A Monte Carlo study to check the hadronic interaction models by a new EAS hybrid experiment in Tibet

Ying Zhang*[†], J. Huang*, L. Jiang*[‡], D. Chen[§], L.K. Ding*, M. Shibata[¶], Y. Katayose[¶], N. Hotta[‖], M. Ohnishi[§], T. Ouchi[**] and T. Saito[††]

*Institute of High Energy Physics, Chinese Academy of Sciences, Beijing 100049, China
[†]Institute of Modern Physics, Southwest Jiaotong University, Chengdu 610031, China
[‡]Department of Physics, Yunnan University, Kunming 650091, China
[§]Institute for Cosmic Ray Research, University of Tokyo, Kashiwa 277-8582, Japan
[¶]Faculty of Engineering, Yokohama National University, Yokohama 240-8501, Japan
[‖]Faculty of Education, Utsunomiya University, Utsunomiya 321-8505, Japan
[**]Faculty of Engineering, Kanagawa University, Yokohama 221-8686, Japan
[††]Tokyo Metropolitan College of Industrial Technology, Tokyo 116-8523, Japan

***Abstract*. A new EAS hybrid experiment has been designed by constructing a YAC (Yangbajing Air shower Core) detector array inside the existing Tibet-III air shower array. The first step of YAC, called "YAC-I", consists of 16 plastic scintillator units (4 rows times 4 columns) each with an area of 40 cm×50 cm which is used to check hadronic interaction models used in AS simulations. A Monte Carlo study shows that YAC-I can record high energy electromagnetic component in the core region of air showers induced by primary particles of several tens TeV energies where the primary composition is directly measured by space experiments. It may provide a direct check of the hadronic interaction models currently used in the air shower simulations in the corresponding energy region. In present paper, the method of the observation and the sensitivity of the characteristics of the observed events to the different interaction models are discussed.**

***Keywords*: cosmic ray, hadronic interaction, Extensive Air Shower**

I. Introduction

The study of primary cosmic-ray energy spectrum and composition above *100 TeV has to depend on the indirect observation of extensive air showers (EASs) because of their low fluxes and the limited detetor acceptance of the on board satellite or baloon experiments. To interprete the EAS data, Monte Carlo (MC) simulations are inevitable. Any hadronic interaction models used in Monte Carlo codes are based on the knowledge obtained from the accelerator hadron-nucleus collision experiments. For accelerator experiments with energies lower than 2 TeV – the corresponding fixed-target energy of the highest ISR energy, the inelastic interaction cross section, the interaction inelasticity and the distribution of large x (Feynman variable) particles (or particles produced in the forward region) have essentially been measured. However, when energy goes higher the inelasticity and the distribution of large x particles produced were no longer directly measured by hadron collider experiments, and one has to use extrapolation of the laws established in lower energies. Obviously, the correctness of the extrapolation determines the correctness of the description of EASs in higher energies. Nowadays many Monte Carlo simulations, when using different interaction models, resulted in different conclusions of the cosmic ray composition at the knee[1]. For multi-parameter measurements of EASs it seemed that no one interaction model can explain all data consistently. This situation asked for a further check and an improvement of the currently used interaction models.

Now we are going to have a chance to know more on the interaction features in the very forward region from the LHC collider experiments such as LHCf, TOTEM and CASTOR[2]. However, since the corresponding energy in the laboratory system of LHC reaches 10^{17}eV, for some physics quantities or features, if they change with energy, one still needs to know how they are in 10^{14}eV, 10^{15}eV, 10^{16}eV, etc. Here we propose an approach to check the hadronic interaction models by observing EAS cores at an energy of *10 TeV using the newly constructed AS core detectors YAC-I.

II. YAC-I experiment

We have planed a new EAS hybrid experiment called YAC (Yangbajing Air shower Core array) in Tibet, 4300 m above sea level (an atmosphere depth of 606 g/cm^{-2}) aiming at the measurement of the primary p, He and Fe spectra in the knee region. Its first phase called YAC-I that consists of 16 EAS core detectors (as shown in Fig.1) has been constructed and started data taking since April, 2009. YAC-I is located near the center of the

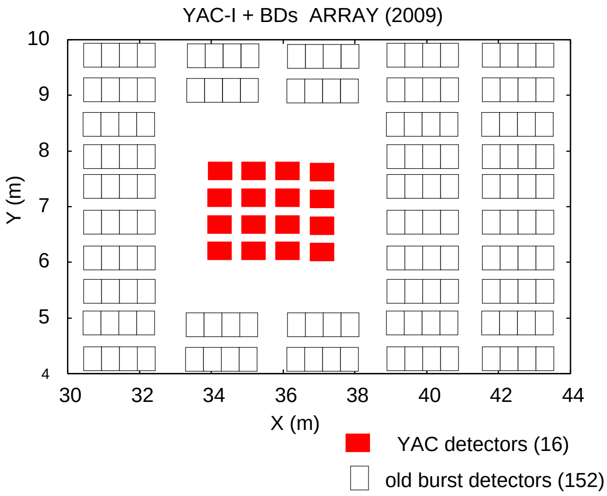

Fig. 1. YAC-I + BDs ARRAY

Tibet-III air-shower array[3], operating simultaneously with Tibet-III and surrounding burst detectors (BD)[1]. For the coincident events Tibet-III provides the total energy and the direction of air showers. BD can provide more accurate information about the core position and YAC-I observes high energy electromagnetic particles in the core region.

The 16 plastic scintillator units of YAC-I are arranged as an array (4 rows times 4 columns) each with an area of 40 cm×50 cm. For our purpose, all detector units should be placed as densely as possible. A 28 cm spacing along x-axis and a 18 cm spacing along y-axis between two neighboring detectors are taken. Each detector consists of lead plates with a thickness of 3.5 cm above the scintillator to convert high energy electrons and gammas to showers. Each unit of YAC-I is attached with two photomultipliers to cover the wide dynamic range from 1 MIP (Minimum Ionization Particle) to 10^6 MIPs that corresponds to *10 TeV of electron or gamma energy[4,5].

III. Simulations and Analysis

A Monte Carlo simulation has been carried out on the development of EAS in the atmosphere and the response in YAC-I. The simulation code CORSIKA (version 6.024) including QGSJET01c and SIBYLL2.1 hadronic interaction models[6] are used to generate AS events. Primary composition is taken from JACEE and RUNJOB[7,8]. At around several TeV to several 10 TeV region, primary composition has been better measured. Primaries isotropically incident at the top of the atmosphere within the zenith angles from 0 to 60 degrees are injected into the atmosphere. The minimum primary energy is set at 1 TeV. Because of the use of Pb plates, secondary particles with lower energies could not reach at the scintillator. Thus, secondary particles are traced to the altitude of 4300 m till 300 MeV. The Monte Carlo air-shower events are randomly dropped onto the detector array plane, 15 m wider in each side of the rectangular-shape array. We choose the value 15 m because the area of 32.84 m×32.14 m is checked to be wide enough to contain 99.5% EAS events under our event selection conditions (see below in the text). The electromagnetic showers in the lead layer induced by electrons or photons that hit any detector unit of the array are treated by a subroutine that is based on the detector simulation code EPICS[9]. The energy, position and angle of incident particle and the structure of surrounding materials were taken into account in the detector simulation. Normally, the following quantities of YAC are used to characterize an EAS core event:

N_b – the number of shower particles hitting a detector unit;
N_d – number of 'fired' detector units each with $N_b \geq$ a given threshold value;
${N_b}^{top}$ – the maximum burst size among fired detectors;
$\sum N_b$ – total burst size of all fired detector units;
<R> – the mean lateral distance from the air shower core to a detector unit.

By using different threshold of N_b, different N_d, different ${N_b}^{top}$, etc, one can obtain different event samples that have different average primary energy and different sample size. For various physics goals one may use different event selection criteria. To see how some physics quantities change with energy one may use different samples simultaneously. Now, only for an example, we choose a sample at the energies of several 10 TeV region. This event sample has been selected under the following conditions:

(1) the number of shower particles hitting a detector unit $N_b \geq 100$;
(2) the number of fired detectors $N_d \geq 4$;
(3) the detector unit with ${N_b}^{top}$ is located at the inner 4 detectors of YAC-I grid in order to reject events falling far from the array.

TABLE I
THE FRACTIONS OF THE COMPONENTS AFTER THE BURST EVENT SELECTION

Int. Model	Component	E_{low}(TeV)[1]	E_{high}(TeV)
		1-20	20-200
QGSJET	proton	96.1	73.6
	He	3.8	21.8
	Medium(CNO)	0.1	2.9
	Heavy(NaMgSi)	0	1.2
	Very Heavy(SClAr)	0	0.2
	Fe	0	0.3
SIBYLL	proton	94.9	70.9
	He	5.0	23.5
	Medium(CNO)	0.1	3.5
	Heavy(NaMgSi)	0	1.3
	Very Heavy(SClAr)	0	0.1
	Fe	0	0.7

[1] E_{low} indicates lower primary energy of the selected sample, E_{high} indicates higher primary energy of the selected sample.

We sampled 7.28×10^9 and 5.41×10^9 primaries for the QGSJET and SIBYLL model, respectively. After the event selection 18715 and 17166 burst events passed for the QGSJET and SIBYLL model, respectively. The average generation efficiencies of the burst events in this energy by SIBYLL is higher than QGSJET by a factor of 1.24. The attenuation length (λ) of the burst events for the QGSJET and SIBYLL model is estimated by using the zenith angle distribution which are 109 $\pm$ 4 (g/cm^{-2}) and 108 $\pm$ 4 (g/cm^{-2}), respectively. It is an important parameter reflecting the characteristics of inelastic cross section and inelasticity used in the model.

It is seen that after the event selection the left burst events are mostly (about ∼96%) induced by protons and heliums. The fractions of the components of the burst events are summarized in Table 1. This is suitable for our aims because primary proton and helium spectra were better measured than other heavier nuclei[7,8] and the systematic uncertainty induced by other nuclei will be smaller than 4%. In order to observe interaction model dependences, the experimental data will be analyzed in the same manner as for the MC data in the procedure.

IV. Results and Discussion

The primary-energy distribution of burst events for QGSJET and SIBYLL are obtained as shown in Fig.2. Fig.2 shows a peak at around 80 TeV for both models, just meeting our requirement. This is the energy region we are going to check the interaction models in the first step.

Fig.3 is the spectrum of the total burst size $\sum$Nb which should depend sensitively on the inelastic interaction cross section, the inelasticity, and particles produced in the forward region. The difference of the flux intensity between two interaction models is 1.26 $\pm$ 0.05. Fig.3 shows an obvious difference of flux intensity between two models, and one may find the reason from the difference of the two models. To compare YAC observation of the burst size flux with these MC predictions, we can provide some evidences on the feature of above mentioned physics quantities.

The spectrum of the top burst size $N_b{}^{top}$ is obtained as shown in Fig.4. It is found that there is a difference about 1.36 $\pm$ 0.05 in the slopes of two models in the energy region. The quantity of $N_b{}^{top}$ may relate with the features of leading particles and transverse momentum of secondary particles produced in hadronic interactions.

The N_d distribution is shown in Fig.5, suggesting a visible model dependence between QGSJET and SIBYLL. It reflects lateral characteristics of high energy particles in the air shower cores. Comparing with YAC observation, we can check these different hadronic interaction models.

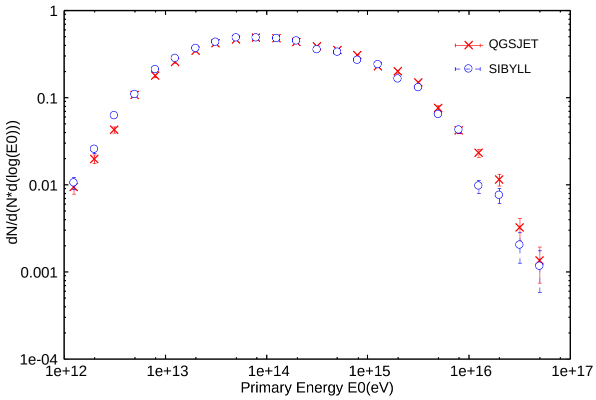

Fig. 2. The distribution of primary energy of the sample selected for QGSJET model and SIBYLL model. The peak position of the primary energy spectrum for both models is about 80 TeV, just meeting our requirement.

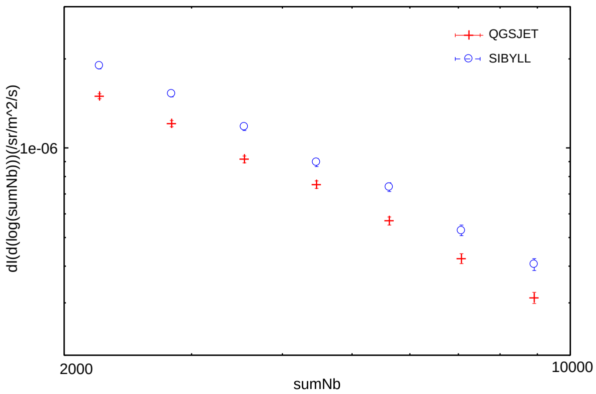

Fig. 3. The total burst size ($\sum$Nb) spectrum obtained by QGSJET and SIBYLL model, where sumNb indicates the total burst size ($\sum$Nb).

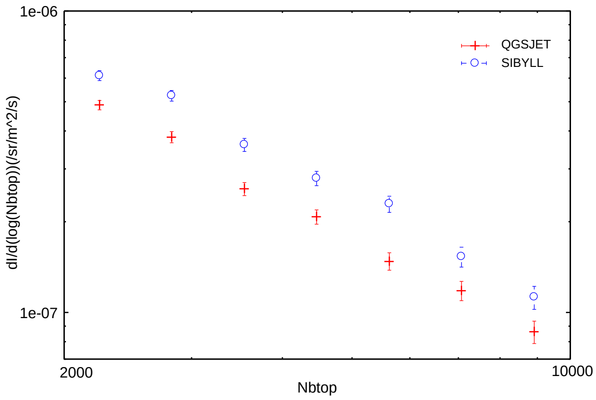

Fig. 4. Top burst size ($N_b{}^{top}$) spectrum obtained by QGSJET and SIBYLL model.

Fig.6 shows the mean lateral spread (<R> = $\sum r_i/(N_d$-1)), where r_i and N_d are the lateral distance from the air shower core to the center of a fired detector and the number of hit detectors, respectively. Here we have imposed the condition of $N_d \geq 4$. The mean

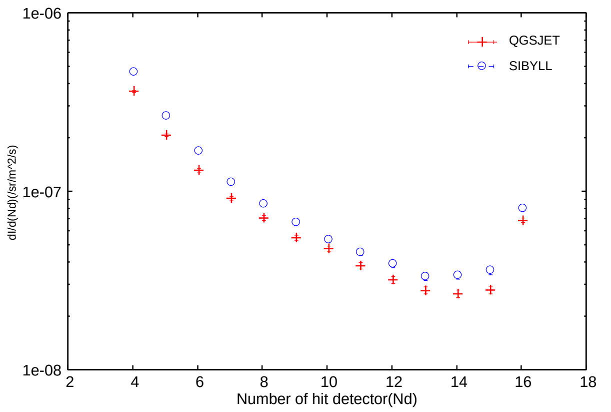

Fig. 5. The spectrum of the number of hit detector (N_d) obtained by QGSJET and SIBYLL model.

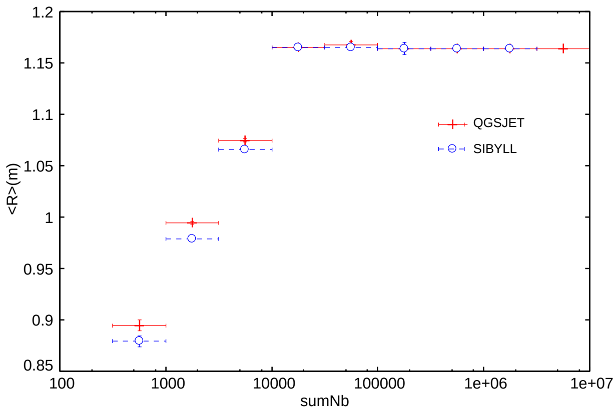

Fig. 6. Distribution of the mean lateral spread (<R>) obtained by QGSJET and SIBYLL model, where sumNb indicates the total burst size $\sum$Nb, <R> indicates mean lateral spread.

lateral spread <R> will be changed at different energy regions that can be reflected by total burst size $\sum N_b$, as shown in Fig.6. It provides a check on the features of transverse momentum in the very forward region.

The area S of the event-dropping is 1.06×10^3 m^2. The effective solid angle is 2.355 sr. Taking 6 months as the effective observation time, the number of primary cosmic rays is calculated to be 7.74×10^9 particles, a factor of 1.06 higher than the Monte Carlo sample. That is to say, the experiment will produce enough statistics in 6 months.

V. Conclusions

The Monte Carlo shows that:
(1) Under the above selection conditions a sample of events with a primary energies at around 80 TeV can be selected. This is an energy region the primary composition being better measured directly;
(2) A sample with large statistics can be obtained in a few months's observation.

In summary, taking the priority of high altitude (like Yangbajing) an EAS core event sample at the energy region around several 10 TeV can be obtained with high statistics by using YAC-I. The hadronic interaction models at this energy region can be checked. Emulsion chamber[1,10] cannot work at this lower energies. Other measurements at low altitudes are also difficult to target the similar aim of checking the hadronic interaction models.

VI. Acknowledgment

The authors would like to express their thanks to the members of the Tibet ASγ collaboration for the fruitful discussion.The support of the Knowledge Innovation Fund (H8515530U1) IHEP, China,to J. Huang is also acknowledged.

References

[1] M. Amenomori et al, Physics Letters B 632(2006) 59, 60.
[2] Totem Project, http://totem.web.cern.ch/totem.
[3] M. Amenomori et al, The Astrophysicsl Journal,678,1167 (2008).
[4] J. Huang et al., ICRC 29 HE 1.2 (2005).
[5] L. jiang et.al., ICRC 31 HE 1.6 (2009).
[6] D. Heck et al., Report FZKA 6019,1998; J. Knapp, D. Heck et al., Report FZKA 3640,1997; D. Heck et al., Report FZKA 5828,Forshungszentru Karldruhe, 1996. Available from http://www-ik3.fzk.deheck/corsika/physics_description/corsika_phys.html.
[7] JACEE Collaboration, Astrophys.*J.502*(1998) 278.
[8] RUNJOB Collaboration, Astropart.Phys.*16*(2001) 13.
[9] K. Kasahara, et al., http://eweb.b6.kanagawa-u.ac.jp/~Kasahara/ResearchHome/EPICSHome/Index.html.
[10] J. Huang et al., Astroparticle Physics 18 (2003) 639.