Primary proton and helium spectra at energy range from 50 TeV to $10^{15}$ eV observed with (YAC-I + Tibet-III) hybrid experiment


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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” has been successfully carried out in 2009-2010 together with Tibet-III air-shower array. YAC-II has also been operated from 2011. In this proceeding, the primary proton and helium spectra at energy range from 50 TeV to $10^{15}$ eV derived from YAC-I data based on the newest interaction model EPOS-LHC (v.3400), QGSJETII-04 and SIBYLL2.1 are reported. The obtained (P+He) spectra is smoothly connected with direct observation data below 100 TeV and also with our previously reported results at higher energies within statistical errors. The knee of the (P+He) spectra is located around 400 TeV. The interaction model dependence in deriving the primary (P+He) spectra are found to be small (less than 25% in absolute intensity, 10% in position of the knee ), and the composition model dependence is less than 10% in absolute intensity.

Keywords: Cosmic rays; Proton; Helium; Knee energy region; Neural network
1 Introduction

A sudden steepening of the cosmic-ray energy spectrum around $4 \times 10^{15}$ eV is called 'knee' where the value of the power index $\gamma$ changes from approximately 2.7 to 3.1 when the energy spectrum is express by a power law $E^{-\gamma}$. The origin of the knee is discussed based on the result of Tibet air-shower experiment over the wide energy range from $10^{14}$ eV to $10^{17}$ eV covering the knee region [1]. There has been a lot of works on the origin of the knee in terms of the acceleration mechanism, the propagation in the galaxy or some nearby sources [2,3,4]. Another point of view is related to the nature of hadronic interactions [3,4].

In order to distinguish many models, measurements of the chemical composition around the knee, especially measurements of the spectra of individual component till their knee will be essentially important. Therefore, we planned a new experiment: 1) to lower down the energy measurement of individual component spectra to $10^{15}$ eV and make connection with direct measurements; 2) to make a high precision measurement of primary p, He, c, Fe till 10 PeV region to see the rigidity cutoff effect. These aims will be realized by our new hybrid experiments YAC (Yangbajing AS Core array). In this proceeding, we will report the primary proton and helium spectra at the knee derived from YAC-I data based on the newest interaction model (EPOS-LHC (v3400), QGSJETII-04 and SIBYLL2.1).

2 (YAC-I+Tibet-III) hybrid experiment

Aiming at the observation of cosmic-ray chemical composition at the knee energy region, a new type air-shower-core detector (YAC, Yangbajing Air shower Core array) has been developed and set up at Yangbajing, 4300 m a.s.l. in Tibet, China since May, 1st, 2009. YAC will work together with the Tibet-III array and a large muon detector as a hybrid experiment as shown in Fig.1. YAC experiment is scheduled in three steps called YAC-I, YAC-II and YAC-III. YAC-I consists of 16 YAC detectors of the size 40 cm $\times$ 50 cm, covering an area about 10 $m^2$, which is used to check hadronic interaction models. YAC-II and YAC-III are used to obtain the individual component spectra of primary cosmic rays in a wide range over 3 decades between 50 TeV and 100 PeV in the near future.

YAC-I detector has the same design as the YAC-II. The only difference between YAC-I, YAC-II is in spacing. Each YAC detector unit consists of lead plates of 3.5 cm (7 r.l.) (Fig.1) thick and a scintillation counter which detects the burst size induced by high energy electromagnetic component at the air-shower core. Wide dynamic range between 1 MIP and 10$^6$ MIPs (Minimum Ionization Particles) is covered by 2 PMTs (Hamamatsu: R4125 and R5325) as shown in Fig.2. The response linearity of each YAC detector was calibrated by cosmic-ray single muons and by the accelerator beam of the BEPCII (Beijing Electron Positron Collider, IHEP, China)[5].

Tibet-III array consists of 789 detectors, with a covering area about 36900 $m^2$. An event trigger signal is issued when any four-fold coincidence occurs in detectors recording more than 0.6 particles. The trigger rate is about 680 Hz and the dead time is 15%. Tibet-III is used to measure the arrival direction ($\theta$) and the air shower size ($N_e$). The angular resolution is about 0.1 degree above 100 TeV and the energy resolution is about 15% at 1 PeV [1]. On-line trigger condition for YAC is 'any 1' detector 'fired' (the discrimination threshold is about 30 mV).

If one YAC detector unit makes a trigger signal, all ADC data from all YAC units are recorded. Also the trigger signal is sent to the DAQ system for Tibet-III array. ADC pedestal values are measured each 10 minutes. Each DAQ system has GPS clock module independently. The matching between YAC data and Tibet-III data is made using coincidence of GPS clocks and the trigger tag to Tibet-III array.

3 Simulation and Analysis

We have carried out a detailed Monte Carlo (MC) simulation of air showers using the simulation code CORSIKA (version 7.3500) including QGSJETII-04, EPOS LHC(v3400) and SIBYLL2.1 hadronic interaction models[4]. Two primary cosmic-ray composition models are examined as the input energy spectra, namely, "Heavy dominant" (HD) [1] and "Non Linear Acceleration" (NLA) model[2]. The minimum primary energy is set at 1 TeV. Primaries isotropically incident at the top of the atmosphere within the zenith angels from 0 to 60 degrees are injected into the atmosphere. The MC events are randomly dropped onto the detector array plane, 15 m wider in each side of the YAC-I array. The dropping area has

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**Figure 1**: Schematic view of (YAC-I+Tibet-III) array. The Tibet-III consists of 789 detector units, the YAC-I consists of 16 detector units.

**Figure 2**: Efficiency $S_Q$ of YAC-I array for Proton+Helium under the models mentioned above.
Table 1: Statistics of air-shower core events in MC simulation and experiment.

<table>
<thead>
<tr>
<th>MC Model</th>
<th>Selected core events</th>
</tr>
</thead>
<tbody>
<tr>
<td>SIBYLL2.1+HD</td>
<td>121536</td>
</tr>
<tr>
<td>SIBYLL2.1+NLA</td>
<td>32037</td>
</tr>
<tr>
<td>QGSJETII+HD</td>
<td>86445</td>
</tr>
<tr>
<td>QGSJETII+NLA</td>
<td>40293</td>
</tr>
<tr>
<td>EPOS-LHC+HD</td>
<td>24315</td>
</tr>
<tr>
<td>QGSJETII-04+HD</td>
<td>18383</td>
</tr>
<tr>
<td><strong>Expt.data</strong></td>
<td><strong>5035</strong></td>
</tr>
</tbody>
</table>

been checked to be wide enough to contain 99.5% EAS events under our event selection conditions (see blow in the text).

All Detector responses is based on the detector simulation code Geant4 (version 9.5)[7]. We confirmed that the shape of the energy loss distribution of YAC, which is determined by probe calibration simulation, shows a reasonable agreement with the charge distribution of the experimental data [8].

The simulated events are passed through the same analysis chains as the experimental data. Normally, the following parameters of (YAC-I+Tibet-III) are used to characterize an air-shower core events:

- $N_b$: the number of shower particles under the lead plate of a detector unit;
- $N_{hit}$: the number of "fired" detector units with $N_b \geq 1$ given threshold value;
- $N_{hit}^{b_{top}}$: the maximum burst size among fired detectors;
- $\sum N_b$: the total burst size of all fired detector units;
- $<R>$: the mean lateral spread; $<R> = \sum r_i (N_{hit} - 1)$;
- $<N_b R>$: the mean energy-flow spread;
- $\sum (N_b \times r_i)/N_{hit}$, where $N_{hit}$ and $r_i$ are the burst size in the $i^{th}$ fired detector unit and the lateral distance from the air-shower core to the center of the $i^{th}$ fired detector, respectively;
- $N_p$: the air shower size, it is estimated by fitting the lateral density distribution using NKG function [1]:

$$N_p = 0.4 N_{hit} R$$

in order to select the high-energy core events, we set $N_{hit}^{b_{top}} \geq 1500$ to reject events falling far from the array. The final data-selected condition is: $N_b \geq 200$, $N_{hit} \geq 4$, $N_{hit}^{b_{top}} \geq 1500$, $N_p \geq 8000$. In this proceeding, we used the experimental data set obtained from May, 2009 through January, 2010. An event coincidence between AS events and YAC-I events is made by their arrival time. Deadtime correction of 18% for AS trigger system and 15% for YAC-I trigger system are taken into account. The data sample coming from successful coincidence corresponds in a live time of 106.05 days. The statistics of such selected core events in MC simulation and experimental data as shown in Table 1. The detection efficiency $\Sigma QG$ is shown in Fig.2.

4 Check of interaction model and primary composition model dependence

First, we checked the interaction model and primary composition model dependence by using (YAC-I+Tibet-III) experimental data. The absolute intensity distribution of $\Sigma N_b$ by using different interaction models and different primary composition models are compared with experimental data as shown in Fig.3. One can see that the experimental shape is compatible with the shape of $\Sigma N_b$ based on QGSJETII-04+HD, EPOS-LHC+HD, SIBYLL2.1+HD, SIBYLL2.1+NLA, QGSJET2+HD and QGSJET2+NLA. $\Sigma N_b$ should depend sensitively on the inelastic interaction cross section, the inelasticity, and particles produced in the forward region. From Fig.3, some discrepancies in the absolute intensities are seen. It shows that the absolute flux derived by these four interaction models deviates from experimental data within 40% error range. On the other hand, we found primary composition model dependence is less than 10%. Some other quantities, such as $N_{hit}^{b_{top}}$, $<N_b R>$ have the same behavior as well, though we did not show them in this proceeding due to the limit of the space.

5 Primary (P+He) energy spectrum

The selection of the (proton+He)-induced events is made with use of a feed-forward artificial neural network (ANN) [17] whose applicability to our experiment was well confirmed by the Monte Carlo simulation[9]. In this proceeding, the events with $T \leq 0.4$ is regarded as (proton+He)-like events(Fig.4) and the average purity and selection efficiency over whole energy range of (P+He) are 95%, 76% at $T_{exp} = 0.4$.

The air-shower size in each event is estimated by fitting the lateral density distribution using modified NKG function. The air-shower size resolution is about 5% around the primary energy of 1000 TeV[1]. The primary energy of cosmic ray is calculated by the function $E_0 = a \times N_p^b$, which is shown in Fig.5, and the energy resolution is about 25% at around 200 TeV.

Finally, we can obtain the primary (P+He) spectrum based on the newest model EPOS-LHC+HD, QGSJETII-04+HD, SIBYLL2.1+HD, SIBYLL2.1+NLA, QGSJET2+HD and QGSJET2+NLA. together with the results from other experiments as shown in Fig.6.

As seen in Fig.6, we found:

1) The obtained P+He spectrum is smoothly connected with direct observation data below 100 TeV and also with
Figure 4: ANN output pattern value (T) distributions compared with MC (EPOS-LHC+HD model). The average purity and selection rate over whole energy range of (P+He) like events are 95%, 76% at $T_c = 0.4$.

Figure 5: Scatter plots of the primary energy $E_0$ and the estimated shower size $N_e$ of (P+He)-like events based on EPOS-LHC+HD model with $\sec \theta \leq 1.1$.

Figure 6: Differential energy spectra of Proton+Helium obtained by the present work compared with other experiments: ATIC1 [11], ATIC2 [12], RUNJOB [14], CREAM3 [15], KASCADE [10], Tibet-ECs [9].

The collaboration 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 a 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 from the National Natural Science Foundation of China (Y11122005B, Y31136005C and Y0293900TF) and the Chinese Academy of Sciences (H9291450S3) and the Key Laboratory of Particle Astrophysics, Institute of High Energy Physics, CAS. The Knowledge Innovation Fund (H95451D0U2 and H8515530U1) of IHEP, China also provide support to this study.

6 Acknowledgements

The collaborative experiment of the Tibet Air Shower Arrays is supported in part by a 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 from the National Natural Science Foundation of China (Y11122005B, Y31136005C and Y0293900TF) and the Chinese Academy of Sciences (H9291450S3) and the Key Laboratory of Particle Astrophysics, Institute of High Energy Physics, CAS. The Knowledge Innovation Fund (H95451D0U2 and H8515530U1) of IHEP, China also provide support to this study.

References


Preliminary