Cosmic ray mass composition measurement with the TALE hybrid detector

Keitaro Fujita¹,* and for the Telescope Array collaboration

¹Institute for Cosmic Ray Research, the University of Tokyo

Abstract. The Telescope Array (TA) located in the State of Utah in the US is the largest ultra-high energy cosmic rays observatory in the northern hemisphere. The Telescope Array Low-energy Extension (TALE) detector was constructed to study the transition of cosmic rays from Galactic to extra-galactic origin. The TALE detector consists of a Fluorescence Detector (FD) station with 10 high elevation telescopes located at the TA Middle Drum FD Station (itself made up of 14 FD telescopes), and a Surface Detector (SD) array made up of 80 scintillation counters, including 40 with 400 m spacing and 40 with 600 m spacing. We have continued stable observation with hybrid mode since 2017. In this contribution, we present the latest result of the cosmic ray mass composition measurement using almost 4 years of TALE hybrid data.

1 Introduction

The Telescope Array (TA) cosmic ray observatory is the largest hybrid cosmic ray detector in the northern hemisphere in Millard Country, Utah St. The main part of the experiment consists of a surface detector (SD) array that is overlooked by 3 fluorescence detector (FD) stations. The TA SD consists of 507 scintillation counters with 1.2 km spacing and covering a total of ~ 700 km² area on the ground. The three TA FD stations are located at Black Rock Mesa (BRM), Long Ridge (LR), and Middle Drum (MD), and these are overlooking the area of SD array. The Telescope Array Low-energy Extension(TALE), located at the north part of the TA experiment site, is aimed at measuring the energy spectrum and the mass composition of very high energy cosmic rays above 10¹⁶ eV. The TALE detector consists of one FD station with ten fluorescence telescopes and an array of 80 scintillation surface detectors, which were deployed to cover a total area of approximately 20 km². All 10 telescopes were refurbished from components previously used by HiRes [1], and view 31° to 59° in elevation, directly above the field of view of the MD telescopes. The TALE FD began operation in 2013 at the MD station. On the other hand, the TALE SD consists of 40 scintillation counters with 400 m and 40 counters with 600 m spacing, and started observation from 2017. In addition, an external trigger from the TALE FD to the TALE SD to detect low energy cosmic rays, so-called hybrid trigger system, was installed in 2018. The full details of the TALE detectors are found in [2] [3]. In this contribution, we report on the performance of the TALE hybrid detector and present preliminary results of mass composition measurements using 4 years of TALE hybrid data.

2 Event Reconstruction

The reconstruction process for the hybrid events is composed of the following 3 steps: the PMT selection for SD side, the determination of shower detector plane (SDP), which is the plane including the shower axis and the SDF location, and the profile constrained geometry fit (PCGF) [4]. At first PMTs to be used in the reconstruction are selected by rejecting those that are spatially and temporally isolated from the shower image. After the good PMTs are selected, the SDP is determined from the pointing direction vectors of the selected PMTs. Once the SDP is determined, we perform the PCGF reconstruction that simultaneously reconstruct the shower geometry and the shower profile. So far the PCGF reconstruction is applied to the SD monocular data, and we perform it in hybrid data. Technically, for each given φ angle, which is the shower inclination angle in the SDP as shown in Fig. 1, the shower geometry is calculated by a time vs angle fit that uses the pointing directions and timings of the PMTs and the one SD. This SD information provides us with more accurate shower geometry than monocular mode. Then the shower profile is fitted in given shower geometry using the Gaisser-Hillas parameterization formula [5]

\[
N(x) = N_{\text{max}} \left( \frac{x - X_0}{X_{\text{max}} - X_0} \right)^{N_{\text{max}} - N_{\text{com}}} \exp \left( \frac{X_{\text{max}} - x}{\lambda} \right). \tag{1} \]

where \(N(x)\) is the number of charged particles at a given slant depth, \(x\), \(X_{\text{max}}\) is the depth of shower maximum, \(N_{\text{max}}\) is the maximum number of particles at \(X_{\text{max}}\), \(X_0\) is the depth of the first interaction, and \(\lambda\) is the interaction length of shower particles. For each trial, a combined \(\chi^2_{\text{com}} = \chi^2_{\text{geo}} + \chi^2_{\text{pfl}}\) is evaluated, and the best expectation of the shower geometry and energy deposit profile from a cosmic ray shower is chosen. All reconstructed events are processed to apply the quality cuts summarized in Table. 1. The obtained shower parameter resolutions energies above

* e-mail: kfujita@icrr.u-tokyo.ac.jp
$10^{16.5}$ eV are ~ 3 % in $R_p$, ~ 1° in $\psi$ angle, ~ 30 g/cm$^2$ in $X_{\text{max}}$ and ~ 10 % in energy (Fig. 2, 3).

Figure 1: The schematics of the monocular and the hybrid shower geometry reconstruction. The relations between the measured values, which are $t_{\text{exp,i}}$, $\alpha_i$ and the fitting parameters, which are $t_{\text{core}}$, $r_{\text{core}}$ and $\psi$. In the hybrid analysis, the two observable, $t_{3D}$ and $r_{3D}$, are added to the relation of the monocular analysis, and as a result the number of the fitting parameter is reduced to two and the geometry determination accuracy is improved.

<table>
<thead>
<tr>
<th>Variable</th>
<th>CL</th>
<th>FL</th>
</tr>
</thead>
<tbody>
<tr>
<td>No saturated PMTs in FD</td>
<td>applied</td>
<td></td>
</tr>
<tr>
<td>$X_{\text{max}}$ bracketing cut</td>
<td>applied</td>
<td></td>
</tr>
<tr>
<td>Angular track-length [dgr]</td>
<td>track &gt; 6.5°</td>
<td>-</td>
</tr>
<tr>
<td>Event duration [ns]</td>
<td>&gt; 100 ns</td>
<td>-</td>
</tr>
<tr>
<td># of PMTs</td>
<td>&gt; 10</td>
<td>-</td>
</tr>
<tr>
<td># of Photo-electrons / # of PMTs</td>
<td>&gt; 50</td>
<td>-</td>
</tr>
<tr>
<td># of Photo-electrons</td>
<td>-</td>
<td>&gt; 2000</td>
</tr>
</tbody>
</table>

Table 1: Quality cuts applied in this work. Here we define fluorescence events as fractional contribution to the total signal of Fluorescence Light (FL) > 0.75, and Cherenkov Light (CL) events as fractional contribution to the total signal of FL ≤ 0.75.

3 Composition Analysis

We presented the preliminary results of a measurement of the cosmic rays mass composition in the energy range of $10^{16.5} - 10^{18.4}$ eV. The result of the mean of the shower maximum, $\langle X_{\text{max}} \rangle$, and the width of the observed $X_{\text{max}}$ distributions, $\sigma(X_{\text{max}})$ as a function of the logarithmic shower energy are presented in Fig. 4. For the comparison, the pure proton and pure iron predictions calculated by our Monte-Carlo simulation are also shown beside the observed ones. In the left panel of Fig. 4, the observed elongation rate shows clearly a break, where the energy is just above $10^{17}$ eV. A linear fit has been rejected with a $p$-value of $2.5 \times 10^{-7}$. The elongation rate before the break energy is $16 \pm 5$ g/cm$^2$/decade and after the break energy is $97 \pm 4$ g/cm$^2$/decade, while the pure proton and iron ones are $68 \pm 2$ g/cm$^2$/decade and $62 \pm 2$ g/cm$^2$/decade, respectively. On the other hand, the $\sigma(X_{\text{max}})$ is compatible or wider than pure proton composition in whole energies. These results indicate that the mass composition at around $10^{17}$ eV, i.e. around the well known 2nd knee in the cosmic ray spectrum, is consistent with mixed composition, and the average mass of cosmic ray increases up to the break energy, then changing to lighter composition with increasing energies.

Figure 2: Reconstruction resolutions of the impact parameter $R_p$, the shower inclination angle in the SDP $\psi$, respectively. Top panels are shown for proton MC case and bottom panels are shown for iron MC case. The black curve is a Gaussian fit to the distribution of the uncertainty.

Figure 3: Reconstruction resolutions of the shower maximum $X_{\text{max}}$, and the shower energy $E$, respectively. Top panels are shown for proton MC case and bottom panels are shown for iron MC case. The black curve is a Gaussian fit to the distribution of the uncertainty.

Figure 4: The histograms of $X_{\text{max}}$, $\psi$, and $\delta$ measured on the FD for the protons and iron MC cases, respectively.}

2
Further comparison with particle detection based experiments, we display a mean logarithmic mass plot. From the observed $X_{\text{max}}$, the mean $\ln A$ can be calculated by:

$$\langle \ln A \rangle = \frac{X_{\text{max}}^{\text{data}} - X_{\text{max}}^{\text{proton}}}{X_{\text{max}}^{\text{iron}} - X_{\text{max}}^{\text{proton}}} \ln A_{\text{iron}},$$

where $X_{\text{max}}^{\text{data}}$ is the mean $X_{\text{max}}$ observed by experiments, $X_{\text{max}}^{\text{proton/iron}}$ are the mean $X_{\text{max}}$ for the proton and the iron primaries obtained by MC simulation, and $\ln A_{\text{iron}}$ is the natural logarithm of the iron atomic mass. The right panel of Fig. 5 shows the $\langle \ln A \rangle$ as a function of energy. The $\langle \ln A \rangle$ values measured by the TALE hybrid detector are shown as black dots with systematic error denoted by gray band.

Figure 4: Top: $\langle X_{\text{max}} \rangle$ as a function of shower energy, measured by using 4 years of the TALE hybrid data. Bottom: $\sigma(X_{\text{max}})$ as a function of shower energy. For both panel, the proton and iron MC rails are also shown.

Figure 5: Top: Comparison of $\langle X_{\text{max}} \rangle$ as a function of shower energy with Auger [6], TA [7, 8], HiRes/MIA [9] measurements. Bottom: Comparison of $\langle \ln A \rangle$ as a function of energy with various measurements. For comparison, two interpretations by KASCADE [10], IceTop [11], Tunka [12], Yakutsk [13], Auger [6], and 8.5 yrs TA BRM/LR hybrid [7] results are shown. The gray band in both figures represents the systematic uncertainty on $X_{\text{max}}$ measurement.

Table 2: Summary of systematic uncertainties on the $X_{\text{max}}$ measurements. Lines with multiple entries represent the values at the low and high end of the considered energy range ($\approx 10^{16.5}$ eV and $\approx 10^{18.5}$ eV, respectively).
4 Conclusion

We report on the preliminary result of the mass composition measurement obtained by using 4 years of TALE hybrid data. In this contribution, we present the measured $\langle X_{\text{max}} \rangle$ and $\sigma(X_{\text{max}})$ as a function of primary energy. The $\langle X_{\text{max}} \rangle$ elongation rate shows a change in the slope at the energy just above $\sim 10^{17}$ eV. This break in the elongation rate is likely correlated with the observed break in the cosmic ray energy spectrum by the TALE FD monocular measurement [3].

Acknowledgement

The Telescope Array experiment is supported by the Japan Society for the Promotion of Science(JSPS) through Grants-in-Aid for Priority Area 431, for Specialy Promoted Research JP21000002, for Scientific Research (S) JP19104006, for Specially Promoted Research JP15H05693, for Scientific Research (S) JP19H05607, for Scientific Research (S) JP15H05741, for Science Research (A) JP18H03705, for Young Scientists (A) JPH26707011, and for Fostering Joint International Research (B) JP19KK0074, by the joint research program of the Institute for Cosmic Ray Research (ICRR), The University of Tokyo; by the Pioneering Program of RIKEN for the Evolution of Matter in the Universe (r-EMU); by the U.S. National Science Foundation awards PHY-1607727, PHY-1712517, PHY-1806797, PHY-2012934, and PHY-2112904; by the National Research Foundation of Korea (2017K1A4A3015188, 2020R1A2C1008230, & 2020R1A2C2102800) ; by the Ministry of Science and Higher Education of the Russian Federation under the contract 075-15-2020-778, IISN project No. 4.4501.18, and Belgian Science Policy under IUAP VII/37 (ULB). This work was partially supported by the grants of the joint research program of the Institute for Space-Earth Environmental Research, Nagoya University and Inter-University Research Program of the Institute for Cosmic Ray Research of University of Tokyo. The foundations of Dr. Ezekiel R. and Edna Watts Dumke, Willard L. Eccles, and George S. and Dolores Doré Eccles all helped with generous donations. The State of Utah supported the project through its Economic Development Board, and the University of Utah through the Office of the Vice President for Research. The experimental site became available through the cooperation of the Utah School and Institutional Trust Lands Administration (SITLA), U.S. Bureau of Land Management (BLM), and the U.S. Air Force. We appreciate the assistance of the State of Utah and Fillmore offices of the BLM in crafting the Plan of Development for the site. Patrick A. Shea assisted the collaboration with valuable advice and supported the collaboration’s efforts. The people and the officials of Millard County, Utah have been a source of steadfast and warm support for our work which we greatly appreciate. We are indebted to the Millard County Road Department for their efforts to maintain and clear the roads which get us to our sites. We gratefully acknowledge the contribution from the technical staffs of our home institutions. An allocation of computer time from the Center for High Performance Computing at the University of Utah is gratefully acknowledged.

References