TA Spectrum Summary

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Outline

- Telescope Array (TA) Experiment
- TA Spectrum Measurements
  - Surface Detector (SD)
  - Fluorescence Detector (FD) Mono
  - TA Low Energy Extension (TALE) Fluorescence and Cherenkov
- Combined Spectrum
- Conclusions
Telescope Array
Hybrid detector
Millard County, UT
39.3° N, 112.9° W,
Alt. 1400m
~880g/cm²
507 Surface Detector (SD) counters, 1.2km apart
16 active TALE infill array counters, 400m spacing

4 Communication Towers (CT): BR, LR, SK, MD
3 Fluorescence Detector sites (FD): BR, LR, MD/TALE

Middle Drum, TALE (MD)
Smelter Knolls (SK) - CT
Long Ridge (LR)
Black Rock Mesa (BR)
TA Surface Detector

- Powered by solar cells; radio readout.
- In operation since March, 2008.
- Self-calibration using single muons.
- Energy deposited by cosmic ray shower particles is measured in **VEM** units (**Vertical Equivalent Muon** = energy deposited by a vertical minimum ionizing muon)
Surface Detector Event

![Diagram showing surface detector event with north and east coordinates, time vs distance along shower axis on the ground, and charge density vs perpendicular distance from shower axis.](image)
A look-up table made from the Monte-Carlo

Event energy ($E_{TBL}$) = function of reconstructed S800 and sec($\theta$)

Energy reconstruction $\leftrightarrow$ interpolation between S800 vs sec($\theta$) contours of constant values of $E_{TBL}$

The overall energy scale locked to the fluorescence detector
SD Energy 2/2: Energy Scale Set to FD

- Energy scale locked to the FD to reduce the systematic due to the model
- Use events well reconstructed separately by SD and FD in hybrid mode:
  - SD \cap [BR U LR U MD Hybrid]
  - \( E^{\text{FINAL}} = \frac{E^{\text{TBL}}}{1.27} \)
- TOP figure: \( E^{\text{FINAL}} \) vs \( E^{\text{FD}} \) scatter plot
- BOTTOM figure: histogram of \( \frac{E^{\text{FINAL}}}{E^{\text{FD}}} \) ratio
- 2008/05/11-2013/05/04
Exposure from Monte Carlo

- Detailed Monte Carlo used for exposure calculation in all measurements of TA

6300 km² sr yr

TA SD
2008/05/11-2015/05/11
Fluorescence Mono Analysis

Black Rock Mesa

Fluorescence
Direct (Cerenkov)
Rayleigh scatt.
Aerosol scatt.

Time fit
Profile fit
TA Low Energy Extension (TALE)

- Study the $10^{16}$ and $10^{17}$ eV decades with a hybrid detector.
  - End of the rigidity-dependent cutoff that starts with the knee (at $3 \times 10^{15}$ eV).
  - The second knee
  - The galactic-extragalactic transition
- High energy physics measurements:
  - $\sigma(p\text{-air})$ and $\sigma(p\text{-p})$ from LHC energy ($10^{17}$) to $10^{19}$ eV.
- Need to observe from $3 \times 10^{16}$ eV to $3 \times 10^{20}$ eV all in one experiment. That is TA and TALE.
TALE FD

- Add 10 telescopes at the Middle Drum site, looking from 31°-59° in elevation.
- Operate in conjunction with the TA Middle Drum FD.
**TALE Infill Array**

- Add infill array (400m and 600m spacing) for hybrid and stand-alone observation.
- Also add counters to build out main TA SD array (1200m separation).
- 105 counters in all, 16 are now taking data which is currently being analyzed.
TALE Events

7 mirror event, \( \log(E) = 16.5 \)

Parallax event, \( R_p = 800 \text{m} \)

Hybrid event
Unexpected result: many Cherenkov events are seen as tracks (most land ~0.5 km from FD). Use profile constrained reconstruction. Cherenkov light is bright ➞ can go lower in energy than expected.
TALE DATA/MC Comparisons

Mixed

KS Probability
6.588e-01

Entries 3023
Mean 1624
RMS 659

Mixed

KS Probability
6.858e-01

Entries 3023
Mean 85.53
RMS 34.83

Data: Inverse Angular Speed

Mixed

KS Probability
6.502e-02

Entries 3023
Mean 0.0494
RMS 0.02231
TA Spectra

- Energy spectrum measurements available in TA for each type of detection technique
- Often, more than one analysis exists
- To form a combined spectrum, we choose analyses with best statistics and energy resolution for their respective energy ranges
TA Resolution and Exposure as Function of Energy

![Graph showing resolution and exposure as a function of energy.](image)
TA SD, \( E > 10^{18.2} \) eV

\[ E^3 \times J \text{ [eV}^2 \times \text{m}^{-2} \times \text{sr}^{-1} \times \text{s}^{-1}] \]

\[ \log_{10} (E/\text{eV}) \]

TA SD 7 year (ICRC 2015)
Add TA BR/LR Mono, $10^{17.2} \text{ eV} < E < 18.8 \text{ eV}$
Add TALE Fluorescence and Cherenkov, $10^{15.5} \text{ eV} < E < 18.3 \text{ eV}$

Preliminary, UHECR 2016

Graph showing $E^3 \times J [\text{eV}^2 \times \text{m}^2 \times \text{sr}^{-1} \times \text{s}^{-1}]$ vs. $\log_{10}(E/\text{eV})$ for TA SD 7 year (ICRC 2015), BR-LR Mono 7 year (ICRC 2015), and TALE Fluorescence & Čerenkov (UHECR 2016).
Combine the TA spectrum

Preliminary, UHECR 2016
4 to 5 features, over nearly 5 orders of magnitude in energy

Second knee at $\sim 10^{17.2} \text{ eV}$

Ankle at $\sim 10^{18.7} \text{ eV}$

Break at $10^{19.8} \text{ eV}$

Low energy ankle at $\sim 10^{16.3} \text{ eV}$

Possibly beginning of the knee feature at $\sim 10^{15.6} \text{ eV}$
Standard SD spectrum analysis

- From 2008/05/11 to 2015/05/11
- Cuts
  - Zenith angle < 45 degrees
  - $N_{SD} \geq 5$
  - Distance of the shower core from the border of the array > 1200m
  - Geometry, LDF Chi2 / d.o.f. < 4
  - Pointing direction uncertainty < 5 degrees
  - S800 fractional uncertainty < 25%
  - $E > 10^{18.2}$ eV
  - $\sim 6300$ km$^2$ sr yr exposure above $10^{19.0}$ eV

For details on BR/LR Mono spectrum, see Astropart. Phys. 80 (2016) 131-140

For details on TALE Combined spectrum see T. AbyZayyad presentation at this conference
Berezinsky $E_{1/2}$ and GZK Cutoff

$E_{1/2} = 10^{19.77 \pm 0.06}$ eV

Consistent with proton propagation on CMB
Declination dependence of SD spectrum

- Position of the 2’nd break point appears to be dependent on the declination band
  - \(\sim 3.9\sigma\) effect
  - This result uses events up to 55 degrees in zenith angle
- See TA/Auger working group report for comparisons with Pierre Auger in different declination bands
Auger / TA (as of ICRC-2015)

- Significant discrepancy with Pierre Auger above ~25 EeV
- Good agreement everywhere else, down to $10^{17.5}$ eV, after Auger energies were rescaled by 10%
- For current status, see TA/Auger spectrum working group report
Combined TA with Other Experiments

Preliminary, UHECR 2016

\[ E^3 \times J \ [\text{eV}^2 \times \text{m}^{-2} \times \text{s}^{-1} \times \text{s}^{-1}] \]

- HiRes-II (2008)
- Yakutsk Cherenkov (2013)
- Tunka-55 (2013)
- Tunka-133 (2013)
- KASCADE-Grande (2011)
- Auger (2013)
- ICETOP (2013)
- TA Combined (UHECR 2016)
Conclusions

• We measured spectrum over ~5 orders of magnitude in energy, starting at $10^{15.5}$ eV

• One experiment, one energy scale, consistent with proton composition at highest energies

• 4 Features:
  • Low Energy Ankle at $\sim10^{16.3}$ eV
  • 2$^{nd}$ knee at $\sim10^{17.2}$ eV
  • Ankle at $\sim10^{18.7}$ eV
  • GZK Break at $\sim10^{19.8}$ eV

• Evidence of TA spectrum declination dependence at highest energies

• Good agreement with HiRes, but discrepancy with Pierre Auger at $\sim25$ EeV (energy rescaling doesn’t help)