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TA 10-Year Stereo Composition Measurement

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The nuclear composition of primary ultra-high energy cosmic rays (UHECRs) can be inferred from the observed distribution of depths of shower maximum (X_{max}) of the induced extensive air showers. The observed X_{max} distributions at various primary energies can be compared with the distributions predicted by detailed detector simulations for any assumed primary particle type and high-energy hadronic interaction model. In this paper, we present measurements of X_{max} by the Telescope Array (TA) fluorescence detectors with stereoscopic shower reconstruction using 10 years of data. We find that for all hadronic models considered, the data collected is consistent with a chiefly light UHECR composition.

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1. Introduction

The flux of Ultra-high-energy cosmic rays (UHECRs; $E > 10^{18}$ eV) is very low, requiring large indirect-detection experiments using the Earth's atmosphere as a calorimeter. The Telescope Array (TA) Experiment covering 700 km^2 of the desert in central Utah, USA, is the largest UHECR detector in the northern hemisphere [1].

One of the primary objectives of TA is the measurement of UHECR nuclear composition. Extensive air showers (EASs) are produced by "primary" UHECRs incident on the atmosphere. An EAS of a given (primary) energy reaches its maximum size at a slant depth X_{max} that gets smaller as the nuclear mass of the primary UHECR gets larger. The TA composition measurement uses the observed X_{max} distribution in comparison with the distributions predicted by detailed simulations that accurately model the detector, for various high-energy hadronic interaction models. The high-energy interaction models are uncertain due to extrapolations from measurements at much lower energies.

We present the observed X_{max} distribution from over 11 years of TA operation compared with simulated distributions created using an identical data analysis. The CORSIKA p0ogram [2] is used to simulate the longitudinal development of hydrogen and iron primaries using several different models (QGSJET-II-04 [3], QGSJET-II-03 [4], QGSJET-01c [5], EPOS LHC [6], and SIBYLL 2.1 [7]). The detector response is then simulated for each shower and simulated data is produced in the same format as the real data from the detector. The X_{max} measurements are performed using shower axes determined by stereoscopic measurements, detailed in Section 2. The detector simulation is described in Section 3, followed by the presentation results in Section 4 and a discussion in Section 5.

2. Stereo Analysis

TA consists of three sets of fluorescence detector (FD) telescopes, located 20–30 km apart, overlooking an array of surface detectors [8, 9]. Two of the FD stations employ identical, FADC-based telescope electronics, while the third station uses refurbished sample-and-hold equipment from the High Resolution Fly's Eye Experiment [10]. The FDs operate only on clear, moonless nights and observe the longitudinal development of EASs. When two FD sites observe the same shower, the intersection of shower-detector planes uniquely determines the location and orientation of the shower trajectory to a high degree of accuracy. If three FD sites observe the same shower, an algorithm selects the best pair of sites based on plane-crossing angles.

Using this shower geometry, and the current atmospheric density profile, one can determine the slant depth along shower track which is observed by each FD pixel. We determine X_{max} by an inverse Monte-Carlo (IMC) method, in which the parameters of a Gaisser-Hillas shower-shape [12] are varied to find the shower profile that minimizes a χ^2 comparison between observed and simulated signals.

Energy reconstruction is done by integration of the best-fit Gaisser-Hillas profile, weighted by a self-consistent energy-deposit model, to obtain a calorimetric energy. A correction for the "missing" energy (from the muons and neutrinos in the shower) is calculated from an analysis of QGSJET-II-03 protons.

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An independent reconstruction of the shower profile is done for each FD observing an event using the stereo geometry. This can result in up to three separate measurements of the Gaisser-Hillas parameters for each shower. When two or three measurements all pass profile quality cuts, we use the unweighted average values of X_{max} and $\log_{10}(E/\mathrm{eV})$ in the analysis. If only one measurement survives the cuts, it is admitted to the final data set only if it passes an additional quality cut based on a pattern-recognition analysis originally developed for "hybrid" reconstruction and described in [13].

3. Simulation Procedure

We use a shower library consisting of Gaisser-Hillas fits to CORISKA-generated shower longitudinal data as the input to our detection simulation. The shower library has a number of bins in energy and shower inclination. Shower trajectories are selected from an isotropic distribution with zenith angles $\theta \leq 80^{\circ}$. Shower energies are chosen according to the HiRes spectrum [10] for energies above $10^{17.7}$ eV. The response of the detector is then simulated, including fluorescence and Cherenkov light production, atmospheric transmission, optical acceptance, and detector electronics simulation including night-sky background noise. The detector simulation is performed for all nights when at least two FDs were operating from 4 Nov 2007 to 28 Nov 2017.

The simulation outputs artificial raw data, which can be processed and analyzed with the analysis chain which is applied to natural night-sky data. This chain includes identification of shower-detector planes, inter-FD coincidence detection, stereo geometry calculation, and profile reconstruction [11].

4. Results

We show our X_{max} distributions in energy bins for $E \geq 10^{18.4}$ eV and the QGSJET-II-04 predictions for hydrogen and iron in Figure 1. In Figure 2 we show the mean of the observed and simulated distributions in several energy bins, and linear fits to these values from all physics models to illustrate the relationships among the various predictions.

5. Discussion and Conclusions

Although iron is an attractive candidate for acceleration to ultra-high energies because of its cosmic abundance, nuclear stability, and large electric charge, the results shown in Section 4 demonstrate that the X_{max} distribution observed by stereo analysis of TA data does not support a significant amount of iron in the composition at any energy above $10^{18.4}$ eV, regardless of the high energy interaction model. A pure-proton composition is attractive when combined with QGSJET-01c, but the agreement is less clear when post-LHC models are considered. This applies marginally to QGSJET-II-04, and more strongly to EPOS LHC, and also to the pre-LHC model SIBYLL 2.1; LHC corrections to SIBYLL are expected to further widen the difference from TA data [14].

On average, our reconstruction of X_{max} and energy are respectively accurate to better than 25 g/cm^2 and 7%. The systematic uncertainty on these TA X_{max} measurements is approximately 15

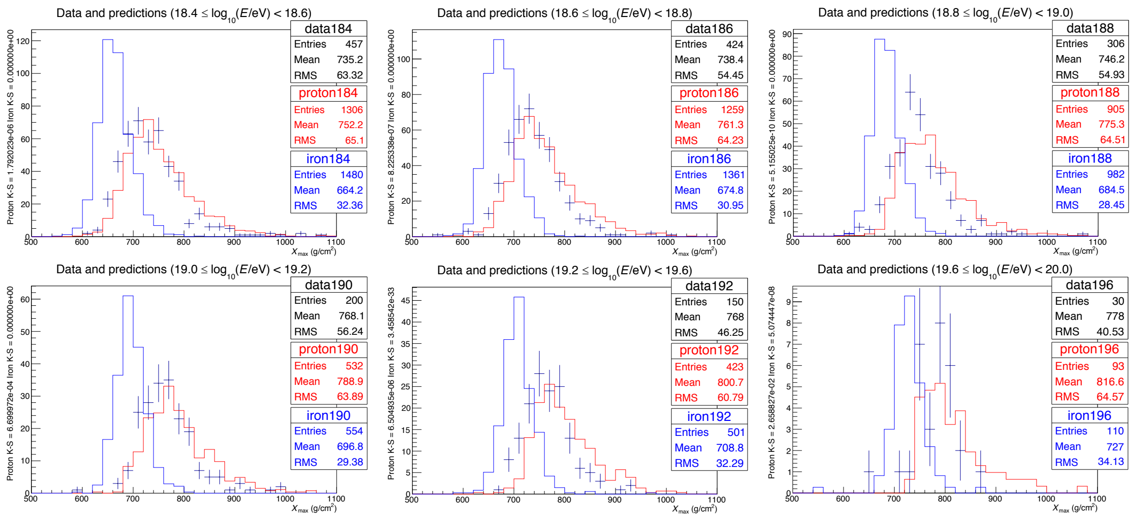

Figure 1: The distribution of reconstructed X_{max}, binned by reconstructed primary energy. The proton and iron predictions are based on the QGSJET-II-04 model for high-energy hadronic interactions. The data and proton histograms agree in both mean and overall shape, while disagreeing strongly with iron.

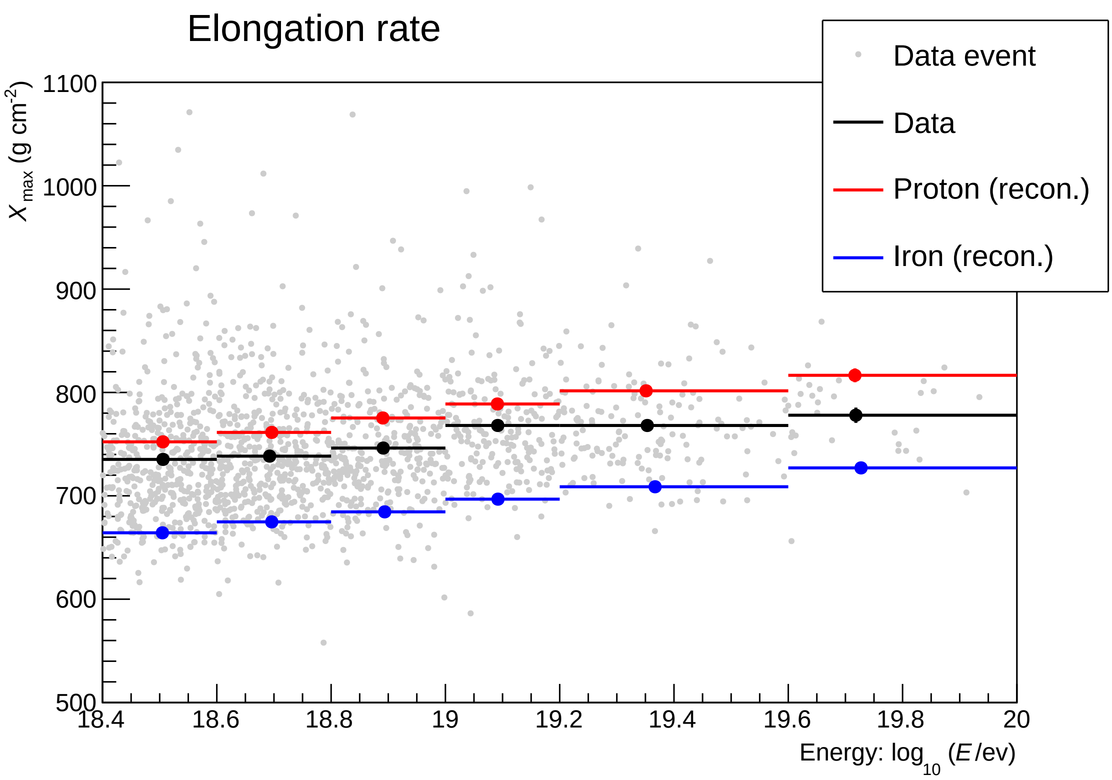

Figure 2: A scatter plot of X_{max} vs. energy for 10 years of data, overlaid with profile histograms showing the energy evolution of the mean X_{max} of the data and each Monte Carlo prediction (proton and iron, according to QGSJET-II-04). The systematic uncertainty on reconstructed X_{max} is 15 g/cm^2.

g/cm^2. Much of this uncertainty originates in the atmospheric models used, both for the density profile and the aerosol distribution.

Further work on this analysis, will help to clarify the extent to which the UHECR composition can be explained only one light element. Contributions from other nuclear constituents may help to bring various moments of the observed and simulated $X_{\rm max}$ distributions into agreement, but we are also exploring the use of statistically robust comparisons that consider the entire distribution. In particular, the Cramér-von Mises test statistic [15], combined with the value of whatever artificially imposed offset minimizes it, shows great promise for quantifying the role played by intermediate-mass elements in the UHECR flux.

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