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Trans**a**ctions

Cosmic-ray energy spectrum around the knee observed with the Tibet air-shower experiment

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Abstract. The energy spectrum of cosmic rays around the knee measured by Tibet air-shower experiment is summarized and its characteristic features are discussed under two possible scenarios. The result of Tibet experiment measured over wide range of $10^{14}-10^{17}$ eV with high statistics provided details of the knee at the energy around 4×10^{15} eV. The study of the chemical composition based on measurements of proton and helium spectra obtained from air-shower core detection indicates the dominance of heavy nuclei around the knee. Such feature can be explained either by contribution of nearby sources with source composition dominated by heavy nuclei or by nonlinear effect in diffusive shock acceleration mechanism.

1 Tibet Air-shower array and core detector

The Tibet air-shower (AS) experiment is characterized by high altitude of the observation site (4300 m a.s.l., 606 g/cm^2), which enables us to determine the primary energy less dependent upon the primary mass and models of hadronic interactions in the energy range over PeV because of the observation of the shower size at nearly maximum development irrespective of the primary mass. The second merit of the high altitude is that it is possible to select the shower events of light nuclei origin such as protons and helium through the detection of high-energy secondary particles (electromagnetic component) located at the AS core, because the probability of association of high energy secondaries depends on primary mass by the difference of the interaction cross section in the atmosphere. The study of the primary mass composition is made by simultaneous operation of the AS array and the core detector. The AS array consists of 761 fast timing (FT) counters, surrounded by 28 density (D) counters with 36 900 m^2 coverage as shown schematically in Fig. 1. The AS array is used to measure the energy and arrival direction of each AS. The details of the installation are described in (Amenomori et al., 2008a). The primary energy of each event is determined by the shower size N_e, which is calculated by fitting the lateral particle density distribution to the modified NKG structure function. The energy resolution is less than 20% for the knee energy range. The arrival direction of an air shower is determined as follows. The direction cosine of the shower axis is determined using a least square method in which the difference is minimized between the arrival time signals of each FT counter and the expected values on the assumed cone with a given direction cosine. This procedure determines the arrival angle with an accuracy smaller than 0.2° at energies above 10^{14} eV, which is calibrated by observing the Moon's shadow (Amenomori et al., 2000a, 2003).

The core detector was designed to detect the high-energy particles at the AS core by converting them into electromagnetic cascade showers (burst) using lead absorber of 160 cm × 50 cm in area and 7 cm (in Phase I) or 3.5 cm (in Phase II) in thickness. The burst size under the lead plate was measured by scintillation counters of the same size as the lead plate in area and 2 cm in thickness. Four photodiodes were attached to the each corner of the scintillator whose attenuation length for the scintillation light was calibrated with electron beam. From the 4 photo-diode signals, we can estimate the burst size and the position of the burst center with spatial resolution of 10 cm. One hundred core detectors were used (total area is 80 m^2) to detect burst size greater than 5×10^4. The study of the primary mass composition was made through two experimental phases. In the first phase, 6 layers of X-ray films were placed between lead plates with 1 cm depth interval to register the development of shower spots induced by high-energy γ and electrons (hereafter abbreviated as γ-rays) over a few TeV which are incident upon the detector, and detailed analysis on the structure of the high energy core has been made with use of image scanner (Ozawa et al., 2004) to obtain proton and helium spectra (Amenomori et al., 2006). The energy determination of the individual γ-rays was made by the comparison of the transition curve of the optical density of the shower spots with electromagnetic shower theory. Such procedure of the energy determination using X-ray films was calibrated using 200 GeV electron beam at FNAL (Hotta et al., 1980). A bundle of the high energy γ-rays originating from successive nuclear interactions of the primary cosmic rays in the atmosphere is called γ-family, which can be detected by spatial reconstruction of the shower spots registered on X-ray films with angular resolution of 2.5°. They are reconstructed as groups of parallel tracks with typical lateral spread of at most several cm among uncorrelated single tracks, which are reduced as background. The assignment of a γ family to an accompanied AS was made through the positional correlation between the X-ray film and the scintillator, and the correlation between the burst and AS was made by their time stamps. The arrival directions obtained from AS and the reconstruction of the shower spots were also used to uniquely determine the AS candidate.

Such γ-family events are more efficiently generated by light primaries than the case of heavy primaries because of the penetrating nature in the atmosphere. Hence, the AS core detector can select the air showers of light primary origin naturally. The contamination of the events of heavy nuclei origin was estimated using Artificial Neural Network (ANN) based on extensive Monte Carlo simulation of air showers (MC) assuming interaction models and primary models using CORSIKA code. Two interaction models of QGSJET and SIBYLL are used in estimating the efficiency of the γ family generation, and also two mass composition models of proton dominant (PD) and heavy dominant (HD) are used to appreciate the contamination rate of heavy primaries. The efficiency of the family generation for various primary nuclei and its energy dependence is calculated by MC and used for obtaining the primary proton and helium fluxes. For ex-

Fig. 1. Air-shower array located at Tibet, Yangbajing (4300 m a.s.l.)

ample, the efficiencies by protons at the knee energy 4 PeV in phase I experiment are about 7% and 10% by QGSJET model and SIBYLL model, respectively. ANN is also used in procedures to obtain proton and helium spectra. Phase I experiment selected 177 γ family events with core energy $\sum E_\gamma > 20$ TeV and AS size $N_e > 2 \times 10^5$.

In the second phase experiment, X-ray films were not used and proton+helium (P+He) spectrum was studied without separating them but with higher statistics than that of phase I. The core detector was tuned to decrease the detection threshold energy of the AS core to have several times higher efficiency. The details of the analysis are described in (Amenomori et al., 2007, 2010).

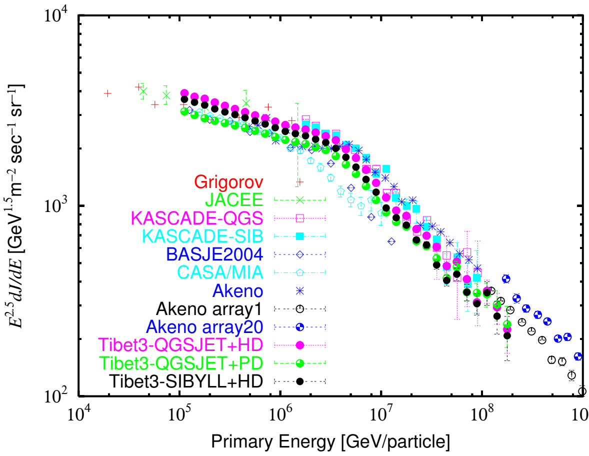

Fig. 2. All particle spectrum obtained by Tibet 3 array. The results from three models of QGSJET+HD, QGSJET+PD, and SIBYLL+HD used in the analysis are shown.

2 Experimental results

The energy spectrum of all particles was obtained as shown in Fig. 2 together with other data (Cited data: Grigorov (Grigorov et al., 1971), JACEE (Asakimori et al., 1998), KASCADE (Antoni et al., 2005), BASJE (Ogio et al., 2004), CASA (Fowler et al., 2001), Akeno (Nagano et al., 1984), Akeno array1 and Akeno array20 (Nagano et al., 1992)). The uncertainty of the absolute intensity due to the interaction models used in the analysis is shown by QGSJET and SIBYLL (10% difference at most). The uncertainty due to the assumed primary mass composition is also shown by HD and PD. Although the composition is fairly different between HD and PD models at energies above 10^{15} eV, the difference of the absolute intensity is 20% at most between the two models and it decreases with increasing primary energy. Note that the shapes of the spectra from different models are almost the same and the position of the knee is clearly found at the energy around 4 PeV.

From the second phase experiment of AS core observation, the energy spectrum of P+He was obtained with high statistics and in good agreement with phase I as shown in Fig. 3, in which QGSJET model was used for the analysis. Use of SIBYLL model results in about 30% lower intensity than that of the QGSJET analysis There is a problem of discrepancy between Tibet and KASCADE data as shown in Fig. 3, e.g., the flux of the light nuclei by KADCADE is higher than Tibet by more than factor 2. However, if SIBYLL model is used in the analysis of KASCADE, the difference between two data is much reduced. This fact does not necessarily mean that SIBYLL model is more preferable to explain the data at this energy range. KASCADE reported that QGSJET model explains high energy data better than SIBYLL, on the other hand, SIBYLL model is better at lower energies. This problem is related to the interaction model dependence of MC calculations and also to the different experimental methods used in two experiments. Tibet experiment observes high energy part of the air showers, namely, the most forward region of the center of momentum system (CMS) of interacting particles, while KASCADE experiment observes $N_e - N_\mu$ correlation, in which muon component is sensitive to the central region of the CMS. The model dependence in forward region

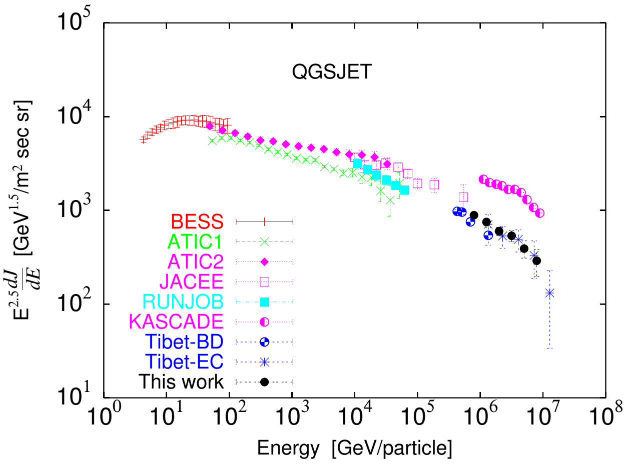

Fig. 3. P+He spectrum obtained by AS core observation (black closed circle).

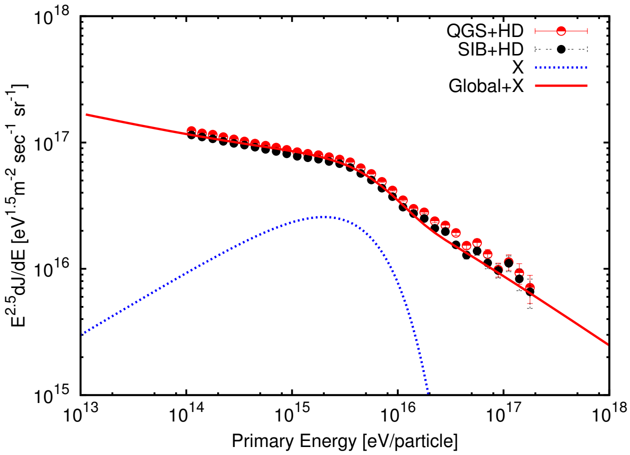

Fig. 4. Model A: Sharp knee is attributed to extra component (dashed line) from nearby source. Solid red line represents sum of the global component and the extra component.

is about 30% as studied by Tibet, but that of central region seems to be as large as factor 2. (Cited data: BESS (Sanuki et al., 2000), ATIC1 (Ahn et al., 2003), ATIC2 (Wefel et al., 2005), JACEE (Asakimori et al., 1998), RUNJOB (Derbina et al., 2005), KASCADE (Antoni et al., 2005), TIBET-BD (Amenomori et al., 2000b), TIBET-EC (Amenomori et al., 2006)).

Remarkable features of the energy spectrum of light component around 10^{15} eV are; (1) The power index is steeper than that of all-particle spectrum before the knee, suggesting that the light component has the break point at lower energy than the knee. (2) The fraction of the light component to the all-particles is less than 30% which tells that the main component responsible for the knee structure is heavier than helium.

3 Discussion

The features of the energy spectrum and primary mass composition obtained by Tibet experiment can be interpreted by two scenarios of the origin of cosmic rays (Shibata et al., 2010).
Model A : Sharp knee is caused by extra component originating from nearby source(s) as first pointed out by single source model of (Erlykin et al., 1997). Fig. 4 shows that the sharp knee of the all-particle spectrum can be reproduced by adding extra component around the knee over the global component which can be calculated as diffusive cosmic rays originating from multiple sources. The energy spectrum of the extra component can be approximated by $\propto E^{-2}\exp(-E/4PeV)$, which is close to the source spectrum expected from diffusive shock acceleration (DSA) mechanism of cosmic rays. A possible explanation of such extra component together with the knee composition is to assume nearby source(s) dominated by heavy elements such as type Ia SNRs or pulsars.
Model B : The knee is due to the characteristics of the DSA mechanism in which nonlinear effect plays an important role resulting in hard source spectrum of cosmic rays near acceleration limit energy. Fig. 5 shows the primary mass composition calculated by nonlinear model in which it is assumed that heavy elements are more efficiently accelerated than light elements (Cited data: Grigorov (Grigorov et al., 1971), SOKOL (Ivanenko et al., 1993), JACEE (Asakimori et al., 1998), RUNJOB (Derbina et al., 2005), ATIC1 (Ahn et al., 2003), ATIC2 (Wefel et al., 2005), CREAM1 (Seo et al., 2005), CREAM2 (Ahn et al., 2009), TRACER (Ave et al., 2008), HESS (Aharonian et al., 2007)). This model predicts the rigidity-dependent hardening of the energy spectrum before the knee and heavy elements dominate at the knee and beyond. Recent direct observations of ATIC and CREAM reported hardening of the energy spectrum in $10^{12}-10^{14}$ eV region (Panov et al., 2006; Ahn et al., 2009) and model B seems to be favorable to account these data. It is also possible that both of models A and B contribute to the structure of the knee.

4 New hybrid experiment (Tibet-AS+YAC+MD)

New detectors are under construction at Tibet for the study of the cosmic-ray origin. Improved AS core array called Yanbajing Air shower Core detector (YAC) is going to be set up in late 2010, which consists of 100 burst detectors with low detection threshold for burst size, located at the center of the AS array. Also, large area (900 m$^2\times 4$) underground muon detectors (MD) are under construction (water Cherenkov detector) as schematically shown in Fig. 6 (Amenomori et al.,

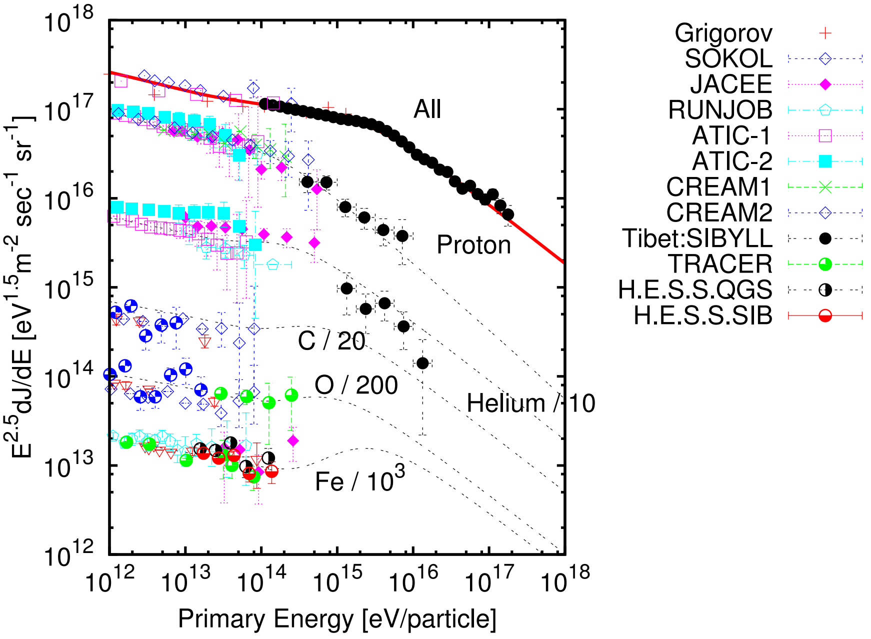

Fig. 5. Model B: Nonlinear effect in the DSA mechanism can explain the structure of the knee when high acceleration efficiency for heavy elements is assumed.

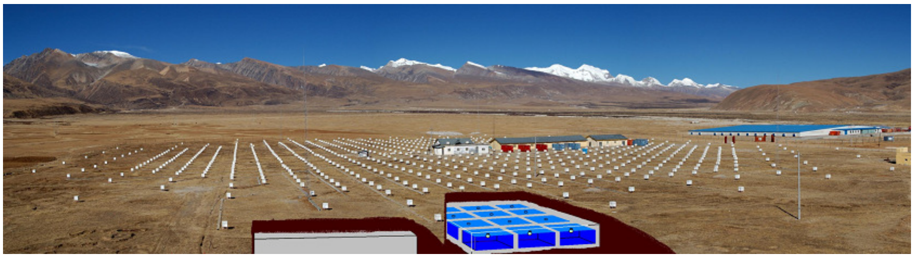

Fig. 6. Underground water Cherenkov muon detector MD under construction.

2008b, 2009). These hybrid detectors will be used for further study of the origin of cosmic rays.

5 Summary

Further measurement of the cosmic-ray energy spectrum above 10^{14} eV is important to solve the problem of the origin of cosmic rays. Existence of the nearby source(s) can be tested by next phase Tibet experiment using MD, which has excellent power for p/γ separation and provides new information of high-energy γ. Nonlinear model of cosmic-ray acceleration predicts the dominance of iron component at the knee and beyond which will be also tested by YAC in near future.

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