Study on the primary mass sensitivity of muon multiplicity measured with (YAC-II +Tibet-III + MD) experiment

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Abstract: A new hybrid experiment (YAC-II+Tibet-III+MD) whose installation consists of Tibet air-shower array (Tibet-III, 789 units, 37000 m^2), Yangbajing air shower core array (YAC-II, 124 units, 500 m^2) and underground water cherenkov muon detector array (MD, 80 units, 5000 m^2), has been constructed by the Tibet ASγ collaboration at Tibet, China. The data taking will be started this year. MC air-shower data of each primary component (P, He, CNO, Fe etc) by using various hadronic interaction models (QGSJETII-04, SIBYLL2.1) are obtained by means of a full MC simulation in which the secondary particles of air showers reaching at Yangbajing level are propagated through the (YAC-II+Tibet-III+MD) detector system by using Geant4 (ver. 9.5). Investigating the correlation between the air-shower size (Ne) and the number of muon (Nμ) for different composition, we will report the primary mass sensitivity and interaction model dependence on the muon multiplicity in our (YAC-II+Tibet-III+MD) hybrid experiment.

Keywords: hybrid; air-shower; component; simulation; muon multiplicity

Introduction

The energy spectrum of cosmic rays is expressed by a power law from about 10^{10} to 10^{20} eV. The all-particle spectrum has a slight break where the spectral index changes from -2.7 to -3.1 at around several times 10^{15} eV. So the break is called the "knee". The chemical composition of the primary cosmic rays at the "knee" is considered as a key information to understand the cosmic-ray origin, acceleration and propagation in the galaxy[1].

At the moment the chemical composition of ultra-high energy cosmic rays from 10^{18} to 10^{20} eV is also under the discussion. The experimental result of TA[2] shows the light elements are dominant but Auger provides the evidence that the composition becomes heavier from $10^{18.5}$ eV as shown in Fig.1[3]. The proportion of various cosmic-ray components at "knee region" could offer some relation to the composition of ultra-high energy cosmic rays.

A new hybrid experiment (YAC-II+Tibet-III+MD) located at Yangbajing with the advantageous geographical conditions(4300m above sea level(a.s.l.), atmospheric depth:606g/m^2), has started to improve the capability of explicit measurement of the cosmic-ray components(P, He, CNO, Fe etc) at energy from 10^{14} to 10^{16} eV. The new hybrid experiment can accurately measure the number of μ and the air-shower size. Present work demonstrates the advantage of Ne-Nμ correlation measured at high altitude which is used for the study of the chemical composition of primary cosmic rays.

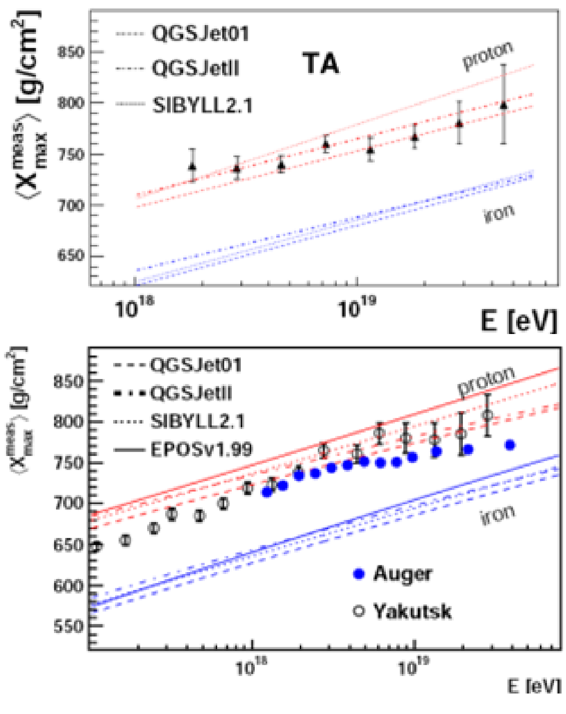

Figure 1: Chemical composition of ultra-high energy cosmic rays

(YAC-II+Tibet-III+MD) experment

The new hybrid experiment including air shower core array, Tibet air-shower array and underground muon detector array located at Yangbajing(90.522 E, 30.102 N, 4300 m above sea level, atmospheric depth:606g/m^2) in Tibet,

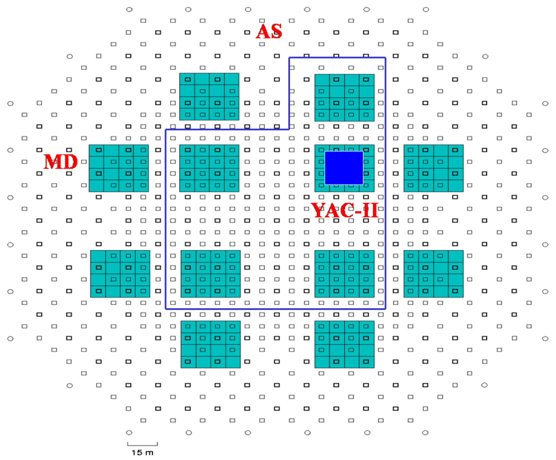

Figure 2: Schematic view of the new hybrid experiment: Air shower core array(blue), Tibet air-shower array(white open squares and white open circles), Underground muon detector array(cyan open squares, MD detectors in blue wire frame have been built)

China has been constructed as shown in Fig.2. and these installations are going to be operated this year. The merit in doing the experiment in Tibet is that the atmospheric depth of the experimental site is close to the maximum development of the air showers with energies around the knee almost independent of the masses of primary cosmic rays. Yangbajing air shower core array(YAC-II, 500 m^2) contains 124 units whose size is 0.5m$\times$0.8m in the center of the new hybrid experiment. The inner 100 YAC-II plastic scintillator units are arranged as an array (10$\times$10 grid) with 1.875 m interval; the outer 24 units are arranged around the inner array. they are used to reject non core events whose shower cores are far from the YAC-II array. Each detector of YAC-II consists of lead plates with a thickness of 3.5 cm above the scintillator to convert high energy electrons and γ into electromagnetic showers. Yangbajing air shower core array is used to observe the high energy particles near the shower axis.

The Tibet air-shower array(Tibet-III) has the coverage (36900 m^2) including 789 units each of which are composed of 0.5cm thick lead plate, plastic scintillator and optical cavity etc. The more details of Tibet-III are illustrated in the paper[4]. The Tibet air-shower array is used to measure the air-shower size and the arrival direction of each air shower. The primary energy of each event is determined by the shower size Ne, which is calculated by fitting the lateral particle density distribution to the modified NKG lateral distribution function. Underground muon detector array(MD) of total coverage $\sim$5000 m^2 consists of 12 units(5 of them have been built), each of which contains 16 muon detectors setup at 2.5m underground. Each muon detector is a waterproof concrete pool of 7.2 m wide $\times$ 7.2 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 improving reflection efficiency of the water Cherenkov light. The soil with a thickness of 2.5m($\sim$ 19 radiation lengths) is used to get rid of most of electromagnetic components and hadronic components with low energy. Although the primary role of MD is to measure the number of muons(E$\mu \geq$ 1 GeV) in an air

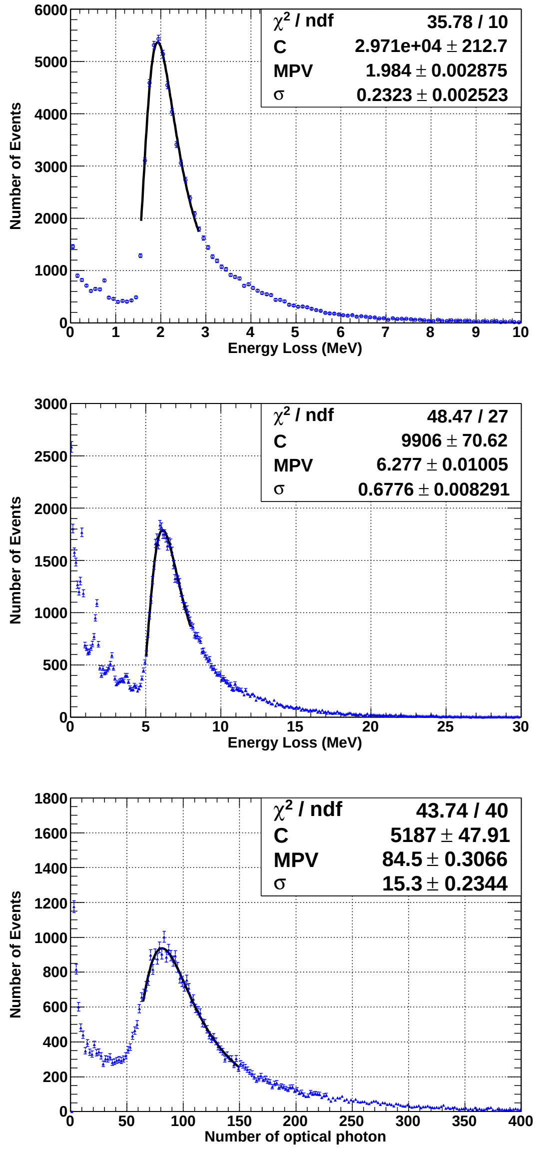

Figure 3: The single peak value of YAC-II(up), Tibet-III(middle) and MD(down)

shower for p/γ separation of the primary particles, it can also play important role to increase the mass resolution in the composition study. The more details of three types of detectors is described in (L. M. Zhai, J. Huang, et al., ICRC 33, ID: 1049, 2013.).

Simulation and Analysis

A Monte Carlo(MC) simulation of the extensive air showers in the atmosphere using the simulation code CORSIKA (version 7.3500) has been carried out. The MC simulation of air showers including two kind of hadronic interaction models(QGSJETII-04 and SIBYLL2.1) and heavy dominant primary composition model(HD)[5] is used to generate air-shower evens. The air-shower events are randomly dropped onto the YAC-II detectors array plane, 15m wider in each side of the YAC-II array. We choose the value 15m because the area of 52m$\times$52m is checked to be wide enough to contain 99.5% EAS events under our event se-

Table 1: The statistics of core events in MC simulation, where M denotes the sum of medium heavy elements between helium and iron.

Interaction Model	Component	E-low(100 TeV-200 TeV)		E-high(1000 TeV-2000 TeV)	
		N(before selection)	N(after selection)	N(before selection)	N(after selection)
QGSJETII-04	P	211937	9955	1972	527
	He	166532	4784	2003	504
	M	229058	1537	5293	1171
	Fe	256202	220	9827	1921
SIBYLL2.1	P	213866	11786	2046	584
	He	167042	6047	1996	544
	M	230072	2379	5359	1333
	Fe	257743	434	9901	2183

lection conditions(see below in the text). In order to treat the MC events in the same way as experimental data analysis, simulated air-shower events were input to the detector with the same detector configuration as the (YAC-II+Tibet-III+MD) array, and the Geant4(version 9.5)[6] was used to calculate the energy deposit of these shower particles. In our experiment, the number of charged particles detected by each detector is defined as the PMT output (charge) divided by that of the single peak, which is determined by a probe calibration. According to the MC, the single peak value of the energy deposit for a single particle in each detector of YAC-II and Tibet-III is calculated as 1.98 MeV and 6.28 MeV, and the similar single peak value of photon yield of MD is 84.5 photons as shown in Fig.3. Based on this result, we can estimate the number of charged particles from the observed ADC value for each hit detector. Then the Nμ can be computed by the sum of muons of all hit MD detectors. The shower size of each event is estimated using the modified NKG function which is optimized by the Monte Carlo simulation by using QGSJETII-04+HD model and SIBYLL2.1+HD model independently.

First, we selected the events accompanying muons with E$\mu \geq 1$ GeV and the zenith angle of air shower events should be smaller than 24.6 degrees (1.0$\leq$secθ<1.1). θ denotes the zenith angle.

Second, the following parameters of YAC-II and MD are used to select the air-shower core events.

N_b - the number of shower particles under the lead plate of a detector unit of YAC-II;

N_{pe} - the number of photoelectron of a detector unit of MD;

$N_{hit-YAC}$ - the number of "fired" detector units of YAC-II with $N_b \geq$ a given threshold value;

N_{hit-MD} - the number of "fired" detector units of MD with $N_{pe} \geq$ a given threshold value;

$\sum N_b$ - the total burst size of all fired detector units of YAC-II;

The selection conditions are are as follows:
$N_b \geq 100$, $N_{pe} \geq 1$, $N_{hit-YAC} \geq 4$, $N_{hit-MD} \geq 1$, $\sum N_b \geq 1000$, Ne$\geq$80000

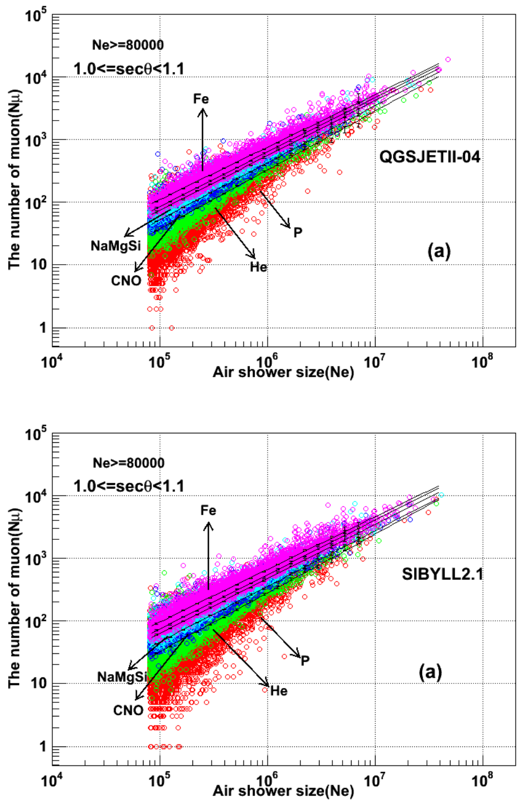

Figure 4: The correlation between Nμ and Ne for air showers with the zenith angle less than 24.6 degrees. The solid line is a best fit curve expressed by the relation Nμ= a$\times$(Ne)^b. θ denotes the zenith angle.

We sampled 2748483 and 2767253 primaries for the QGSJETII-04 and SIBYLL2.1 model, respectively. After the event selection, we can obtain 63243 and 76966 core events for the QGSJETII-04 and SIBYLL2.1 model, respectively. The average generation efficiencies of the burst events in this energy by SIBYLL2.1 is higher than QGSJETII-04 by a factor of 15%. The details of the statistics is shown in Table 1, where M denotes the sum of

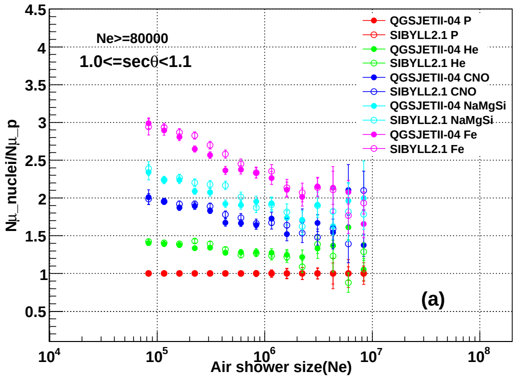

Figure 5: Fraction of the number of muons in air showers of nuclei origin to that of proton origin calculated for interaction models of QGSJETII-04 and SIBYLL2.1. θ denotes the zenith angle.

medium heavy elements between helium and iron.

Results and Discussions

The correlation between the air shower size and the number of muons induced by each primary event using QGSJETII-04 and SIBYLL2.1 is shown in the Fig.4. The solid line is a best fit curve expressed by the relation $N\mu = a \times Ne^b$. It is seen from this figure that there exists no significant difference between the QGSJETII-04 and SIBYLL2.1 interaction models. This suggests that if we further impose an air shower core information ([7],[8],[9]) on the correlation shown in Fig.4, we can study the details of the primary composition at energies around and over the knee.

Fig.5 shows that fraction of the number of muons in air showers of nuclei origin to that of proton origin calculated for interaction models of QGSJETII-04 and SIBYLL2.1. The average difference between QGSJETII-04 model and SIBYLL2.1 model is less than 20% from Fig.5. Combining the data from the new hybrid experiment, we can classify the experimental data into different primary mass group.

Summary

With the advantage of the new hybrid experiment capable of observing Ne and Nμ at a high altitude, the study of the chemical composition of the primary cosmic rays at energies from 50 TeV to 10 PeV is going to be further developed in the very near future. The present simulation shows that the interaction model dependence is not significant in the new hybrid experiment and it 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. 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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