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# Absolute Energy Scale Calibration of Multi-TeV Cosmic Rays Using the Moon's Shadow Observed by the Tibet Air Shower Array

The Tibet AS$\gamma$ Collaboration
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The Tibet air shower array has been in operation since 1999 as Tibet III with an energy threshold of a few TeV. As primary cosmic rays are shielded by the Moon having the finite size of 0.5° in diameter, we observe a deficit in cosmic rays called the Moon's shadow with a significance of 40 $\sigma$ level for 1041 live days. The center of the Moon's shadow shifts westward depending on primary cosmic-ray energies due to the geomagnetic field. We calibrate the absolute energy scale of the primary cosmic rays observed by the Tibet III array using this effect. The Moon's shadow simulation including a precise calculation of the geomagnetic effect shows a good agreement with observational data. As a result, the systematic error in the absolute energy scale is estimated to be less than approximately $\pm 8\%$ level by means of the geomagnetic field as a spectrometer.

## 1. Introduction

The Tibet air shower (AS) experiment has been successfully operated at Yangbajing (90.522° E, 30.102° N, 4,300 m above sea level) in Tibet, China since 1990. The array constructed first in 1990 was gradually upgraded by increasing the number of counters, and then the Tibet III array, used in the present analysis, was completed in the late fall of 1999 [1]. This array consists of 533 plastic scintillation counters of 0.5 $m^2$ each viewed by a fast-timing (FT) photo-multiplier tube, placed on a 7.5 m square grid with an enclosed area of 22,050 $m^2$ to detect high-energy ( $>$ a few TeV) cosmic-ray showers. The AS trigger rate is about 680 Hz. In the late fall of 2003, the area of the Tibet III array was further enlarged up to 36,900 $m^2$ by adding 256 counters. This final array configuration has been successfully in operation since then, triggering AS events at a rate of 1,700 Hz.

The observation of the Moon's or Sun's shadows by a ground-based AS array is very useful to calibrate the performance of the AS array itself. The Moon's shadow was first observed by the CYGNUS collaboration in 1991 [2], then sharpness of the observed Moon's shadow was used to estimate its angular resolution. Almost all of primary cosmic rays are positively charged, they are bent westward by the geomagnetic field at Yangbajing, therefore, the position of the Moon's shadow shifts from the original Moon's position. On the contrary, they are unaffected in the north-south direction as the east-west component of the geomagnetic field is negligible ($\sim$10%) at Yangbajing. Since the geomagnetic field between the Earth and the Moon is accurately measured and modeled, and the energy spectrum and the composition of cosmic rays at $<$ 100 TeV are measured by direct measurements, the observed position and the shape of the Moon's shadow enable us to calibrate the possible systematic error in the absolute energy scale (westward shift), angular resolution and absolute pointing (north-south direction) by multi-TeV primary cosmic-ray directions estimated by the AS event reconstruction procedure. The long-term stability in the pointing accuracy, angular resolution and absolute energy scale of the AS array also can be directly checked by monitoring the Moon's shadow continuously [1]. In addition, the Moon's and Sun's shadows are used as a tool to study the cosmic-ray $\bar{p}/p$ flux ratio [3] and the interplanetary magnetic field between the Sun and the Earth [4].

In this paper, we will report mainly on a method of the absolute energy scale calibration of multi-TeV cosmic rays using the energy dependence of the westward shift in the Moon's shadow observed by the Tibet AS array.

## 2. Simulation

We develop a detailed Monte Calro (MC) simulation code of the Moon's shadow assuming the geomagnetic field is the dipole magneticfield model (moment $M = 8.07 \times 10^{25}$ Gauss $cm^3$, south geomagnetic pole 78.3°S, 111.0°E). The relative chemical composition of primary cosmic rays was adopted based mainly on direct observational data [5, 6, 7] in the energy range from 0.3 TeV to 1000 TeV. The AS events were generated by the Corsika Ver.6.200 code [8] with QGSJET or SIBYLL for the hadronic interaction models along the Moon's orbit around the Earth. First, the generated secondary particles by the Corsika code are traced down to the Yangbajing site, and time and charge information of each particle is converted to ADC and TDC values by the detailed detector response simulation. Thus, we treat and analyze the MC events in the same way as the experimental data. Secondly, An opposite charge is assigned to a triggered MC primary particle, and the primary particle are imaginarily shot back toward the Moon from the Yangbajing site considering the estimated the angular resolution by the detector response simulation. The primary particle which hits the Moon produce the Moon's peak. In this way, we obtain the expected Moon's peak which is equivalent to the observed Moon's shadow.

## 3. Analysis

In the present paper, we employ the data obtained by the 22,050 $\mathrm{m}^2$ array configuration described in § 1 for the whole period in order to simplify the analysis. The Tibet III array collected $6.1 \times 10^{10}$ events during the period from November, 1999 through October, 2004, and the live time is calculated to be 1041 days. The event selection is made by imposing the following conditions on the recorded data: (1) Trigger threshold: Each shower event should fire four or more the inner FT-counters recording 1.25 particles or more; (2) Core location: Among the 9 hottest FT-counters in each event, 8 should be contained in a fiducial area (22,050 $\mathrm{m}^2$); and (3) Zenith angle: The zenith angle of the arrival direction should be less than $40°$. After these selections and quality cuts, $1.5 \times 10^{10}$ events remain for further analysis.

In order to extract a deficit in cosmic-ray events coming around the Moon, the background event density must be carefully estimated. The background is estimated by the number of events averaged over 8 off-source cells with the same size as on-source, at the same zenith angle, recorded at the same time intervals as the on-source cell events. This method, so-called "equi-zenith angle background estimation" [1], can reliably estimate the background events under the same condition as on-source events.

## 4. Results and Discussions

The closed circles in Fig. 1 (a)–(f) show the deficit counts around the Moon projected to the east-west axis for each $\sum \rho_{\mathrm{FT}}$ bin, where $\sum \rho_{\mathrm{FT}}$ is a sampling AS size defined as the sum of the number of particles per $\mathrm{m}^2$ for each FT detector. In these figures, the peak position of deficit counts shifts westward as the cosmic-ray energy decreases. The solid histograms in Fig. 1 show the results by the MC simulation of the Moon's shadow. These results are in good agreement with the experimental data.

Fortunately, the north-south displacement of the Moon's shadow observed by the Tibet III array does not depend on the cosmic-ray energy, because the geomagnetic strength of the east-west component at our site is negligible. Therefore, the displacement of the center of the Moon's shadow in the north-south direction enables us to estimate the magnitude of the systematic pointing error without the Moon's shadow simulation. Figure 2 (a) shows the energy dependence of the displacement of the Moon's shadow in the north-south direction. A $\chi^2$ fitting gives $-0.0034° \pm 0.011°$ assuming a constant function independent of energy. From this, the systematic pointing error is estimated to be smaller than $0.011°$.

Figure 2 (b) shows the shower size dependence of the displacement of the Moon's shadow in the east-west

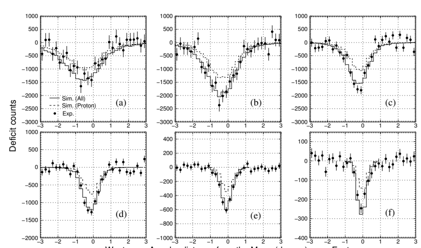


**Figure 1.** Closed circles show experimental data for deficit counts around the Moon projected to the east-west axis for each $\sum \rho_{\mathrm{FT}}$. We use the events contained in an angular band, centered at and parallel to the east-west axis, compatible with the $\sum \rho_{\mathrm{FT}}$-dependent angular resolution: (a): $\pm 1.4°$ for $18 < \sum \rho_{\mathrm{FT}} \leq 32$; (b): $\pm 1.0°$ for $32 < \sum \rho_{\mathrm{FT}} \leq 56$; (c): $\pm 0.7°$ for $56 < \sum \rho_{\mathrm{FT}} \leq 100$; (d): $\pm 0.5°$ for $100 < \sum \rho_{\mathrm{FT}} \leq 215$; (e): $\pm 0.3°$ for $215 < \sum \rho_{\mathrm{FT}} \leq 464$; (f): $\pm 0.2°$ for $464 < \sum \rho_{\mathrm{FT}} \leq 1000$, respectively. Solid histograms denote the Moon's shadow simulation assuming a relative primary cosmic-ray composition based on the direct observational data, while the dashed histograms represent the events induced by protons.

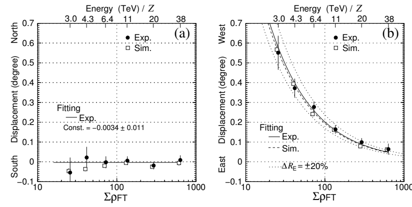


**Figure 2.** Shower size dependence of the displacement of the Moon's shadow in the north-south direction (a) and in the east-west direction (b). The closed circles show the experimental data, and the open squares represent the Moon's shadow simulation. The solid line in (a) shows the fitting to the experimental data assuming a constant function, resulting in $-0.0034° \pm 0.011°$. The solid and dashed lines in (b) are fitted to the experimental data and the MC simulation data, respectively (see text). Upper scale indicates the log-scale mean of rigidity (TeV / $Z$) in each $\sum \rho_{\rm FT}$ bin.

direction. In this figure, the open squares show the expected deflection, and the MC simulation is quite consistent with the observational data. First, the MC simulation data points are fitted by a function $\alpha\ (\sum \rho_{\rm FT})^{-\beta}$ to define a curvature function, resulting in $\alpha$ = 6.895 and $\beta$ = 0.775 as shown by a dashed curve in Fig. 2 (b), where MC statistical errors are negligible compared with the experimental data. Secondly, the experimental data (closed circles) is fitted by the curvature function $6.895\ [\sum \rho_{\rm FT}(1-\Delta R_{\rm S})]^{-0.775}$ to estimate a possible shift in the $\sum \rho_{\rm FT}$ between the experimental data and the MC simulation as shown by a solid curve in Fig. 2 (b), where $\Delta R_{\rm S}$ is the $\sum \rho_{\rm FT}$ shift ratio, resulting in $\Delta R_{\rm S} = (+4.8 \pm 8.3)\%$. However, we should convert this to the energy shift ratio $\Delta R_{\rm E}$ as a final result. To determine the relation between $\Delta R_{\rm S}$ and $\Delta R_{\rm E}$, we prepare 6 simulation data sets in which the energy of primary particles is systematically shifted event by event in the Moon's shadow simulation. These 6 $\Delta R_{\rm E}$s are $\pm 20\%$, $\pm 15\%$ and $\pm 8\%$, respectively. At each simulation data set, the $\sum \rho_{\rm FT}$ dependence of the displacement of the Moon's shadow is calculated in the same way, and the $\sum \rho_{\rm FT}$ shift ratio $\Delta R_{\rm S}$ is estimated by fitting the curvature function of $6.895[\sum \rho_{\rm FT}(1-\Delta R_{\rm S})]^{-0.775}$ as described above. Finally, we get a relation $\Delta R_{\rm E} = (-0.91 \pm 0.05)\ \Delta R_{\rm S}$ assuming a linear function, therefore, the systematic error in the absolute energy scale is estimated to be $\Delta R_{\rm E} = (-4.4 \pm 7.9)\%$. This result is calculated based on the QGSJET hadronic interaction model in the AS simulation. Note that we also obtain a similar result to the QGSJET one, based on the SIBYLL hadronic interaction model. As a result, the systematic error in the absolute energy scale is estimated to be less than approximately $\pm 8\%$ level by means of the geomagnetic field as a spectrometer.

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