region is dominated by heavy components [2]. Thus, a new type of large underground muon detector array (MD) is under the development where the capability of the explicit measurement of the heavy components are investigated. The merit in doing the experiment in Tibet is that the atmospheric depth of the experimental site (4300 m a.s.l., 606 g/cm^2) is close to the maximum development of the air showers with energies around the knee almost independent of the masses of primary cosmic rays. Thus, Tibet-AS+MD array has a capability of performing the explicit measurement of the heavy components at energies around and over the knee.

Tibet-III air shower array and Muon detector array

The Tibet air shower experiment has been successfully operating at Yangbajing (90.522° E, 30.102° N, 4,300 m above sea level) in Tibet, China, since 1990. The details of the Tibet-III air shower array (AS) are described in the paper [3]. The Tibet-III AS array (36,900 m^2) is used to measure the shower size and the arrival direction of each air shower. The primary energy of each event is determined by the shower size N_e, which is calculated by fitting the lateral particle density distribution to the modified NKG structure function.

We are also planning to set up a new burst detector array (BD) in the central part of the Tibet-III array.

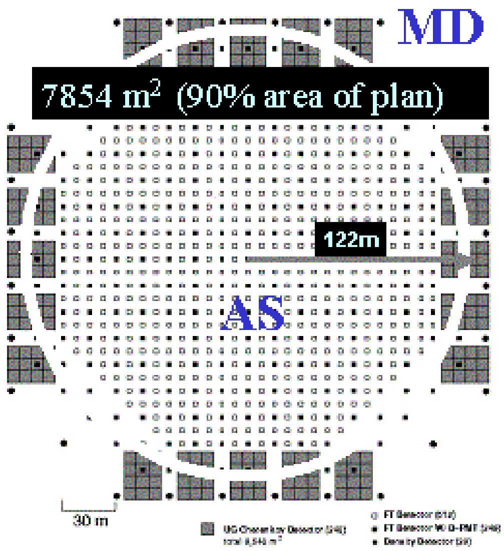

Figure 1: Schematic view of the Tibet-AS+MD array. Open squares and open circles represent the surface scintillation detectors that compose the Tibet-III AS array. Filled squares show the proposed Tibet MD array 2.5 m underground.

This BD array will be composed of about 400 burst detectors which are uniformly placed in the area of about 5000 m^2. Each detector is a sandwich of lead plate of about 3.5 cm thickness and plastic scintillator to detect high energy air shower cores. The details of the BD array are described in the paper [4],[5]. This array will be operated together with the following MD array in the near future. We do not, however, discuss the performance of this BD array in this paper.

A proposed configuration of the Tibet-MD array is shown in Fig.1. The MD array consists of 20 units, each of which contains 12 muon detectors of 36 m^2 in area. Each muon detector is a waterproof concrete pool of 6 m wide $\times$ 6 m long $\times$ 1.5 m deep in size. Two 20 inch-in-diameter photomultiplier tubes (PMTs, Hamamatsu R3600) are put on its ceiling, facing downwards. Its inside is painted with white epoxy resin for waterproof and efficient reflection of the water Cherenkov light. This MD array is set up 2.5 m underground ($\sim$ 19 radiation lengths) in order to detect the penetrating muon component of air showers, suppressing the electromagnetic one. Its total effective area is 8,640 m^2, and this MD array is used to measure the number of muons ($E_\mu > 1$ GeV) accompanying an air shower.

Simulation

We have carried out a full Monte Carlo (MC) simulation of air showers using the simulation code CORSIKA (version 6.204) including QGSJET01c and SIBYLL2.1 hadronic interaction models [6]. Since the Tibet hybrid experiment of the air shower array and the burst detector array to measure the energy spectrum of the light components (proton and helium) strongly suggests that the knee region is dominated by heavy components [2], a heavy dominant (HD) composition model [7] is adopted in this MC simulation. All secondary particles are traced until their energies become 1 MeV in the atmosphere. Simulated air-shower events were input to the detector with the same detector configuration as the Tibet-III array with use of Epics code (ver. 8.64) [8] to calculate the energy deposit of these shower particles.

In our experiment, the number of charged particles detected by each scintillation detector is defined as the PMT output (charge) divided by that of the single peak, which is determined by a probe calibration using cosmic rays. According to the MC, the peak value of the energy deposit for a single particle in each detector is calculated as 6.11 MeV. Based on this result, we can estimate the number of charged particles from the observed ADC value for each hit detector. Thus, all detector responses including the materialization of photons inside the detector are taken into account in this simulation. In this paper, we define the shower size as the sum of the number of charged particles passing through the plastic scintillator in all detectors.

In this paper, we have not done muon detector simulation yet, but instead of this, we did the following approximate simulation, that is, when a muon event ($E_\mu > 1$ GeV) enters the circle area (90% area of plan) as shown in Fig.1, this event is recorded, and its accompanying air shower is then recorded simultaneously.

Analysis

First, we selected only the events accompanying muons with $E_\mu > 1$ GeV which fall in the circular ring of 122 m $<$ r $<$ 132 m, where r is a radius from the center of the Tibet-III array (Fig.1). The following conditions are then imposed on the selection of air shower events : 1) more than 10 detectors should detect a signal of more than five particles per detector, 2) the central positions weighted by the 8th power of the number of particles at each detector should be inside the innermost 135 m $\times$ 135 m area, and 3) the zenith angle of air shower events should be smaller than 25 degrees ($1.0 < \sec\theta < 1.1$). The effective area of the array in the condition 2) is chosen with use of MC events so that the following two cases are just canceling out each other, namely, the number of events originally inside of this area but falling outside after event reconstruction equals to the number of events in the opposite case.

The shower size of each event is estimated using the modified NKG function which is optimized by the Monte Carlo simulation by using QGSJET01c+HD model and SIBYLL+HD model independently [3].

Results and Discussions

Shown in Fig.2 is the correlation between the number of muons and air shower size on each event observed with the Tibet-AS+MD array. The solid line is a best fit curve expressed by the relation N_μ = a $\times$ $(Ne/1000)^b$. It is seen from this figure that there exists no significant difference between the QGSJET01c and SIBYLL interaction models. This suggests that if we further impose an air shower core information ([4],[5]) on the correlation shown in Fig.2, we can study the details of the primary composition at energies around and over the knee.

Fig.3 shows the ratio of the number of muons in air showers of nuclei origin to that of proton origin plotted as a function of the shower size N_e. Combining both data from the MD array and from the BD array in the future, we may be able to classify the experimental data into different primary mass group.

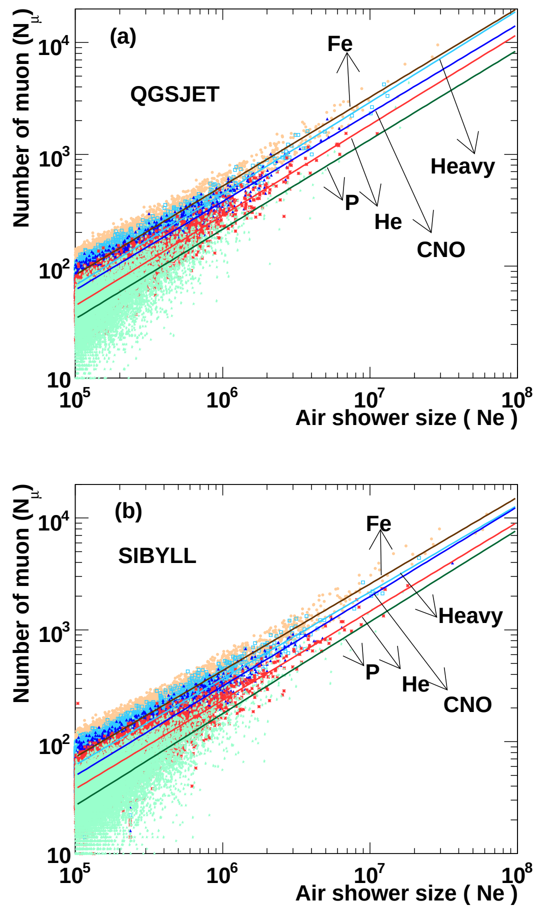

Figure 2: The correlation between the number of muons and the air shower size (Ne) for air showers with the zenith angle less than 25 degrees under the lead plate at the Tibet observation level. The solid line is a best fit curve expressed by the relation N_μ = a $\times$ $(Ne/1000)^b$.

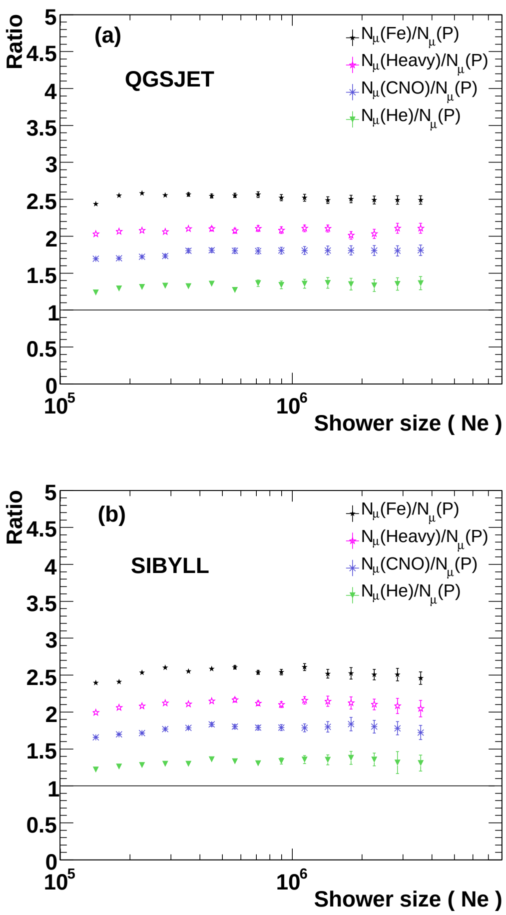

Figure 3: Fraction of the number of muons in air showers of nuclei origin to that of proton origin calculated for interaction models of (a) QGSJET and (b) SIBYLL.

Summary

With the advent of the Tibet-AS+MD array capable of observing Ne and N_μ, a study on the chemical composition of the cosmic rays at energies around and over the knee will be further developed in the very near future. While the present simulation is still limited on the number of muons in the air shower without taking into account of the details of the detector response of MD, it is shown that a new AS+MD array is powerful enough to study the chemical composition, in particular the primary cosmic ray composition including heavy components at energies around and over the knee. A test experiment of the muon detector with the area 100 m^2 will start from this year. More detailed MC study is still under way to estimate the systematic errors due to the primary composition and interaction model, as well as some other biases.

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