Highlights from the Telescope Array experiment

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2. Recent results (energy spectrum, composition, anisotropy, other studies)
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Study of muons from ultrahigh energy cosmic ray air showers measured in 6 countries
Telescope Array: The largest cosmic ray observatory in the norther hemisphere

Telescope Array
Delta, Utah, USA. ~1400 m a.s. l.
Collaborators from HiRes, AGASA and other institutes
**Map of the TA site**

- **Fluorescence Detectors (FDs)**
  - Middle Drum (MD) station = 14 FDs
  - TA Low energy Extension (TALE) 10 FDs

- **Surface detectors (SDs)**
  - 507 scintillation detectors
  - 3m²
  - 1.2km spacing
  - total coverage ~700km²

- **Central Laser Facility**

- **FDs**
  - Black Rock Mesa (BRM) station 12 FDs

- **Border of FD station FOV**

- **3 communication towers**
  - For the SD array

- **20km**

- **Border of FD station FOV**
TALE FD

Located in TA MD site
10 FDs in the TALE station
Elevation: $30^\circ$-$57^\circ$ (higher elevation than MD)
Azimuthal: $114^\circ$

Refurbished HiRes telescopes & electronics
Mirror: same as TA FD (MD)
Elec.: 10 MHz 8bit FADC

Installed in Nov. 2012
Operation since Sep. 2013
Hybrid trigger: Sep. 2018
Event sample by SD array

zenith ~38°
Event reconstruction

Event map:
Size = # of particles
Color = timing

Time fit

\[ \tau = a \left(1 - \frac{l}{12 \times 10^3 \text{m}}\right)^{1.05} \left(1.0 + \frac{s}{30 \text{m}}\right)^{1.35} \rho^{-0.5} \]

Modified empirical formula in AGASA

Lateral distribution profile fit

\[ \rho = A \left(\frac{s}{91.6 \text{m}}\right)^{-1.2} \left(1 + \frac{s}{91.6 \text{m}}\right)^{-\eta(\theta)-1.2} \left(1 + \left[\frac{s}{1000 \text{m}}\right]^2\right)^{-0.6} \]

\[ \eta(\theta) = 3.97 - 1.79 \left[\sec(\theta) - 1\right] \]

Empirical formula used by AGASA

\( r = 800 \text{m} \)

S800 -> primary energy
Primary energy determination

\[ E'_{SD} = E'_{SD}(S800, \theta) \]

Scale to FD energy

\[ E_{SD} = \frac{E'_{SD}}{1.27} \]

FD energy \( E_{FD} \)

Hybrid events

SD energy \( E_{SD} \)

Charge density [VEM/m²] vs. distance from shower axis [1200m]

S800

\( r = 800 \text{m} \)
Event reconstruction

Stereo

Line intersection of shower detector planes

Hybrid

Reconstructed shower profiles

Comparing with MC \( \rightarrow \) Xmax
Integration of signals \( \rightarrow \) 1ry E
Status of 11 years of operations

SD array
94.5% of 507 SDs are in operation on 11 year average

FD (BRM, LR)
Duty factors
11.0% for BRM station,
9.0% for LR station
Energy spectrum
Energy spectrum from 11 years of TA SD data, from May 11, 2008 to May 11, 2019

\[ \gamma = -3.28 \pm 0.02 \]
\[ \gamma = -2.68 \pm 0.02 \]
\[ \gamma = -4.84 \pm 0.48 \]

\[ \text{ankle} @ \log E = 18.69 \pm 0.01 \]
\[ \text{cutoff} @ \log E = 19.81 \pm 0.03 \]
\[ \log E/2 = 19.79 \pm 0.04 \]
Significance of suppression is 8.4 \( \sigma \)

Expanding the zenith angle range for \( \log E > 18.8 \) (100 % efficiency)

\[ \gamma = -2.67 \pm 0.02 \]
\[ \gamma = -5.3 \pm 0.5 \]
\[ \log E/2 = 19.97 \pm 0.04 \]
Significance of suppression is 12.0 \( \sigma \)

Energy resolution = 18 % \( \log E > 19.0 \)
Energy scale systematic uncertainty = 21 %
Declination dependence of the TA SD spectrum

The break point of
\[
\log E = 19.64 \pm 0.04 \text{ for lower dec. band (-16° - 24.8°)}
\]
\[
\log E = 19.84 \pm 0.02 \text{ for higher dec. band (24.8° - 90°)}
\]
global significance = 4.3σ (local 4.7σ)

Combined TA spectrum using
22 months TALE FD monocular data +
11 years TA SD data

knee @ \log E \sim 15.5
low energy ankle @ \log E = 16.22 \pm 0.02
second knee \hspace{1cm} @ \log E = 17.04 \pm 0.04
ankle \hspace{1cm} @ \log E = 18.69 \pm 0.01
cutoff \hspace{1cm} @ \log E = 19.81 \pm 0.03
TALE FD monocular reconstruction

Energy spectrum from 4 years of data measured by TALE FD with monocular reconstruction (Jun. 2014 - Nov. 2018)  

**KIM, Jihee**

![Image](attachment:TALE_FD_monocular_reconstruction.png)

Cherenkov-dominant and mixed events are used.

Aperture is calculated by EPO-LHC MC.

**Result of resolution studies by MC**

- **SDP angle:** 1°
- **Rp:** 5%
- **E:** 14%
- **Xmax:** 44 g/cm²
Chemical composition
Scatter plot of $X_{\text{max}}$ vs energy.

$\langle X_{\text{max}} \rangle$ from measured data and from QGSJET II-04 MC predictions (proton and iron)

Data support a light component at any energy.

Systematic uncertainty on $\langle X_{\text{max}} \rangle$ is 15 g/cm$^2$

$X_{\text{max}}$ resolution < 25 g/cm$^2$, Energy resolution < 7 % (energy dependent)

Quality cuts: Coincidence FDs within 2 ms, Downward-going, SDP angle < 170°, track length >= 6°, duration >= 2 us, Xmax in FOV
TA BRM+LR+SD hybrid: $<X_{\text{max}}>$ and $\sigma_{X_{\text{max}}}$

W. Hanlon

$<X_{\text{max}}>$ along with predictions of QGSJET II-04 p, He, N and Fe

10 years data $10^{18.2}$ to $10^{19.1}$ eV
3560 events after the quality cuts

Systematic uncertainty on $<X_{\text{max}}>$ is 17 g/cm$^2$
Xmax bias $<1$ g/cm$^2$
Xmax resolution $=17.2$ g/cm$^2$
Energy resolution $=5.7\%$

$\sigma_{X_{\text{max}}}$ along with predictions of QGSJET II-04 p, He, N and Fe
The measured data are compatible with the protons below $10^{19}$ eV.

Quality cuts:
$D_{\text{border}}>100$m, FD track length $>10^\circ$, 
# FD good PMT $>11$, SDP angle $<130^\circ$,
FD track $>7$us, $\Theta < 55^\circ$, Xmax in FOV,
Good weather
Test the agreement of data and single element models by comparing data and MC Xmax distributions including a systematic shift of data.

Proton and He agree with the data especially in the tail of distributions, whereas N and Fe do not resemble the data.

(Xmax systematic uncertainty = 17 g/cm²)

Data is compatible with QGSJET II-04 proton from $10^{18.2}$ to $10^{19.9}$ eV with systematic shifting about 20 g/cm².

Other components are not compatible in $E < 10^{19}$eV

All 4 single components are compatible in the highest energy bin. ← low statistics (19 events)

Fe requires a shift of ~ 50 g/cm²
TA BRM+LR+SD hybrid: 4 element model

W. Hanlon

QGSJET II-04 proton, He, N, Fe, data: 0 g/cm²

Test the agreement of data and 4 component mix by comparing data and MC Xmax distributions (No systematic shifting).

For $10^{18.2}-10^{19.1}$ eV, minimum $\chi^2$ is found at the fraction, proton = 57%, He = 18%, N = 17%, Fe = 8%.

(Xmax systematic uncertainty = 17 g/cm²)
Xmax measured by TALE FD with monocular reconstruction
4 years of data (Jun. 2014 - Nov. 2018)

Change in Xmax elongation rate at an energy of ~10^{17} eV
(It is likely correlated with 2nd knee in the energy spectrum)

Smooth connection of the low(TALE) and the high(BR/LR hybrid) energy rails.

**Figure 20:** TALE cosmic rays energy spectrum measured with 22 months of data. A mixed primary composition given by the TXF is assumed. The gray band indicates the size of the systematic uncertainties.

**Figure 22:** A comparison of the spectrum obtained with different compositions. With respect to the energy spectrum for the case of pure iron composition assumption, note that composition measurements by other experiments, e.g. [48, 49] exclude the possibility of iron dominated flux at energies below 10^{16} eV. The spectrum is included in the plot simply to demonstrate the extreme case of all heavy primaries.

**Figure 23** compares the current result with some recent results from other experiments. We note that qualitatively the spectra are in agreement. The difference in normalization is within the systematics of the energy scales of the different experiments. In particular, we note that a 6.5% downward shift in the IceTop energy scale, results in a spectrum that lies on top of the TALE spectrum for energies below 10^{17} eV.

**Figure 24** compares the current result with some recent results from TA Fluorescence [55] and surface detector [56] measurements. We note that above 10^{17} eV there is excellent agreement between the different results, demonstrating that the TALE spectrum can be seen as an extension of the measurements in the ultra-high energy regime down to lower energies.
TALE FD monocular reconstruction

Xmax measured by TALE FD with monocular reconstruction
4 years of data (Jun. 2014 - Nov. 2018)

4 component fit to measured Xmax distribution

Change in composition from predominantly light mix at lower energy to heavy mix at $\sim 10^{17}$ eV
Anisotropy study
“Hotspot” update from 11 years of data

Original hotspot reported in 2014, from 5 years of data
E > 57 EeV (Observed 72 events)
20° over-sampling circle
19 events fall in “Hotspot” centered at (146.7°, 43.2°)
(Expected = 4.5 events)
local significance 5.1σ, post trial significance 3.4σ

E > 57 EeV in total 168 events
38 events fall in Hotspot (α=144.3°, δ=40.3°, 25° radius, 22° from SGP), expected=14.2 events
local significance = 5.1 σ, chance probability → 2.9σ
25° over-sampling radius shows the highest local significance (scanned 15° to 35° with 5° step)
“Hotspot” update from 11 years of data

K. Kawata

There is a marginal excess is seen along the SGP (around the Perseus-Pisces Supercluster) at the local significance of ~ 3σ.

The increase rate of the events inside the hotspot circle is consistent with a constant within ±1σ fluctuation.

Hotspot from 11 years of TA SD data, from May 11, 2008 to May 11, 2019

E > 57 EeV, in total 168 events
38 events fall in Hotspot (α=144.3°, δ=40.3°, 25° radius, 22° from SGP), expected=14.2 events
local significance = 5.1 σ, chance probability → 2.9σ
25° over-sampling radius shows the highest local significance (scanned 15° to 35° with 5° step)
Other studies
EAS time structure analysis

R. Mayta

Analyzing the shower structure (curvature and thickness) as functions of R, θ and E using 11 years of TA SD data.

Averaged shower thickness, \( < t_R > \), are fitted to a linear function,

\[
\langle t_R \rangle = b + a \times R
\]

where \( a \) and \( b \) are the fitting parameters.

Averaged delay from the plane, \( < t_d > \), are fitted to the function,

\[
t_d = 2.6 \times \left( 1 + \frac{R}{30m} \right)^A \times \rho^B [m^{-2}][ns]
\]

where, \( \rho \) is the particle density at R. A and B are the fitting parameters.
Non Imaging CHErenkov array (NICHE)

NICHE is a low energy extension of TALE sensitivity in order to measure the chemical composition of cosmic rays in the energy from 1 to 100 PeV.

D. Bergman
Y. Omura

14 Cherenkov light detectors (3inch PMT+45° Winston corn), ~800 m from TALE FD, 100 m spacing. Deployment started Sep. 2017, commissioning until Feb. 2019.

A coincidence event detected by NICHE and by TALE-FD at Sep. 21, 2017. And a hybrid geometry reconstruction from NICHE and TALE-FD data.
Current status of extension projects

1. TALE hybrid
2. TAx4
TALE hybrid

TALE hybrid =
low energy extension of TA hybrid
sensitivity down to $10^{16}$ eV, with
FDs observing higher elevation,
Densely-arrayed SDs

Precise measurement of the composition:
FD + SD hybrid measurement

TALE-FD: 10 telescopes are in operation
since Sep. 2013

→ Installed 80 SDs with 400m, 600m spacing
TALE-SD array in operation since Feb. 2018
TALE-hybrid started running at Sep. 2018

Expected specifications of TALE hybrid
Threshold energy $E : \log E = 16.0$
Event rate: ~5,000 events/year
$\Delta \theta = 1.0^\circ$ (FD mono: 5.3$^\circ$)
$\Delta X_{\text{max}} = 20 \text{ g/cm}^2$ (FD mono: 44 g/cm$^2$)
**TA×4**

In order to increase the event statistics@UHE

\[ \downarrow \]

To increase the coverage from

TA = 700 km\(^2\)

\[ \downarrow \]

TA×4 = 3,000 km\(^2\)

SD array of \(\sim\)3000 km\(^2\)

by 500 SDs

with 2 km spacing

+ 2 FD stations (12 HiRes-II telescopes)

4 FDs at the northern station

8 FDs at the southern station
New PMT (Hamamatsu R8619)
- QE ~20% @500nm (TA: ~10%)
- Linear range max @~50mA (TA: ~25mA)
- Photo-cathode uniformity

→ reduce total length of WLSF ~33% of TA
**TA×4**

Feb. 19 - Mar. 12, 2019

257 SDs

6 communication towers

were installed in the site
**TA×4@Apr. 2019**

**Trigger efficiency:**
> 95%@57EeV

**Energy resolution:**
25%

**Angular resolution:**
2.2°
TA×4

TA×4 northern FD station

First light @ Feb. 16, 2018

TA×4 southern FD station

under construction

TA×4 array

TALE SD array

TA SD array

TA×4 FD FOV

TA×4 FD FOV
TA site: Platform for next generation

FAST
Fluorescence detector Array of Single-pixel Telescopes

EUSO-TA
(connect to POEMMA)

CRAFFT
(Cosmic Ray Air Fluorescence Fresnel lens Telescope)

Next generation detector for ultra-high energy cosmic ray air shower observation
Developing a low cost FD using Fresnel lens and single pixel
Deployed four CRAFFT detectors at TA FD site.
Test observation: 2017 Nov. 9 – Nov. 23 (10 nights, 63.5 h)
Succeeded to detect 10 UHECR air shower events!!
TA site: Platform for future

F. Biscotti for JEM-EUSO collaboration

EUSO-TA

UHECR event on May 13, 2015

EUSO-TA
(external trigger from TA BRM)

TA BRM-FD
$R_p = 2.5\text{ km, } \log E = 18$

EUSO-TA F.O.V.
5. Installation of a FAST prototype at the Pierre Auger Observatory further understanding of the telescope calibration factors are required to reduce the discrepancy.

Waveforms corresponding to these parameters show reasonable agreement with the data, although reconstruction. The preliminary energy and binary waveforms of the FAST prototypes with simulated signals from the result of the top-down reconstruction. The preliminary energy and shower parameters are reconstructed by the top-down method using a library of simulated templates. Figure 4 shows event displays of the two highest energy cosmic rays detected by the TA FD and FAST prototypes, along with a comparison between the preliminary energy and shower parameters reconstructed by the TA FD.

The design of the full-scale FAST prototype and the three FAST prototypes installed at the Black Rock Mesa site of the Telescope Array Experiment.

We installed an additional identical FAST prototype at the Auger site in April 2019 and began a "top-down" reconstruction algorithm for data collected by the FAST prototypes has been implemented to determine the best-fit shower parameters by comparing the measured signal trace with a library of simulated templates. Figure 5 shows photographs taken during the installation. Signals from a distant object were observed with this new prototype. The total observation time is 85 hours as of June 2019. This prototype observed the EAS event with the highest energy recorded in the history of the Auger Observatory.

The impact parameter and time-average brightness of detected the EAS as a function of the energy is shown in Figure 6. The observed impact parameter distribution is consistent with the expectations from the simulation. The time-average brightness is proportional to the square of the energy of the detected cosmic rays. The energy spectrum of the detected cosmic rays is consistent with the expectations from the simulation. The observed energy spectrum is consistent with the expectations from the simulation.

One of the highest energy events detected by TA FD, SD and FAST prototype.

Y. Tameda for CRAFFT collaboration

One of events detected by TA FD & CRAFFT

T. Fujii for FAST collaboration
Summary (1/2)

- Telescope Array is UHECR observatory in the northern hemisphere.
- Hybrid = Fluorescence Detectors + 700 km² Surface Detector array
- Energy spectrum from 11 year observations by TA SD array
  - Indication of the declination dependence
- TA Low Energy Extension (TALE) FD have measured energy spectrum.
- TA FD stereo and hybrid Xmax measurements
  - Below $10^{19.1}$ eV TA hybrid data is found to be compatible with mixtures composed of predominantly light elements such as protons and helium.
- Hot spot from 11 years of data, it is seen in the direction of Ursa Major (post trial 3σ significance). It now appears larger (extended) than we originally thought.
- NICHE is in operation since Sep. 2017.
- We need much more data at high energy end – > TAx4 is in operation!
- Full TALE SD is now on-line! Hybrid observations since Sep. 2018.
  - Hybrid measurement has extended the energy reach below $~10^{16}$ eV
- TA site is a platform for FUTURE!
Summary (2/2)

10th anniversary of Telescope Array operation symposium and ceremony at Dec. 19, 2018

in ICRR, University of Tokyo

Thank you for your continuous support toward 20th anniversary!