Energy Spectrum and Mass Composition of Ultra-High Energy Cosmic Rays Measured with the Telescope Array Fluorescence Detector Using a Monocular Analysis

CR-EX 714
PoS(ICRC2015)320

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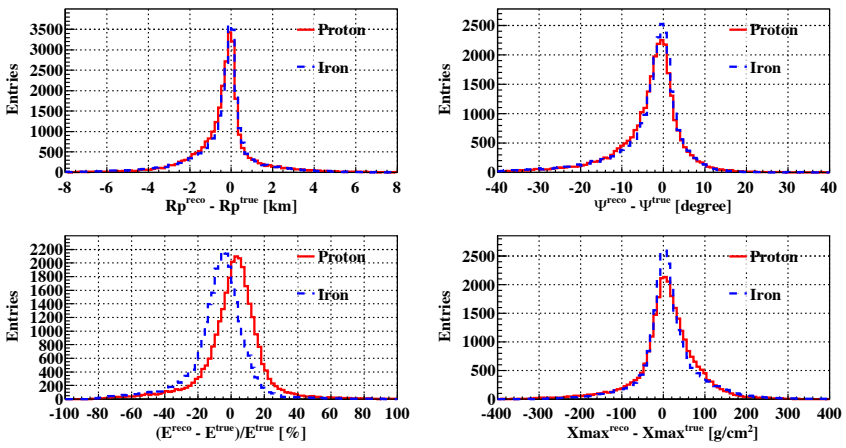
Telescope Array Fluorescence Detectors

- Largest cosmic ray detector in the northern hemisphere. 507 surface detectors covering an effective area of about 700 km^2, overlooked by 38 fluorescence detectors (FDs) [Telescope Array Collaboration, Nucl.Instrum.Meth. A689 (2012) 87].
- The FDs observe atmospheric fluorescence photons emitted by molecules excited by an ultra-high energy cosmic rays (UHECRs), providing a determination of the primary energy and the longitudinal development including $X_{\max}$.
- $X_{\max}$ is a slant depth at which the longitudinal development of cosmic ray reaches its maximum and it depends on the mass composition of UHECRs.
- The newly designed and constructed FDs start a stable observation from 2008 [H. Tokuno et al., Nucl.Instrum.Meth. A601 (2009) 364]

New fluorescence detector in the Telescope Array Experiment

Monocular Analysis and Performance

- Reconstruct UHECRs using the measured data by one FD station.
- An arrival timing of the signal in each photomultiplier tube is fitted to reconstruct the geometry. The longitudinal development is calculated by the inverse Monte Carlo method [T. Fujii et al., AIP Conf.Proc. 1367 (2011) 149]
- The performance of the monocular analysis is estimated by the Monte Carlo (MC) simulation and reconstruction.



Resolution of monocular analysis: 1.4 km on impact parameter (R_p), 7.7 degree on angle on SDP (ψ), 17% on Energy, 72 g/cm^2 on $X_{\max}$

Aperture calculation by Monte Carlo simulation

- Aperture of FD, AΩ, is estimated by MC simulation as a function of primary energy, E,

$$A\Omega(E) = A\Omega_{\text{gen}} \cdot N_{\text{reco}}(E)/N_{\text{thrown}}(E)$$

where $A\Omega_{\text{gen}}$ is the generated aperture region of MC simulation.
- The obtained aperture is fitted by a broken exponential function.
- The aperture assuming proton fraction is calculated by,

$$A\Omega^f = A\Omega^{\text{P}}(R + f \cdot (1 - R))$$

- R is relative difference of aperture between proton and iron,

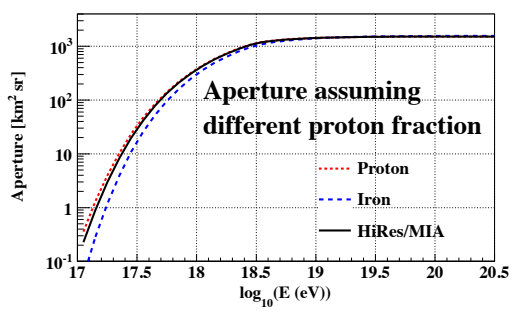
$$R = A\Omega^{\text{Fe}}/A\Omega^{\text{P}}$$

The broken exponential function

$$\log A\Omega = p_1\left(1 - \exp\left(-\frac{\log E - p_2}{p_3}\right)\right), E \le E_b$$
$$= \gamma p_1\left(1 - \exp\left(-\frac{\log E - p_4}{p_5}\right)\right), E \ge E_b$$

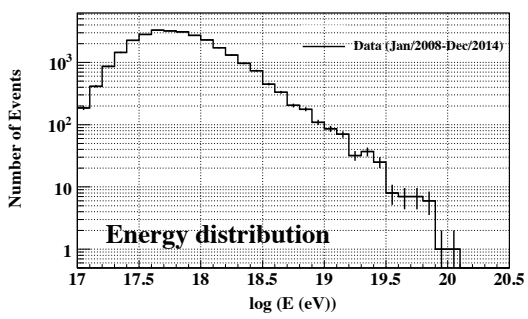
where E_b is the energy of the break and

$$\gamma = \frac{1 - \exp(-(\log E_b - p_2)/p_3)}{1 - \exp(-(\log E_b - p_4)/p_5)}$$



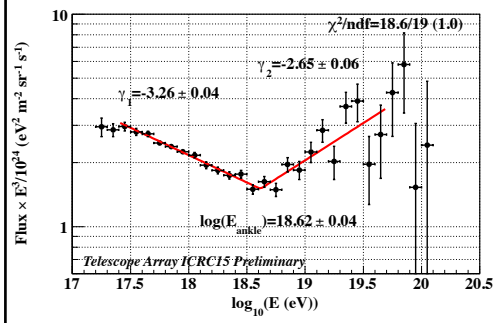
Observed Data Analysis

- Data period: January 2008 - December 2014 (7 years)
- Newly constructed FD stations at two locations.
- 28869 events above 10^{17} eV
- Exposure: 650 (km^2 sr yr) at 10^{19} eV

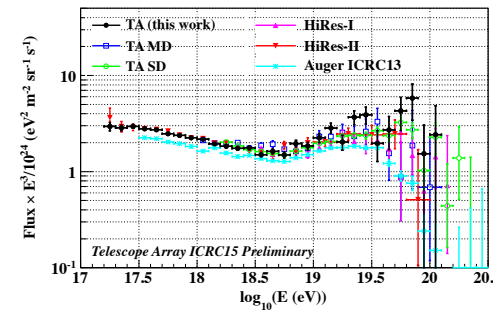


Energy Spectrum Measurement

Energy spectrum in the first seven years

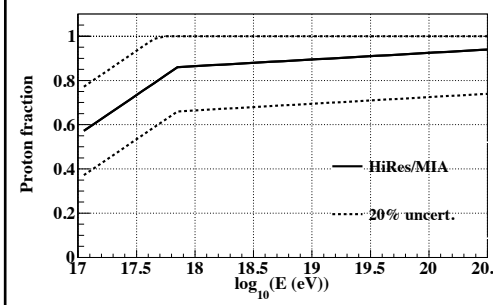


Comparison with other results

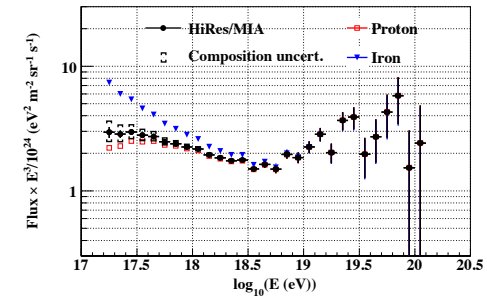


21% systematic uncertainty on energy scale; fluorescence (11%), atmosphere (11%), calibration (10%), geometry (4%) and reconstruction (10%).

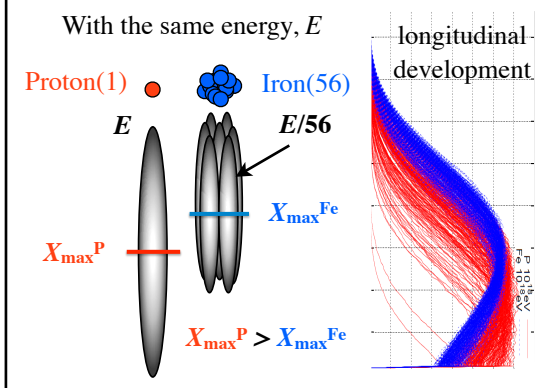
Assumed proton fraction (HiRes/MIA)



Systematic uncertainty on proton fraction

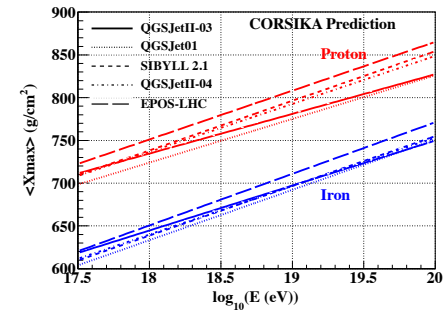


Mass Composition Measurement



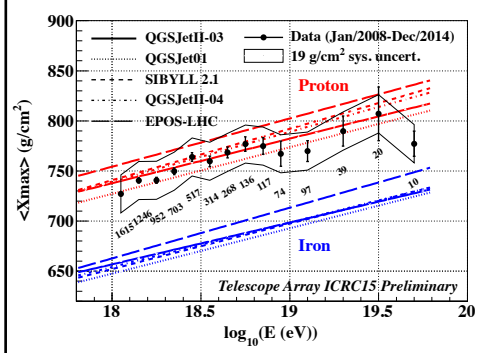
Generated average $X_{\max}$ by CORSIKA

[D. Heck et al., FZKA-6019 (1998)]

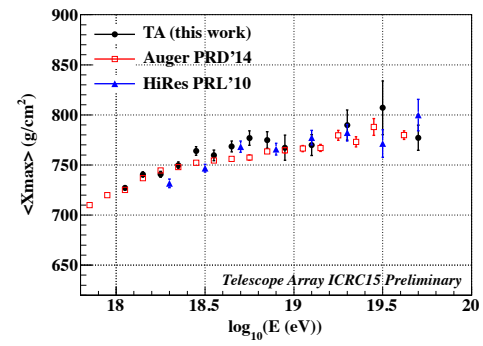


- The fiducial FoV cuts are defined to reduce detection bias on Xmax.
- The identical cuts are applied in analysis of both observed data and MC simulation.
  $X_{\text{start}}(E) \leqq 45.8 \times \log(E) - 215.8$, $X_{\text{end}} \geqq 20.8 \times \log(E) + 501.4$

Average $X_{\max}$

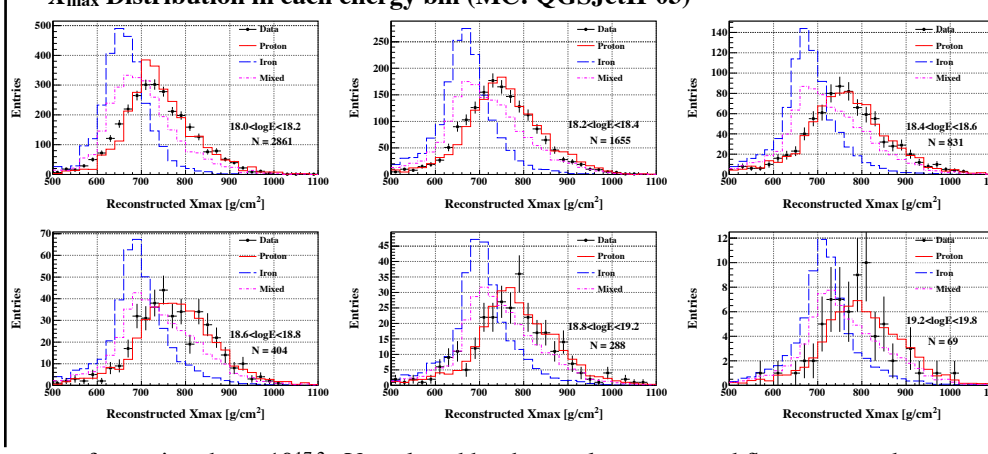


Comparison with other results



Systematic uncertainty on Average $X_{\max}$ is 19 g/cm^2; fluorescence (5 g/cm^2), atmosphere (12 g/cm^2), calibration (5 g/cm^2), geometry (9 g/cm^2), reconstruction (10 g/cm^2).

$X_{\max}$ Distribution in each energy bin (MC: QGSJetII-03)



Conclusions

Conclusions: We report on a measurement of the cosmic ray spectrum covering a broad range of energies above $10^{17.2}$ eV analyzed by the newly constructed fluorescence detectors of the Telescope Array experiment using the monocular analysis during the first seven years. The obtained spectrum has an obvious broken structure at energy of $\log(E_{\text{ankle}}) = 18.62 \pm 0.04$. The structure is in good agreement with the spectra reported using the TA surface detector, and by the HiRes-II. We report the mass composition using the fiducial FoV cuts to reduce observation bias on $X_{\max}$. The obtained average $X_{\max}$ and its distribution shows proton-dominated composition at this energy range which is consistent with already reported results within the systematic uncertainty.