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Performance of the Tibet-III Air-Shower Array
The Tibet ASγ Collaboration

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Abstract. The Tibet-III air-shower array, which is still in the middle of construction, has been successfully operating at Yangbajing (4,300 m a.s.l.) since November of 1999. At present, the Tibet-III array consists of 533 scintillation detectors of each 0.5 m^2. The threshold energy of observed air shower is estimated to be 1.5 TeV for protons, and the angular resolution is estimated to be 0.87 ± 0.02 degrees above 3 TeV using a Monte Carlo simulation. This angular resolution is well confirmed by observing the cosmic-ray shadow by the Moon. We present the performance of the new array using a Monte Carlo simulation.

1 Introduction

Air shower arrays are wide-aperture and high duty cycle instruments, in contrast to atmospheric Cherenkov telescopes with relatively narrow fields of view and small duty cycle of $\sim 10\%$. In particular, a high altitude as Tibet enables us to observe cosmic ray showers with energies as low as several TeV with a high resolution air-shower array. These features are indispensable for understanding a time variability of emission of high-energy gamma rays from point sources such as Mrk 501 (Amenomori *et al.*, 2000a) & Mrk 421 (Amenomori *et al.*, 2001).

A collaboration experiment on cosmic-ray physics between Japan and China has been successfully continued at Yangbajing (4,300 m above sea level) since 1990 and succeeded to detect cosmic ray showers around 10 TeV with an angular resolution better than 1° (Amenomori *et al.*, 1992) (Amenomori *et al.*, 1993). On the basis of this experiment, the Tibet air shower array has been gradually expanded and condensed to increase the sensitivity of detecting cosmic ray showers with energy as low as much possible.

A Tibet-III air-shower array, which is an expansion of a high density array (Tibet-HD array) (Amenomori *et al.*, 1999), was constructed in 1999 to detect cosmic ray showers in the multi-TeV region with a good statistics. We report the performance of this new array based on a Monte Carlo simulation.

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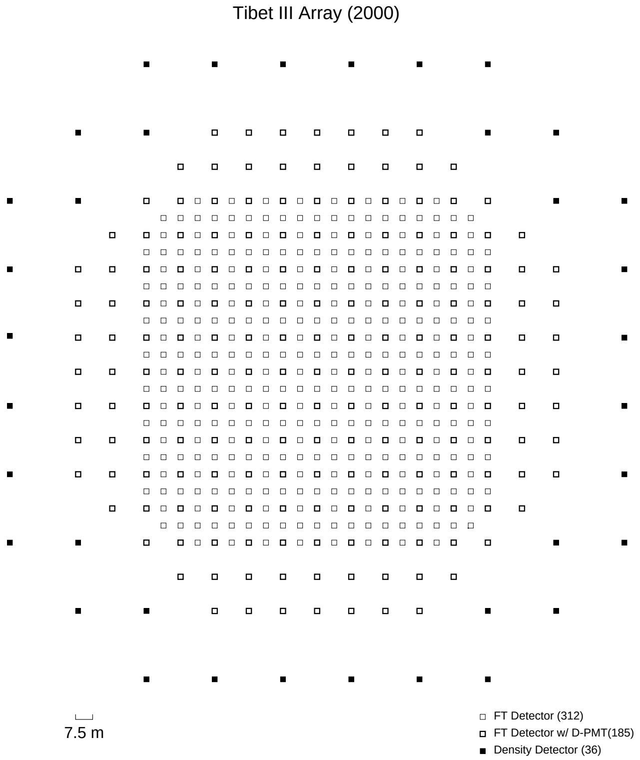

Fig. 1. The Tibet Air Shower Array in 2000.

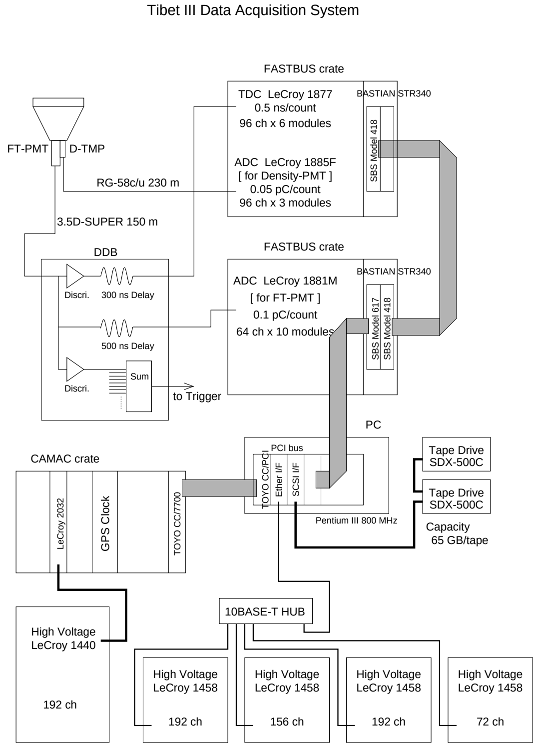

Fig. 2. Data acquisition system of the Tibet Air Shower Array in 2000.

2 Present status of the Tibet III

The Tibet-III air-shower array is composed of 497 FT (fast timing) - detectors and 36 D (density) - detectors (Fig. 1). Each detector has a cross area of 0.5 m^2 and contains a plastic scintillator of 71 cm $\times$ 71 cm $\times$ 3 cm thickness (Amenomori *et al.*, 1992). A lead plate of 5 mm is placed on the top of each detector to improve the fast timing data by converting gamma rays in the showers to electron pairs. A signal detected by photomultiplier tube (PMT) is sent to the central control room, passing through a 150 m-long cable. Here, the trigger pulse of the data acquisition system, charge measurement of each detector using an ADC and timing measurement using a TDC are made. Currently, the trigger pulse is formed when 4 units or more among 433 FT-detectors, excluding the outermost two layers in the array, give a signal of 0.8 particles or more.

Calculating the number of incident particles from the charge measured with each ADC, the energy of each primary particle is estimated from air shower size $\sum \rho_{\rm FT}$, where $\rho_{\rm FT}$ is the number of particles observed in each detector and the summation is taken for all fired detectors. The number of particles in each detector can be measured with a fast-timing PMT in the FT-detector up to 15 particles. Beyond this it can be measured up to 4000 particles per detector with the FT/D-detector where a wide range PMT is equipped together with a fast-timing PMT. Arrival direction of each air shower is calculated using the relative time of pulses measured with each TDC. The ADCs and TDCs are connected to a FASTBUS. The digitized data by these ADCs and TDCs are read through a computer via a VMEbus / FASTBUS interface module, and recorded on the AIT-2 tape which has the capacity of 65 GB. Figure 2 shows the data acquisition system of the Tibet-III array. The present trigger rate is 680 event/sec, and the dead time is estimated to be 10%. The stored event rate amounts to about 20 GB/day, and 3-day data fill one tape.

3 Monte Carlo simulation and analysis

A Monte Carlo simulation was done to estimate the performance of the Tibet-III array. The Cosmos code (Kasahara, 2001a) was used for calculating the development of air showers in the atmosphere, and the Epics code (Kasahara, 2001b) was used for simulating the detector response. A heavy dominant model (Amenomori *et al.*, 2000b) was assumed for a chemical composition of primary cosmic rays. We assumed the energy spectrum of all-particle cosmic rays expressed as $1.5 \times 10^{-20}(E_0/10^{14.75}{\rm eV})^{-2.60}$ ${\rm m^{-2}s^{-1}sr^{-1}eV^{-1}}$ (Amenomori *et al.*, 1996). Primary particles were thrown isotropically within the zenith angle 0 to 60 degrees on the top of the atmosphere, and generated air showers were gathered within the circle of the radius 300 m from the center of the array.

We used the experimental data obtained on November 18, 1999 to compare it with the simulation data. This is the first run of the Tibet-III array, corresponding to the 1.81 hours ob-

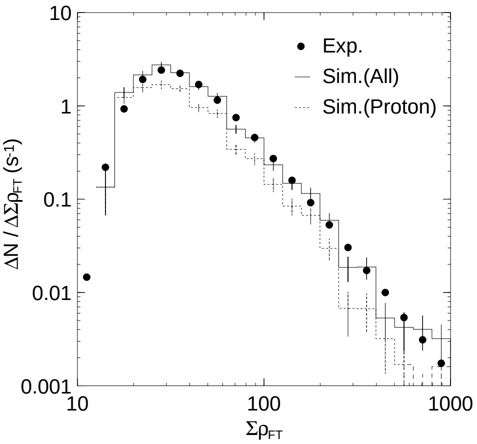

Fig. 3. $\sum \rho_{\mathrm{FT}}$ spectrum. Closed circles show experimental data. Solid line shows the MC simulation assuming a heavy dominant primary flux and dashed line extracts its proton component.

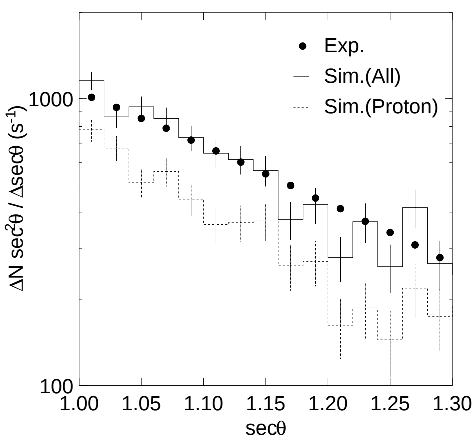

Fig. 4. Zenith angle distribution. Closed circles show experimental data. Solid line shows the MC simulation assuming a heavy dominant primary flux and dashed line extracts its proton component.

servation time. The event selection was done by imposing the following three conditions on both of the simulation and experimental data: (1) Each of any four detectors should record a signal of more than 1.25 particles; (2) estimated core location should be inside of the array; and (3) estimated zenith angle of the incident direction should be less than 40°. After data processing and quality cuts, 1.2×10^3 and 8.5×10^5 events survived for the simulation and experimental data, respectively.

4 Performance of Tibet III

A distribution of the sum of shower particle densities, $\sum \rho_{\mathrm{FT}}$, of 497 FT-detectors is shown in Fig. 3. The simulation and the experimental results are in good agreement with $\chi^2 = 33.1$ / 19 degrees of freedom for $15 < \sum \rho_{\mathrm{FT}} < 1000$. The integral event rates in this region are calculated to be 144.64 ± 4.22 events/s and 142.40 ± 0.16 events/s for the simulation and the experimental data, respectively. Both are well in agreement. The systematic error in the size scale is estimated to be less than 10% level, assuming a ±30% normalization uncertainly for the absolute flux of primary cosmic rays. Figure 4 shows their zenith angle distributions. The simulation and the experimental data are in good agreement each other with $\chi^2 = 21.1$ / 15 degrees of freedom for $1.0 < \sec\theta < 1.3$. Figure 5 shows a correlation between $\sum \rho_{\mathrm{FT}}$ and the primary energy per particle obtained by the simulation. Then, the primary proton energy $< E_0 >$ is expressed as $(12.7\pm0.5)\times(\sum \rho_{\mathrm{FT}}/100)^{(0.95\pm0.04)}$ TeV ($15 < \sum \rho_{\mathrm{FT}} < 700$) as a function of $\sum \rho_{\mathrm{FT}}$. Figure 6 shows an effective area of the Tibet III as a function of $\sum \rho_{\mathrm{FT}}$. The threshold energy, as defined that the effective area become 1% of real area, is 1.5 TeV for protons.

The systematic pointing error and angular resolution of the Tibet-III array can be estimated by observing the Moon shadow in the cosmic ray flux. Primary charged particles

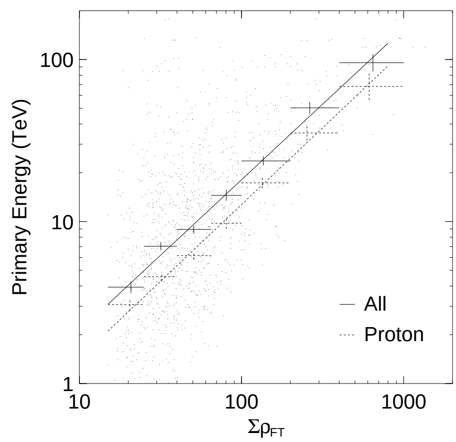

Fig. 5. Correlation between $\sum \rho_{\mathrm{FT}}$ and the primary energy. Closed circles show the MC simulation data for all primaries and crosses denote protons in the primary.

are bent by the geomagnetic field before reaching the Earth (Amenomori *et al.*, 1993). Figure 7 shows the Moon shadow observed with the Tibet-III array for the effective observation time of 156 days during the period from November 18th 1999 through June 29th, 2000. The maximum deficit depth is estimated to be more than 16σ. An angular resolution of the array is estimated by the sharpness of the shadow. The Moon shadow should also be observed at the position somewhat shifted to the west due to the effect of the geomagnetic field. As seen in Fig. 7, the center of the Moon shadow is observed at the position shifted to the west by $\sim 0.25°$. This value is consistent with the expected deviation of 0.23°. The north-south deviation of 0.1° from the shadow center is regarded as the systematic pointing error of the Tibet-III array since the geomagnetic field does not move the shadow in the north-south direction.

Here, we define the angular resolution of the array as the

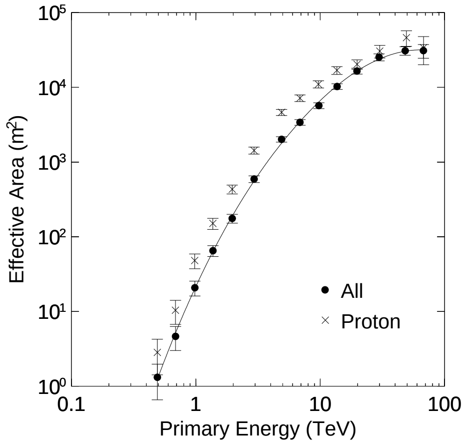

Fig. 6. Effective area. Closed circles show the MC results plotted as a function of primary energy per particle and crosses denote for protons.

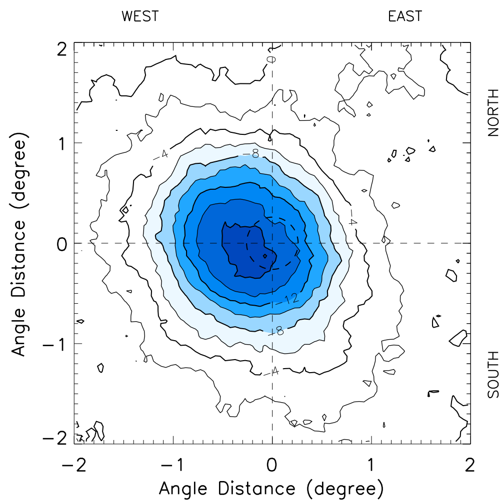

Fig. 7. Moon shadow observed by the Tibet III.

radius of a circle in which 50% of shower events coming from a point source are contained. Figure 8 shows the angular resolutions obtained from the simulation and the Moon shadow observation. They are in a good agreement with $\chi^2 = 9.2$ / 6 degrees of freedom for $20 < \sum \rho_{\rm FT} < 300$. The angular resolution can be expressed as the following function of $\sum \rho_{\rm FT}$: $\Delta\theta(\sum \rho_{\rm FT}) = (0.62 \pm 0.02) \times (\sum \rho_{\rm FT}/100)^{(-0.54\pm0.04)}$ degree ($20 < \sum \rho_{\rm FT} < 300$). The angular resolution integrated for all $\sum \rho_{\rm FT} > 15$ is estimated to be 0.87 ± 0.02 degrees.

5 Summary

The Tibet-III air-shower array has been successfully operating at Yangbajing since November 1999. We estimated the performance this array using the Monte Carlo simulation. The threshold energy for detecting proton-induced showers is estimated to be 1.5 TeV. The angular resolution is esti-

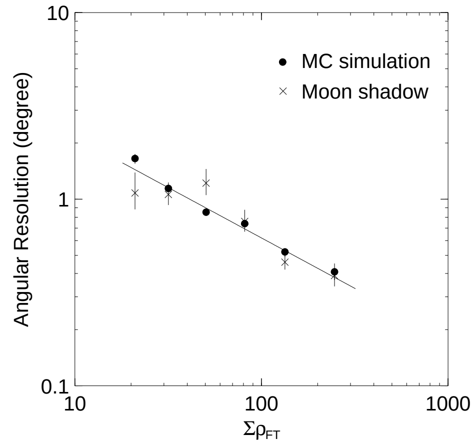

Fig. 8. Angular resolution. Closed circles and crosses show the angular resolution obtained from the simulation and the moon shadow. solid line shows the best fit line using the simulation results.

mated to be 0.87 ± 0.02 degrees in the energy region above 3 TeV. This angular resolution is well confirmed by observing the Moon shadow. The high density part of the array will be further enlarged up to 36900 m^2 by adding 190 detectors in the fall of 2002 and then the sensitivity will increase by about 1.3 times.

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