Air-shower core detector array to study the mass composition of cosmic rays beyond 100 TeV by Tibet hybrid experiment.

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DOI: 10.7529/ICRC2011/V06/0356

Abstract: New air-shower core detector YAC has been developed to measure cosmic-ray mass composition around the energy region of the knee. Prototype experiment YAC1 was successfully carried out in 2009-2010 together with Tibet III air-shower array. Enlarged installation YAC2 is also under construction and will be operated in fall 2011. Preliminary result of YAC1 and performance of YAC2 are presented in this paper. The test of interaction models currently used in air-shower simulation was made using YAC1 results. Burst size flux predicted by QGSJET2 and SIBYLL models are compatible with data of YAC1 while QGSJET1 predicts 20 % lower flux and EPOS does 30 % lower flux. Proton flux was derived from YAC1 data based on QGSJET2 model and it is smoothly connected with direct observation data at lower energies and also with previously reported our works at higher energies.

Keywords: Air shower, Chemical composition, Knee, Cosmic ray origin and acceleration

1 Introduction

Detailed measurement of the energy spectrum of cosmic rays provides information on origin of cosmic rays and their acceleration mechanism [1]. The energy range around 10^{15}eV is especially important because of the change of the power index which is known as 'knee'. The study of the mass composition of cosmic rays around the knee energy region has been made in the last decade by Tibet experiment using high threshold (>TeV) air-shower (AS) core detector [2, 3, 4] because of its sensitivity to the primary-particle mass. It was aimed to separate AS events induced by primary light nuclei such as protons and helium. The main result from these observations are the low intensities of proton and helium spectra which amount less than 30% of all-particle spectrum suggesting that the knee is dominated by nuclei heavier than helium. Problems included in this method are; firstly the statistics are limited due to the selection of high-energy core events, secondly the reconstruction of the primary energy spectrum is based on the AS simulations in which the hadronic interaction model is not fully established yet, although the model dependence of AS core events at high observation level are at most few tens % as already reported. To overcome these problems, new low threshold core detector named YAC (Yangbajing Air shower Core detector) has been developed, which can detect the core events with high statistics and also be able to test the interaction models. The feature of the YAC detector is described in section 2. YAC experiment is scheduled in three steps called YAC1, YAC2 and YAC3. YAC1 is a small array consisting of 16 prototype detectors (~8 m^2) located near the center of the Tibet III AS array. YAC1 can detect through a few months observation the AS core events of primary energies around 10^{14}eV where mass composition of cosmic rays are known by direct observations [5, 6]. Therefore, the role of YAC1 is to test the interaction models currently used by Monte Carlo (MC) simulations such as QGSJET1, SIBYLL, and lately QGSJET2, EPOS. YAC2 is an array of 100 detectors (~150 m^2). It is aimed in YAC2 to obtain proton and helium spectra with high statistics in energy range between 10^{14}eV and several times 10^{15}eV covering the knee and also being connected with data obtained by direct observations. Finally, YAC3 with large area (400 detectors, ~ 5000m^2) is planed to obtain iron spectrum above 10^{15} eV. This paper reports the result of YAC1 which has been already carried out in 2009-2010 and the performance of YAC2.

2 YAC1 detector

YAC1 detector consists of a scintillator of 40 cm × 50 cm in area with 1 cm thickness and lead absorber of 3.5 cm thickness supported by 1cm thick iron plate above the scintillator. High energy electromagnetic particles near the AS axis induces local cascade showers (burst) through lead and these shower particles enter to the scintillators. The scintillator is divided into 10 pieces of 5cm width and wavelength shifting fiber is used to collect the scintillation light through each pieces. Such design provides geometrical uniformity of the detector response within 5 %. Two phototubes (PMT) of high-gain and low-gain are used to cover wide dynamic range of the number of particles (burst size) from one to 10^5. The determination of the burst size N_b is calibrated using single muon peak. The stability of the PMT gain is checked and corrected assuming constant flux of the cosmic rays.

3 YAC1 experiment

Prototype 16 YAC detectors were constructed near the center of the Tibet III AS array with dense spacing. Simultaneous data taking by YAC and AS array was successfully made for live time of 43 days. AS size N_e and age parameter s were determined by lateral density fitting (LDF). Event selection condition for AS core event was studied by MC and following criteria were adopted to reject non core events whose shower axis is far from the YAC array; (1) Minimum burst size $N_{bmin} = 30$, (2) $N_e > 4 \times 10^4$, (3) Zenith angle of arrival direction $\theta < 60$ deg, (4) More than 8 YACs satisfy $N_b > 30$, (5) $\sum N_b > 3000$, (6) $\sum N_b$ of inner 4 detectors is greater than 35% of $\sum N_b$, (7) AS axis estimated by LDF is within 5 m from the burst center. Extensive MC simulation was made using four interaction models with primary energy above 10^{13}eV. The mass composition is taken from direct observation data. The statistics of core events are shown in Table 1.

Model	Primary ($E > 10$ TeV)	Core events
QGSJET1	10988630	856
SIBYLL	11562549	998
QGSJET2	16273967	1445
EPOS	10802723	739
YAC16	-	739

Table 1: Statistics of core events in MC simulation and experiment.

4 Test of interaction models

The comparison of the experimental data with each of four MC calculations shows no serious deviation in most of event characteristics except slightly different absolute intensity as shown in Fig.1 for inclusive burst size spectrum (16 YAC detectors are treated independently), where four model predictions are plotted by symbols and experimental data by histogram. The ratio of the model prediction to experimental data is plotted in Fig.2 to see the difference clearly for burst size range with high statistics (100-1000). QGSJET2 and SIBYLL models are close to experimental data and QGSJET1 gives about 20 % lower flux, EPOS gives the lowest flux by about 30%.

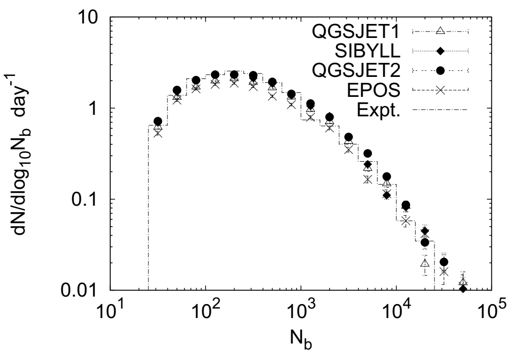

Figure 1: Inclusive burst size spectrum by YAC1 is compared with MC predictions with four interaction models.

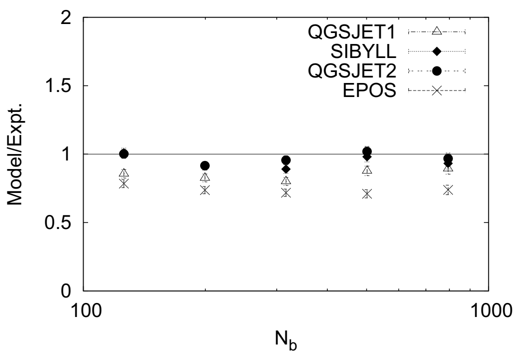

Figure 2: Flux ratio of burst size spectrum (Model/YAC1).

5 Proton spectrum

Random Forest algorithm (RF) [7] was used to separate proton induced events. Eight parameters were used for training; (1) N_e, (2) s, (3) θ, (4) $\sum N_b$, (5) number of hit detectors N_{hit}, (6) the largest burst size among hit detectors N_b^{top}, (7) geometrical average lateral spread of hit burst detectors $< R_b >_g$, (8) average lateral spread of hit burst detectors weighted by burst size $< R_b >$.

Fig.3 shows how RF can select correctly proton candidates using QGSJET2-MC events as a function of primary energy. True proton events are plotted by open circles and estimated proton candidates by closed circles. One can see proton events are well selected by RF with a slightly energy dependent deviation. Main miss judge arises from helium events. Fig.4 shows separation of experimental data into proton candidates and others. The distribution of proton candidates is in a good agreement with expected one from MC as shown in Fig.5. The estimation of primary proton spectrum was made taking into account of following effects; (a) dead time correction of 12 % for AS trigger system, (b) effective $S\Omega$ calculation as shown in Fig.6,

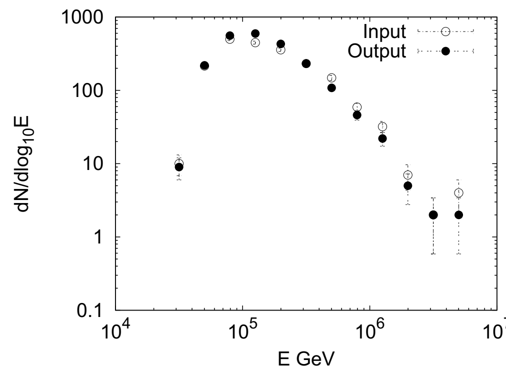

Figure 3: Selection of proton candidates using RF trained by QGSJET2-MC.

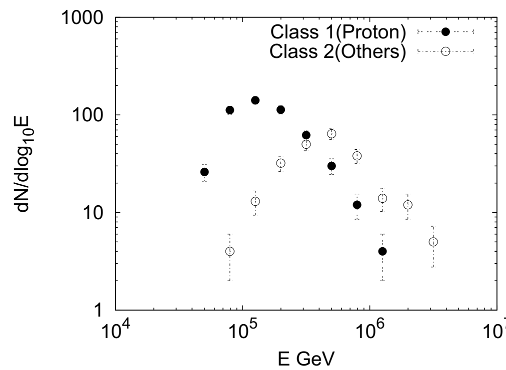

Figure 4: Separation of proton candidates by RF trained by QGSJET2-MC.

(c) correction for the energy dependence of RF analysis, (d) flux correction due to the primary energy resolution. Fig.7 shows proton spectrum obtained by YAC1 based on QGSJET2-MC in comparison with direct observations and previously reported works at high energies. The proton spectrum based on other three MC models were also derived and they showed at most 30 % higher intensity than the result by QGSJET2 as expected from the comparison of burst size flux in Fig.1 and Fig.2.

6 Performance of YAC2

YAC2 is expected to start operation in fall 2011. The upgrade of the installation is not only the increase of the number of YAC detectors but also 24 anti-detectors will be added to reject such events whose AS axis falls far from YAC array, and thoroughly underground muon detector MD [8] will be co-operated. New parameter N_μ will be added to train RF. Hence, the performance of YAC2 will be strong enough to separate primary particles into four classes, namely, proton, helium, intermediate nuclei

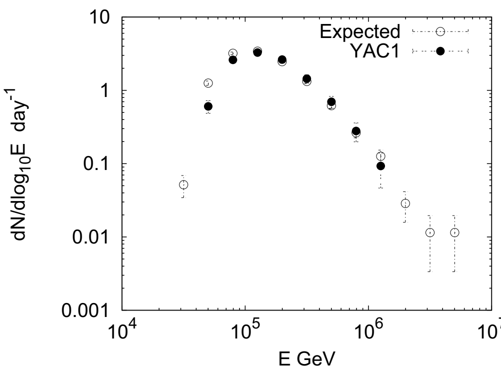

Figure 5: Proton candidates by YAC1 compared with QGSJET2-MC prediction.

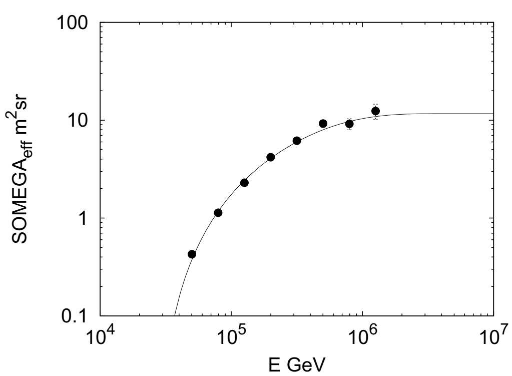

Figure 6: Effective $S\Omega$ of YAC1 array with core event selection criteria.

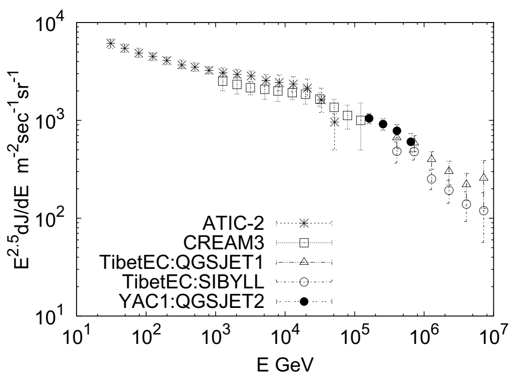

Figure 7: Proton spectrum obtained by YAC1 compared with other data: ATIC2[5], CREAM3[6], TibetEC[2].

(He$<$A$<$Fe), and iron group as shown in Fig.8 where lines are input fluxes and symbols represent estimated distribution by RF for each class.

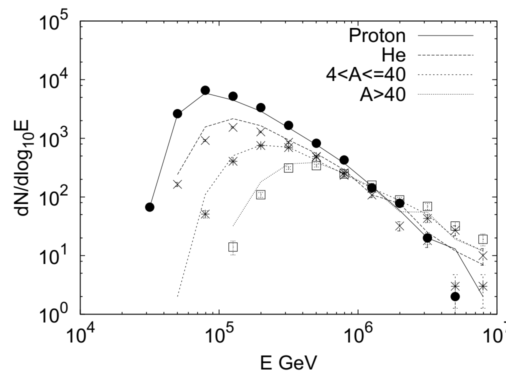

Figure 8: Separation of AS core events into four classes by YAC2 experiment using RF trained by QGSJET2-MC.

Acknowledgments

The collaborative experiment of the Tibet Air Shower Arrays has been performed under the auspices of the Ministry of Science and Technology of China and the Ministry of Foreign Affairs of Japan. This work was supported in part by Grant-in-Aid for Scientific Research on Priority Areas from the Ministry of Education, Culture, Sports, Science and Technology, by Grants-in-Aid for Science Research from the Japan Society for the Promotion of Science in Japan, and by the Grants-in-Aid from the National Natural Science Foundation of China and the Chinese Academy of Sciences (H9291450S3), the Key Laboratory of Particle Astrophysics, Institute of High Energy Physics, CAS. The Knowledge Innovation Fund (H95451D0U2 and H8515530U1) of IHEP, China and the project Y0293900TF of NSFC also provide support to this study.

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