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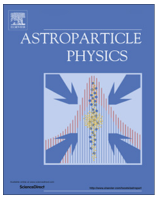

Performance of the Tibet hybrid experiment (YAC-II + Tibet-III + MD) to measure the energy spectra of the light primary cosmic rays at energies 50–10,000 TeV

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ABSTRACT

A new hybrid detector system has been constructed by the Tibet ASγ collaboration at Tibet, China, since 2014 to measure the chemical composition of cosmic rays around the knee in the wide energy range. They consist of an air-shower-core detector-grid (YAC-II) to detect high energy electromagnetic component, the Tibet air-shower array (Tibet-III) and a large underground water-Cherenkov muon-detector array (MD). We have carried out a detailed air-shower Monte Carlo (MC) simulation to study the performance of the hybrid detectors by using CORSIKA (version 6.204), which includes QGSJET01c and SIBYLL2.1 hadronic interaction models. Assumed primary cosmic ray models are based on helium poor, helium rich and Gaisser's fit compositions around the knee. All detector responses are calculated using Geant4 (version 9.5) according to the real detector configurations and the MC events are reconstructed by the same procedure as the experimental data analysis. The energy determination is made by lateral density fitting (LDF) method using modified NKG function and the separation of the light components (proton, helium) is made by means of the artificial neural network (ANN) method and the random forest (RF) method. The systematic errors of the spectra of proton and helium caused by each steps of the analysis procedure are investigated including the dependence of the MC data on the hadronic interaction models and the primary composition models, and the algorithms for the primary mass identification. The systematic errors of the flux to be obtained by the new experiment are summarized as less than 30% in total. Our results show that the new hybrid experiment is powerful enough to study the chemical composition of the cosmic rays, in particular, to obtain the light-component spectra of the primary cosmic rays in 50–10,000 TeV energy range overlapping to the direct observation data at low energy side and ground-based indirect observations at high energy side. It is possible in this energy range to find the break points of the power indices of proton and helium (the knee of individual component spectrum) which are basically important parameter for the study of the cosmic-ray origin.

1. Introduction

The all-particle energy spectrum of primary cosmic rays can be well described by a power law $\mathrm{d}j/\mathrm{d}E \propto E^{-\gamma}$ over many orders of magnitude, with the power index γ changes sharply from 2.7 to 3.1 at about 4 PeV [1,2]. Such break structure of the all-particle energy spectrum is called the "knee", and the corresponding energy range is so called "knee region". The special structure of the power law spectrum is considered to be closely related to the origin, acceleration and propagation mechanism of cosmic rays in the galaxy; however, its origin has not been well understood [3] due to the lack of detailed information about the chemical composition around the knee. The best ways to study the chemical

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compositions are direct measurements of primary cosmic rays by balloon flights or satellites, but the energy range with sufficient event statistics is limited to 10^{14} eV because of limited exposure time and small detective area. So the task of studying chemical components of knee region still relies on the ground-based indirect measurements. The early works doing the research of the chemical composition of the knee region were the Tibet emulsion chamber (Tibet-EC) experiment [4] and the KASCADE experiment [5]. The results of the Tibet-EC suggest that the main component responsible for making the knee structure is composed of nuclei heavier than helium, however, the KASCADE claims that the knee is due to the steepening of the spectra of light elements with an exponential type cutoff as shown in Fig. 1. It is also noted that the experimental data points are still poor in the energy range between the direct measurements and the indirect measurements waiting us to study. Explicit determination of the break point of the spectral index for individual chemical component is essentially important for the study of the cosmic-ray origin.

In order to explicitly observe the break point of the spectral index for individual chemical component, we have recently made the upgrade of the Tibet-EC experiment and started a new Tibet-YAC experiment, the reasons are as follows: Tibet-EC experiment was carried out to measure the Proton and Helium spectrum around the knee by detecting high energy electromagnetic particles at the air-shower core with detection threshold of the core energy 20 TeV (corresponding primary energy is several times 100 TeV). Such high-energy shower cores can be mostly generated by light primary nuclei penetrating deep in the atmosphere. It could reveal the energy spectrum of Proton and Helium in the energy range 5×10^{14} eV– 10^{16} eV covering the knee. The result showed steep power indices of Proton and Helium close to 3.1, which is apparently larger than the results by direct observations (about 2.7) measured below 10^{14} eV. The break points of the power indices of Proton and Helium spectrum are expected at the energy between 10^{14} eV and 10^{15} eV, however there are still poor experimental data at this energy range. The extension of the Tibet-EC experiment for wider energy range needed new AS core detector with lower detection threshold energy and wider dynamic range with good geometrical uniformity for the incident particles upon a detector. YAC detector was developed to satisfy these demands. The detection threshold energy of the YAC can be set at several 10 times lower than EC (300 GeV, corresponding primary energy is several times 10 TeV) by adopting the scintillator instead of the X-ray film for the detection of cascade showers induced in the lead plate by high energy electromagnetic particles at the AS core, and the wide dynamic range of 1–10^6 MIPs (Minimum Ionization Particles) for the burst size detection is realized by installing 2 PMTs (high gain PMT and low gain PMT). Use of the wave length shifting fiber to collect the scintillating light improves the geometrical uniformity. This new experimental condition improves the statistics of the high energy core event compared with Tibet-EC experiment by a factor of 100. The new hybrid experiment (YAC-II + Tibet-III + MD) aims to observe the energy spectrum of Proton and Helium whose energy range will overlap with direct observations at lower energies such as CREAM, ATIC and TRACER, and Tibet-EC experiment at higher energies. On the other hand, we add underground muon detector to new Tibet hybrid experiment, to measure the muon component of the cosmic rays at the high attitude where dependence on hadronic interaction models is expected to be much less than the cases of the sea-level observations. So the new Tibet hybrid experiment (YAC-II + Tibet-III + MD) consists of the Yangbajing air-shower Core detector array (YAC, the second step of YAC is called YAC-II), the Tibet air-shower array (Tibet-III) and an underground water-Cherenkov muon-detector array (MD), as shown in Fig. 2. In this paper, the capability of the measurement of the light-chemical components (proton, helium) with the new Tibet hybrid experiment is investigated.

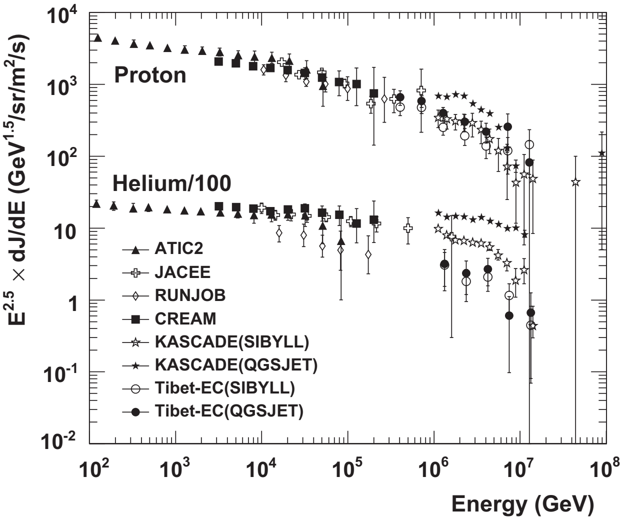

Fig. 1. Energy spectra of primary cosmic-ray proton and helium nuclei obtained by Tibet-EC [4], and they are compared with some other experimental results: ATIC2 [6], JACEE [7], RUNJOB [8], CREAM3 [9], KASCADE [5].

2. The experimental setup

The new Tibet hybrid experiment has been operated in Tibet, China, since March, 2014. The merit of this experiment is that the atmospheric depth of the experimental site (4300 m above sea level; 606 g/cm^2) is close to the maximum of the air shower development with energies around the knee and the primary mass dependence of the values of the shower maximum are minimized [1]. This hybrid experiment is designed not only for observation of air showers of nuclear component origin, but also for observation of high-energy celestial gamma rays by using (MD + Tibet-III). To address these multiple purposes, the detector was constructed to cover a wide dynamic range of particle densities. The dynamic range is 0.1 to 5000 MIPs for the Tibet-III, 1 to 10^6 MIPs for the YAC-II, and 1 to 10^4 MIPs for the MD.

The Tibet-III ($\sim$50,000 m^2) at present consists of 761 fast timing (FT) counters with 28 density (D) counters around them as shown in Fig. 2. In the inner 36,900 m^2, the FT counters are deployed at 7.5 m lattice intervals, and 249 counters among the 761 FT counters are equipped with a density-PMT (D-PMT) too.

The YAC-II consists of 124 detectors, covering a total area of $\sim$500 m^2, as shown in Fig. 3. Each YAC detector is attached with two photomultipliers (PMT) of high-gain (HAMAMATSU: R4125) and low-gain (HAMAMATSU: R5325) to cover the wide dynamic range from 1 MIP (Minimum Ionization Particle) to 10^6 MIPs, the details of the hardware of YAC-II is described in [10,11].

The MD array now consists of 5 pools set up 2.5 m underground, each with 16 cells, covering a total area of $\sim$4500 m^2, as shown in Fig. 2. Each cell of the MD [12] array is composed of a concrete water tank 7.2 m wide × 7.2 m long × 1.5 m deep, equipped with two downward-facing 20-inch-in-diameter PMTs (HAMAMATSU: R3600) on the ceiling, and the inside of each cell is painted with white epoxy resin for waterproof and efficient reflection of the water-Cherenkov light.

The YAC-II is aiming to distinguish the primary cosmic-ray nuclei through recording the electromagnetic showers induced by high energy electrons and photons in the EAS cores, and each detector of YAC has lead plates above the scintillator to convert high-energy electrons and photons into electromagnetic cascade showers. We carried out detailed Monte Carlo simulation on the